THE READINESS OF ROAD NETWORK AND ITS IMPLICATIONS FOR AUTOMATED VEHICLE OPERATIONS

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by

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INTELLECTUAL PROPERTY AND PUBLICATIONS

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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The work presented in **Chapter 2** of the thesis has appeared in publication as follows: Tengilimoglu, O., Carsten, O., Wadud, Z., 2023. Implications of automated vehicles for physical road environment: A comprehensive review. Transportation Research Part E: Logistics and Transportation Review 169, 102989. doi.org/10.1016/j.tre.2022.102989
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Under the guidance of Zia Wadud and Oliver Carsten, the candidate contributed substantially to the conception and design of the study. The candidate conducted a survey with key international stakeholders in vehicle automation. He collected, analysed, and interpreted the data, and wrote the article. Zia Wadud and Oliver Carsten provided recommendations on the study design, modelling work and comments on the results. The manuscript was improved by comments from all the co-authors.

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ABSTRACT

The emergence of Automated Vehicles (AVs) introduces new challenges and opportunities for transportation networks and the built environment, with their potential impacts broadly investigated over the last decade. However, integrating AVs safely and efficiently into current and near-future road infrastructure represents a significant, yet largely unexplored, challenge. In this context, understanding the infrastructure-related requirements of AVs and their interaction with road infrastructure is crucial to assess the readiness of the existing road networks and prepare them for future developments. As such this thesis aims to evaluate the readiness of existing (or near-future) road infrastructure to support the deployment of AVs. In this regard, the study begins with a comprehensive literature review of the implications of AVs for road infrastructure. Thirteen key topics related to the infrastructure side of vehicle automation have been revealed and discussed, but various critical areas require further exploration through expert insights. Drawing on primary responses from 168 experts across 29 countries, this thesis captures stakeholders' perspectives on some of these unexplored aspects. Building on this foundation, the thesis then introduces a novel and practical assessment framework to evaluate road network readiness for the operation of highly automated vehicles, taking into consideration the uncertainties in the development of automated driving technologies. By defining two AV capability levels and adopting three potential network scenarios the framework offers a holistic view on the impacts of future deployment strategies and technological advancements on the suitability of current infrastructure for AV operations. Applied empirically in Leeds, United Kingdom, the study demonstrates the framework's practicality, uncovering significant heterogeneity in readiness across the road network. This diversity ranges from highly structured environments with robust support to less structured areas lacking infrastructure, highlighting the complexity of AV integration. Building on the developed readiness index, the study then investigates the impact of heterogeneity in road infrastructure readiness on the usefulness of AVs for urban commuting. Employing a hypothetical scenario where current car commuters have access to AVs for their daily trips, this research explores the possibility of replacing commuting trips with AVs, given the existing levels of infrastructure readiness. The study evaluates the usefulness of AVs for such journeys by examining various road network configurations and AV capabilities. The findings reveal that infrastructure readiness levels significantly impact AV usefulness, showing that infrastructure upgrades are required to accommodate future AV deployment. Overall, the research offers vital insights that contribute to the understanding of AV integration into road networks and support decision-makers and transport planners in developing informed and future-oriented policies, regulations, and guidelines.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

Abbreviation	Full form
5GAA	5G Automotive Association
AASHTO	American Association of State Highway and Transportation Officials
ACC	Adaptive Cruise Control
AD	Automated Driving
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving System
AV	Automated Vehicle
AVP	Automated Valet Parking
AVSC	Automated Vehicle Safety Consortium
BASt	German Federal Highway Research Institute
BSI	British Standards Institution
CAR	Center for Automotive Research
CAV	Connected and Automated Vehicle
CCAV	Centre for Connected and Autonomous Vehicles
CDRC	Consumer Data Research Centre
CV	Connected Vehicle
C-V2X	Cellular-Vehicle-to-Everything
DARPA	Defense Advanced Research Projects Agency
DDT	Dynamic Driving Task
DEM	Digital Elevation Model
DfT	Department for Transport
DMRB	Design Manual for Roads and Bridges
DSD	Decision Sight Distance
DSRC	Dedicated Short-Range Communication
ERF	European Union Road Federation
ERTRAC	European Road Transport Research Advisory Council
EUREKA	European Research Cooperation Agency
Euro NCAP	European New Car Assessment Programme
EuroRAP	European Road Assessment Programme
FHWA	Federal Highway Administration
FTIA	Finnish Transport Infrastructure Agency
GIS	Geographic Information System
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite Systems

GPS	Global Positioning System
GRVA	Working Party on Automated/Autonomous and Connected Vehicles
HC	High Capability
HD	High Definition
HDV	Human Driven Vehicle
I2V	Infrastructure-to-Vehicle
ICT	Information and Communications Technology
IMD	Indices of Multiple Deprivation
IMU	Inertial Measurement Unit
IOO	Infrastructure Owner Operator
IoT	Internet of Things
iRAP	International Road Assessment Programme
ISAD	Infrastructure Support for Automated Driving
ISD	Intersection Sight Distance
ITF	International Transport Forum
ITS	Intelligent Transportation Systems
KPMG	Klynveld Peat Marwick Goerdeler
LC	Low Capability
LiDAR	Light Detection and Ranging
LKA	Lane Keeping Assist
LSOA	Lower Layer Super Output Area
LTE	Long-Term Evolution
MfS	Manual for Streets
MSOA	Middle Layer Super Output Areas
MUTCD	Manual on Uniform Traffic Control Devices
MV	Machine Vision
NACTO	National Association of City Transportation Officials
NapTAN	National Public Transport Access Nodes
NHTSA	National Highway Traffic Safety Administration
NLOS	Non-Line of Sight
OD	Origin Destination
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
ONS	Office for National Statistics
PIARC	Permanent International Association of Road Congresses
PPP	Precise Point Positioning
PROMETHEUS	Programme for a European traffic of highest efficiency and unprecedented safety
PRT	Perception Reaction Time
PSC	Public Sector Consultants
PSD	Passing Sight Distance

RCI	Road Condition Indicator
ROCA	ROad Curvature Analysis
RRI	Road Readiness Index
RSRP	Reference Signals Received Power
RSRQ	Reference Signal Received Quality
RSU	Road Side Unit
RTK	Real Time Kinematic
SAE	Society of Automotive Engineers
SCNANER	Surface Condition Assessment for the National Network of Roads
SINR	Signal-to-Noise Ratio
SMMT	The Society of Motor Manufacturers and Traders
SPaT	Signal Phase and Timing
SSD	Stopping Sight Distance
TRACS	Traffic Speed Condition Surveys
TRID	Transport Research International Documentation
TSC	Transport Systems Catapult
TxME	Texas Mechanistic-Empirical Flexible Pavement Design System
UNECE	United Nations Economic Commission for Europe
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VaMoRs	Versuchsfahrzeug für autonome Mobilität und Rechnersehen
VaMP	Versuchsfahrzeug für autonome Mobilität PKW
VDA	German Association of the Automotive
ViTA	Vision Technology Application
VMT	Vehicle Mile Travelled
VRU	Vulnerable Road User

CHAPTER 1

Introduction

This chapter sets the scene for the study by outlining its background and delineating the motivations for examining the infrastructure aspect of vehicle automation. It begins with a presentation of a brief history of automated vehicles, followed by an overview of the current state of automated driving technologies and a classification of their capabilities. This is followed by a clear statement of the problem, highlighting the specific challenges that this thesis seeks to address. The research aim and objectives are then detailed, providing a solid foundation for the investigation of the thesis as a whole. Finally, the chapter concludes with an overview of the structure of the thesis. It methodically guides the reader through the planned progression of the research and outlines the contributions it aims to make to the field of vehicle automation and infrastructure readiness.

1.1 Background

The transition from horse-powered to internal combustion engine vehicles was a transformative moment in the history of road transport, leading to significant changes in street layouts and the built environment to accommodate the new motorised era. For instance, road user segregation, pedestrian crossings, smoother road surface installation, road markings, traffic signs and control devices, parking garages, and service stations are some examples of these car-centred alterations (see **Figure 1.1**). Today, one century later, we stand on the brink of another technological revolution in the transportation sector that promises to reshape urban life once more. Automated vehicles (AVs), though still in their nascent phase, are beginning to make their presence felt on roads. There is a growing consensus among policymakers, transport planners, and urban designers that AVs hold the potential to fundamentally redefine urban mobility in the foreseeable future (Duarte and Ratti, 2018; Maheshwari, 2020).

Automated driving, together with electrification and shared mobility, is currently recognised as one of the three ongoing revolutions in road transportation (Fulton et al., 2018; Sperling, 2018). Automated driving technologies, which shift driving responsibilities from humans to computer-based systems, are poised to enhance road safety, comfort, and efficiency in ways previously unattainable by human drivers. They offer the prospect of optimising traffic flow, expanding road capacity, and elevating transport efficiency—achievements that have been challenging to attain with human drivers, despite some controversies surrounding their impact (Calvert et al., 2017; Currie, 2018).

Figure 1.1 A historical change of Byward Market in Ottawa, Canada – 1918 & 2015, original photograph by James Topley.[1]

The potential benefits of AVs extend beyond technical improvements; they promise a societal transformation by potentially reducing traffic accidents caused by human error, decreasing pollution through more efficient driving patterns, and enhancing mobility for those unable to drive due to physical or age-related limitations Furthermore, AVs could revolutionise cityscapes by reducing the need for parking spaces, thus freeing up land for green spaces or additional housing (Fagnant and Kockelman, 2015; Bagloee et al., 2016; Wadud et al.,2016; Milakis et al., 2017b; Soteropoulos et al., 2019; Rahman and Thill, 2023).

However, the transition towards automated driving brings with it a host of challenges and concerns, including safety, regulations, costs, data privacy, liability, the integration of various intelligent systems, cybersecurity, ethical decision-making, and job displacement (Shladover and Bishop, 2015; Anderson et al., 2016; Alawadhi et al., 2020; Raj et al., 2020). As such, current policy-decisions are critical for determining the future trajectory of this technological revolution, shaping how vehicles and mobility services will evolve, who will benefit from them, and their impact on the environment (Sperling, 2018). This phase is also critical for guiding the future of transportation, ensuring that the deployment of AVs is equitable, sustainable, environmentally friendly, and aligns with broader urban development goals (Hjälmdahl et al., 2020). Recently acknowledged as fundamental, addressing

[1] Source: http://www.ottawahh.com/?p=2005

infrastructure-related requirements and overcoming the integration challenges of AVs into urban environments are now recognised as essential elements of this transition. This thesis specifically focuses on the infrastructure aspects of vehicle automation, examining how they underpin the successful integration and operation of automated driving systems.

1.1.1 Automated vehicles: From science fiction to reality

A century ago, the urban population was heavily reliant on equine modes for transporting goods and passengers. The introduction of internal-combustion vehicles, initially termed "*horse-less carriages*", revolutionised city life by eliminating issues associated with animal traffic, such as horse droppings, odours, and carcasses (Duarte and Ratti, 2018). However, the onset of mass motorisation in the United States of America (USA) during the 1920s led to a dramatic increase in fatal traffic accidents, which rapidly became a significant social concern (Kröger, 2016). Initially, driver error was identified as the primary cause of accidents, with little recognition given to the critical roles of infrastructure and vehicle design in the frequency and severity of accidents. Therefore, the idea of replacing error-prone human drivers with technology began to take root. That is the aspiration for "*driver-less*" (self-driving) vehicles was rooted in the quest for safety as well as comfort and convenience of the user (Kröger, 2016).

In this context, technical efforts to develop self-driving vehicles date back at least a century. In the 1920s and 1930s, what we now refer to as self-driving vehicles were known as *"Phantom Autos"* and their demonstrations attracted thousands of spectators in various cities across the USA (Kröger, 2016). These early versions were controlled remotely, utilising advances in aviation and radio engineering. By today's standards, this invention would not be classified as self-driving or driverless, since the navigator (i.e., the driver) was just outside the vehicle (Toliyat, 2022). The vehicle was operated via radio from another car, marking an early instance of vehicle-to-vehicle communication (Gora and Rüb, 2016).

By 1940, concepts for transferring driving tasks to vehicles were already being articulated, as demonstrated by General Motors' *"Futurama: Highways & Horizons"* exhibit and Norman Bel Geddes' book *"Magic Motorways"* (Bel Geddes, 1940). The 1950s marked another utopian phase in the history of self-driving vehicles, with a General Motors advertisement depicting a family enjoying a ride on a landscaped highway, engaged in conversation, and playing dominoes inside a lounge-like vehicle (refer to **Figure 1.2**). In these early visions, automation was integrated into the tracks along the roads rather than the vehicles themselves, yet the promise of liberating time while driving remained constant. These envisioned driverless cars were electric, powered by circuits embedded in the roadway and controlled by radio. Despite the innovative imagery, such advancements were impractical at the time due to the extensive changes required in infrastructure, since these vehicles primarily operated with the help of devices installed within the roadway to guide them (Beikzadeh Marzbani, 2015). However, this period had already seen successful simulations of primary vehicle controls such as automatic braking, acceleration, and steering, which fuelled the imagination of engineers with the prospect of self-driving cars (Duarte and Ratti, 2018; Divakarla et al. 2019).

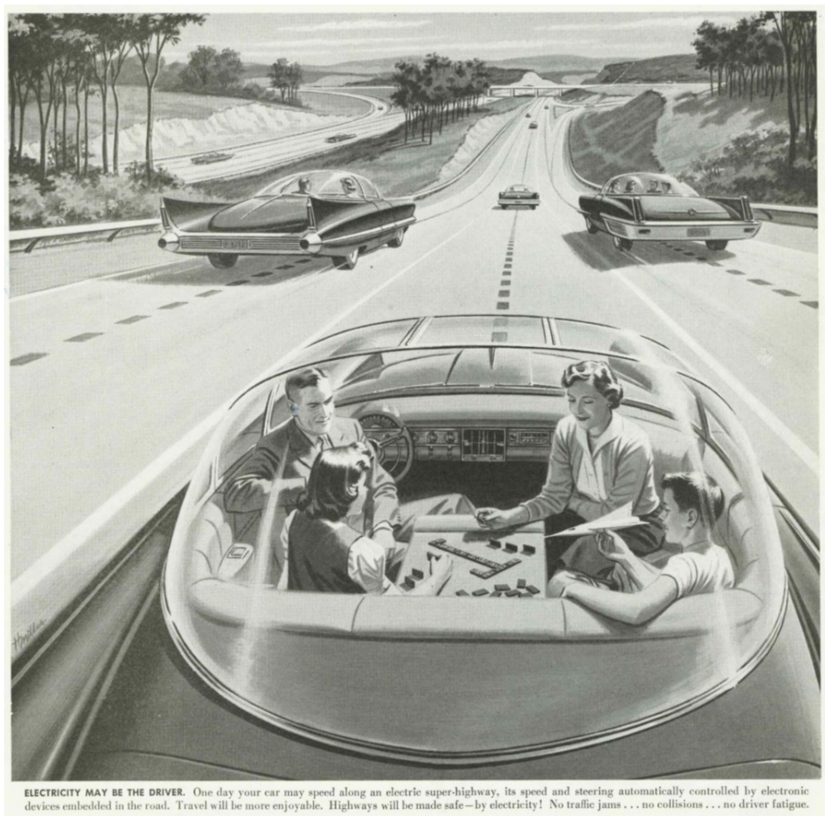

Figure 1.2 Driverless Car of the Future, advertisement for “America’s Electric Light and Power Companies,” Saturday Evening Post, 1950s. Credit: The Everett Collection.

From the second half of the 20th century, the pursuit of automated driving transformed from mere fiction into a tangible goal, capturing the public's imagination (Beikzadeh Marzbani, 2015). This period marked the beginning of a quest to develop the first automated vehicle — robust, reliable, and safe for high-speed driving in real-world environments.[2] Researchers and industry leaders worldwide competed in this

[2] A detail overview of the history of automated driving can be found in various studies such as (Lari et al., 2015; Beikzadeh Marzbani, 2015; Kröger, 2016; Lipson and Kurman, 2016; Duarte and Ratti, 2018; Van Brummelen et al., 2018; Toliyat, 2022).

endeavour, with significant advances attributed to global AV tests and competitions. These events allowed for a thorough assessment of AV capabilities and limitations in diverse driving conditions (Van Brummelen et al., 2018).

In the late 1970s, Japan's Tsukuba Mechanical Engineering Laboratory designed the first vision-based automated vehicles that did not rely on rails or wires under the road. This vehicle was equipped with two cameras and utilised analogue computer technology for signal processing (Kröger, 2016). During the 1980s, the concept of vision-based automated driving gained momentum, and research increasingly focused on vehicles that did not depend on infrastructure, such as guide wires. The year 1987 may be considered a significant milestone in the development of road vehicle guidance by machine vision (Dickmanns 2003). Ernst Dickmanns' test vehicle VaMoRs (Versuchsfahrzeug für autonome Mobilität und Rechnersehen), a 5-ton Mercedes 508 D commercial van, successfully drove—solely using cameras, without radar or GPS—for more than 20 km at speeds up to 60 mph (96 km/h) on streets without traffic (Dickmanns 2003; Kröger, 2016).

Figure 1.3 VaMoRs (left) and VaMP (right) test vehicles by Ernst Dickmann, taken from (Russell, 2015)

Following this progress, the PROMETHEUS (Programme for a European traffic of highest efficiency and unprecedented safety) project conducted by EUREKA from 1987 to 1995, contributed greatly to the realisation of the dream of a vehicle which can drive passengers without any help from human beings, come true (Beikzadeh Marzbani, 2015). Within this project, four automated vehicles were developed: two commercial vans, VaMoRs and VITA and two passenger vehicles, VITA-2 and VaMP which were known as twin autonomous vehicles (see **Figure 1.3**). These vehicles demonstrated significant advances in the field of autonomous vehicles (Divakarla et al. 2019). During the final event of this project, these twin robot vehicles travelled more than 1,000 km on a Paris three-lane highway in standard heavy traffic, reaching speeds of up to 130 km/h (Dickmanns 2003). They demonstrated the capability of deriving autonomously the decision for lane changing and passing (Kröger, 2016). In the subsequent years, VaMP (a S-Class Mercedes) showcased its capability to complete a fully autonomous long-distance drive—both laterally and longitudinally—on the Autobahn, covering more than 1600 km from Neubiberg near Munich to Odense in Denmark. Approximately 95% of the distance was covered without intervention from the safety driver (Kröger, 2016).

Additionally, Alberto Broggi's ARGO and Carnegie Mellon University's NavLab were among the most significant and successful automated-capable vehicle projects of the 1990s (Beikzadeh Marzbani, 2015; Kröger, 2016; Divakarla et al. 2019). For instance, the NavLab project, more popularly known as "No Hands Across America", featured a partially automated vehicle that drove from Pittsburgh to San Diego in 1995, although a human driver was still required to control the brakes and acceleration. In the USA, a pivotal moment occurred in 2003 when the Defense Advanced Research Projects Agency (DARPA) launched a competition to prompt the development of AVs capable of navigating desert trails and roads (Campbell et al., 2010). Although no vehicle completed the inaugural DARPA Grand Challenge in March 2004, the subsequent year saw a remarkable improvement, with five vehicles completing the 132 miles (212 km) of driving with no human input. The third round of the competition shifted to urban driving, with six vehicles completing approximately 60 miles (97 km) of driving in environments that included city streets, parking lots, traffic intersections and both human and robotically controlled vehicles (Campbell et al., 2010).

Figure 1.4 Examples of current automated vehicles and trucks, taken from (Waymo, 2021)

The early 2010s saw a significant increase in interest in self-driving cars, mainly due to the progress made by Waymo, which originated from Google's self-driving car project, and partly due to the introduction of Tesla's Autopilot feature (Sperling, 2018; Madadi, 2021). The advancements made by Waymo have been particularly noteworthy, demonstrating vehicles equipped with the capability to operate independently in specific scenarios (see **Figure 1.4**). Nonetheless, the high cost of the underlying technology poses a significant challenge to the widespread adoption and mass-market integration of such automobiles. In addition, operational conditions and geographic areas where these vehicles can function have been notably restricted due to technological immaturity and regulatory obstacles. Therefore, this era is viewed as a pivotal testing phase for these technologies, driving increased engineering efforts to achieve more affordable solutions for mass adoption.

The late 2010s and early 2020s witnessed a significant acceleration in the development and launch of early prototypes of highly automated vehicles by numerous companies and consortia across the globe, including Cruise and Waymo in the USA, Mobileye in Europe, Baidu in China, and Wayve in the UK. This period was marked by rapid advancements in AV technology and the remarkable expansion of operational domains for these vehicles. However, the debates about the safety of AVs were thrust into the spotlight by the end of 2023. California regulators have charged San Francisco-based robotaxi service Cruise, owned by General Motors, with misconduct. This action resulted in the suspension of the company's license in California (The Guardian, 2023). This situation has had significant repercussions for the AV industry, attracting media attention and creating a wave of industry introspection. The reaction to the incident led to widespread speculation about public sentiment towards self-driving technology, similar to Tesla's fatal Autopilot crash in 2016. These incidents serve as an important reminder of the challenges facing the AV industry, particularly in terms of safety assurances and public confidence, emphasising the need for rigorous testing, transparency and regulatory compliance to advance the acceptance and success of autonomous vehicles.

Consequently, the evolution of self-driving vehicles has been gradual but consistent, with features of driving automation (i.e. driving assistance systems such as adaptive cruise control and lane-keeping assistance) incrementally being incorporated into new vehicles aimed at the mass market. Yet, the reality of fully automated vehicles remains unclear (Litman, 2023) with their future closely tied to the reliability of highly automated vehicles that are presently in their infancy.

1.1.2 The current state of automated driving and its supporting technologies

As explained in the previous section, the journey towards realising fully automated vehicles has been a long and winding one, marked by a curious phenomenon where the dream of driverless vehicles has seemingly been "just 20 years away" for nearly a century (Kröger, 2016). Despite expectations, the close of the first quarter of the twenty-first century will most likely not witness these vehicles becoming a widespread reality. This delay can be attributed to what has been termed the “Da Vinci Problem” (Lipson and Kurman, 2016), a scenario where the lack of requisite supporting technologies hinders the implementation of a visionary idea, rather than any inherent flaw in the concept itself.

However, recent advances in transport technology offer promising solutions to overcome the Da Vinci Problem (Maheshwari, 2020). Despite the optimism surrounding these technological breakthroughs, there remains significant uncertainty about the large-scale deployment of fully automated vehicles, especially in urban environments. Optimistic forecasts often come from those with financial stakes in the industry, potentially underestimating significant obstacles such as cost, infrastructure readiness, and public acceptance (Litman, 2023). This era has also seen considerable media hype, frequently presenting an overly optimistic view of the capabilities and imminent rollout of automated driving systems (ADS). Such optimism has also been echoed in much of the technical literature over the past decade, with projections based more on aspiration than on grounded empirical evidence (Shladover, 2022). Nevertheless, recent developments in information and communication technologies, artificial intelligence, sensor technologies (e.g. cameras, radar and LiDAR) and digital mapping (e.g. high-definition maps) all have brought the driverless future nearer than ever before (Huggins et al., 2017; Maheshwari, 2020).

1.1.2.1 An overview of automated vehicle architecture and its classifications

The architecture of AVs is influenced by a variety of factors, such as the level of autonomy, the technologies utilised, regulatory requirements, and the intended use of the vehicle. This diversity in influencing factors results in a wide range of design concepts, making it challenging to define a universal structure for AVs (Lipson and Kurman, 2016; Shladover, 2022). Despite these differences, a commonality across all AVs is their reliance on the use of a set of sensors to perceive the environment, advanced software to process inputs and decide the vehicle's path, and a set of actuators to act on decisions (Wevolver, 2020).

The operational principles of automated driving systems, particularly those classified as Level 3 and above (which will be further discussed in the subsequent part of this section), can be distilled into three essential subsystems: perception, planning, and control (Tas et al., 2016; Pendleton et al., 2017; Eskandarian et al., 2021). At the forefront of these subsystems is the perception layer, which enables an AV to interpret meaningful information from its sensors and to understand its environment comprehensively. This crucial layer employs on-board sensors such as cameras, LiDARs, and radars, alongside advanced sensor fusion techniques and potentially data from remote sources like roadside communication units, to gather this information (see **Figure 1.5**).

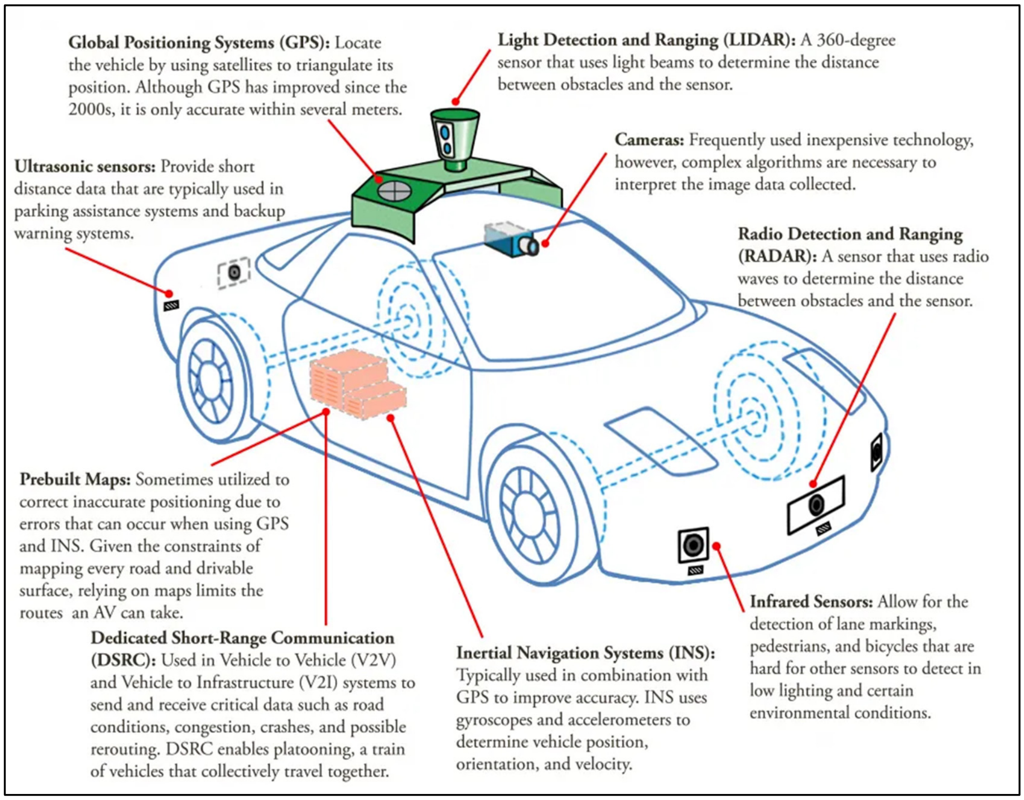

Figure 1.5 A simple overview of automated driving technologies, taken from (Center for Sustainable Systems, 2023).

The primary function of the perception layer is to ascertain both the global and local positions of the vehicle within its environment and to construct a detailed map of its surroundings (Van Brummelen et al., 2018). Essentially, this involves identifying the location of obstacles, recognizing road signs and markings, and categorizing objects according to their semantic significance (Pendleton et al., 2017). Through these processes, the perception layer forms the foundational understanding that enables AVs to navigate and interact safely and effectively with their environment.

The planning layer plays a pivotal role in the operation of automated driving systems. It is responsible for coordinating functions such as action prediction, path planning, and obstacle avoidance to develop an effective real-time navigation strategy. The layer initially selects the optimal global route from the vehicle's current position to the designated destination, using remote map data that includes road layouts and traffic information. Subsequently, the route is refined into a locally optimal trajectory based on the real-time states of the vehicle and the immediate environmental conditions as interpreted by the perception layer. This refinement incorporates decision-making and trajectory planning processes (Eskandarian et al., 2021).

Moreover, the advent of vehicle connectivity has the potential to enhance the functionality of the planning layer by enabling the sharing of perception data with other road users. This capability facilitates cooperative driving strategies, allowing for more synchronized and safe interactions on the road (Guanetti et al., 2018). Following the establishment of the optimal route, which may include specific manoeuvres such as lane changes or right turns, the control layer assumes responsibility. It precisely manages the vehicle's longitudinal and lateral movements by calculating and issuing the necessary commands to the vehicle's actuators. This ensures the vehicle adheres to the planned route and manoeuvres safely and efficiently (I. Meneguette et al., 2018).

However, the rapid expansion of automated road vehicle technologies has resulted in confusion regarding the correct terminology for these systems, both within the industry and among the general public. This situation underscores the necessity for clear definitions and consistent terminology to accurately describe the various systems and their capabilities. In response to this need, the classification of automation levels has become a crucial tool for guiding the industry and consumers towards understanding the operational principles of fully automated vehicles. The six-level, SAE J3016 classification by SAE International (2021) is widely used today to describe the degree of functionality delivered by different technologies, and to clarify whether a human or a vehicle is taking responsibility for driving tasks:

- *Level 0, No automation:* The human driver is entirely in control, managing all dynamic driving tasks (DDTs) including steering, acceleration, braking, and environmental monitoring throughout the journey.

- *Level 1, Driver assistance*: The vehicle features driving assistance systems that aid the driver with either longitudinal (e.g., adaptive cruise control) or lateral (e.g., lane-keeping assistance) vehicle motion control, but not both simultaneously

- *Level 2, Partial automation*: At this level, the vehicle can take over both steering and acceleration/deceleration tasks under certain conditions, for example, traffic jam assist systems. The driver must remain engaged with the driving task and continue to monitor the environment.

- *Level 3, Conditional automation*: The vehicle's automated driving system (ADS) can perform all aspects of the DDTs in certain situations, such as in a traffic jam chauffeur system. However, the driver (DDT fallback-ready user) is expected to be available for the takeover of the vehicle with appropriate reaction time when required.

- *Level 4, High automation*: At this level, the ADS is capable of managing all aspects of the driving task and responding to fail-safe scenarios independently within a defined operational design domain (ODD). This means the system can function without human intervention under certain conditions outlined by the ODD, which includes variables such as weather conditions, types of road infrastructure, and specific vehicle-related parameters. Although the system is designed to operate autonomously within these predefined conditions, a driver still has the option to manually take control of the vehicle whenever desired or necessary. The concept of ODD is crucial, defining the precise conditions under which the ADS can perform safely and effectively.

- *Level 5, Full automation*: Automated driving systems are able to perform all aspects of the DDT under all roadway and environmental conditions, which means that its ODD is unlimited. This level is often referred to as *autonomous* or *self-driving* in the media, though Level 4 AVs may specifically be labelled as self-driving within their ODD.

Detailed information regarding the classifications and deployment pathways of automated vehicles (AVs) is thoroughly discussed in **Chapter 2.2**.

1.2 Problem statement

The literature presents a wide range of estimates for the adoption of AVs over the next three decades. While some optimistic predictions anticipate a high adoption rate by 2040, other estimates propose that less than 20% of vehicles will be automated by 2050 (Rashidi et al., 2020; Jiang et al., 2023). Despite the clear emergence of vehicle automation technology, the rate of AV adoption will heavily rely on the strategies policymakers and governments employ to tackle a myriad of challenges (Shladover and Bishop, 2015; Jing et al., 2020). In particular, concerns regarding the safety of automated driving technologies (Moody et al., 2020) may lead to AVs being perceived as science fiction once again in public perception.

Innovation inherently involves navigating uncertainties and addressing unknowns (Toliyat, 2022). Within the field of AVs, there is a focused effort to identify factors influencing their operation. Empirical studies of AV trials (Ramanagopal et al., 2018; Klauer et al., 2023) and analyses of accident or disengagement data from manufacturers (Boggs et al., 2020; Ye et al., 2021) provide valuable insights into these factors. Despite this, the data publicly available today do not suffice to draw clear empirical correlations regarding these operational factors. Kalra and Paddock (2016) have indicated that more than 10 billion miles of real-world driving might be required to statistically prove automated driving systems technology's effectiveness in preventing fatal accidents and its superiority over human drivers. However, reaching such an extensive mileage with the current fleets involved in trials could take many years (Scanlon et al., 2021). To address this gap, significant progress has been made recently in developing risk assessment methodologies (Toliyat, 2022) and safety verification for automated driving systems (Khastgir et al., 2021). Scenario-based approaches, in particular, have emerged as a pivotal strategy, simulating specific traffic situations in virtual settings against a backdrop of diverse variables to assess AV safety (Riedmaier et al., 2020). Furthermore, several studies have introduced models that assess the complexity of driving environments or traffic scenarios using the sensor data from AVs (Wang et al., 2018; Li et al., 2019; Cheng et al., 2022).

However, the successful integration of AVs into existing road systems requires comprehensive preparation across multiple domains, such as transport infrastructure, policy and legislation, technological innovation, and consumer acceptance (Alawadhi et al., 2020; KPMG International, 2020; Lim et al., 2023). Among these, the role of infrastructure in facilitating automated driving has been underestimated in the last decades (Farah et al., 2018; Tafidis et al., 2021). Efforts within the field have predominantly focused on the vehicle and corresponding technologies, with safety and reliability concerns primarily evaluated from a vehicle-centric viewpoint. However, conventional thinking that assesses an automated vehicle's capabilities solely based on its onboard technology overlooks the equally crucial role of the vehicle's surroundings. Infrastructure constitutes a vital component of any AV's operating environment, significantly influencing where and how these vehicles can function (International Transport Forum, 2023).

Over the last decade, only a few studies have concentrated on how infrastructure can either facilitate or hinder the progress and integration of automated driving technologies. The first gap observed in the literature is that there are limited studies investigating the impact of AVs on the physical environment (Farah et al., 2018) and desirable physical infrastructure requirements for their safe operation. The impact of infrastructure on the deployment paths of automated driving technologies is critical and needs to be thoroughly evaluated to ensure a safe and efficient transition (a detailed discussion is provided in **Chapter 2.2**). Despite earlier disregard, recent years have witnessed a growing consensus among stakeholders about the critical importance of infrastructure, particularly digital infrastructure, sometimes referred to as invisible infrastructure, in preparing the ground for the deployment of highly automated vehicles. This paradigm shift is supported by some empirical research on current AV trials (Ramanagopal et al., 2018; Klauer et al., 2023) and analyses of incidents involving AVs or disengagement reports (Ye et al., 2021), all of which highlight the necessity for road infrastructure that meets the operational needs of AVs.

Nonetheless, the operation of AVs has predominantly been limited to testing and pilot projects within specific geographical regions, characterised by well-defined road conditions and predictable environments (Erdelean et al., 2019). This deliberate focus has played a crucial role in enabling repeated testing scenarios essential for learning and continuous improvement, pivotal for realising the benefits of automation. However, this approach has also limited the geographical expansion of automated services provided by developers. As AVs begin to expand to a wider array of road networks, it becomes increasingly important to identify the types of infrastructure enhancements necessary to support their safety-critical functions (International Transport Forum, 2023). Addressing these considerations is crucial for gaining valuable insights into how AVs can be safely and effectively integrated into the broader roadway ecosystem, which includes both connected and intelligent systems. To date, there has been limited research focused on examining the infrastructure-related challenges of integrating automated driving into urban road networks, marking a significant gap in the current literature (this refers to the second identified gap). Therefore, the primary concerns for policymakers and authorities regarding AVs need to shift from questioning whether AVs will be adopted to determining where they can feasibly be implemented (International Transport Forum, 2023).

In response, road authorities and safety organisations worldwide are investigating potential infrastructure upgrades or adjustments needed to effectively support AV operations (Huggins et al., 2017; Santec and ARA, 2020; Gopalakrishna et al., 2021; PIARC, 2021). Besides, regulatory bodies are actively involved in developing and implementing legislation to facilitate the integration and safe deployment of AVs (Lee and Hess, 2020). For instance, the European Commission has assumed a leadership role in crafting policies and regulations within the European Union to advance AV deployment. Initiatives like the European Strategy on Cooperative Intelligent Transport Systems and the European Framework for the Deployment of Intelligent Transport Systems are aimed at harmonising legal requirements and enhancing cross-border cooperation. Furthermore, the United Nations Economic Commission for Europe (UNECE) has been instrumental in shaping international legislation for AVs. The UNECE's Working Party on Automated/Autonomous and Connected Vehicles (GRVA) has introduced standards and regulations, such as UNECE Regulation No. 157 on automated vehicles. Moreover, countries like the USA and the UK have adopted proactive approaches to foster CAV innovation and deployment. In the USA, agencies such as the National Highway Traffic Safety Administration (NHTSA) have promulgated guidelines and regulatory frameworks at both federal and state levels. In the UK, the Centre for Connected and Autonomous Vehicles (CCAV) has spearheaded legislation and initiatives, including the Code of Practice, to promote CAV testing and development (CCAV, 2023).

Within the academic domain, only a limited number of studies have detailed potential infrastructure modifications to support the safe integration of AVs, relying on extensive literature reviews (Farah et al., 2018; Liu et al., 2019) and expert opinions (Lu et al., 2019; Wang et al., 2022). This lack of comprehensive research represents the third identified important gap in the literature. Implementing the infrastructure changes proposed in these limited studies presents significant challenges, requiring significant resources and financial investments. As a response, various studies have employed optimisation techniques or cost-benefit analysis to identify the most cost-effective, network-wide plans for deploying AVs. Such research has led to the proposition of various policies and infrastructural strategies tailored to AV-compatible road systems (Madadi et al., 2021; Manivasakan et al., 2021), including the establishment of dedicated AV lanes (Razmi Rad et al., 2020), designated AV zones (Conceição et al., 2017), and AV-ready subnetworks that facilitate mixed traffic or hybrid configurations (Madadi et al., 2019, 2021).

Nevertheless, to minimise infrastructure investment costs, evaluating the readiness level of current road sections is also critical in order to formulate a more economical plan. This consideration is particularly relevant given the financial constraints faced by infrastructure owners and operators in maintaining their roads to a certain quality standard. Currently, there is a notable absence of an official standard or benchmark for assessing the readiness or compatibility of roads for AVs. Moreover, with the capabilities of higher levels of AVs yet to be fully understood, defining their precise operational areas within the network poses a challenge. This marked the fourth significant gap observed in the literature.

In response, recent research efforts, particularly in Europe, have adopted a holistic approach to develop and apply assessment frameworks for evaluating both the physical and digital road infrastructure's readiness to support the safe operation of AVs (Soteropoulos et al., 2020; Cucor et al., 2022). These studies have revealed significant diversity within the road network, ranging from highly structured environments with robust infrastructure support to less structured environments with limited or no support. The potential heterogeneity of the road network raises the possibility that AVs may not be able to operate seamlessly without infrastructure modifications or upgrades to meet automated driving requirements. In other words, infrastructure deficiencies could impact the usefulness of AVs—for example, limiting their ability to complete trips if they are restricted to specific roads. This also raises the possibility that when AVs are deployed, they might be less efficient in terms of trip distance and duration compared to human-driven vehicles. However, no study has yet empirically assessed the impact of infrastructure readiness levels on the usefulness and performance of AVs. This highlights the final gap identified in the literature.

1.3 Research aim and objectives

The primary aim of this thesis is to evaluate the readiness of existing (or near-future) road infrastructure to support the deployment of highly automated vehicles (SAE Level 4 AVs) and to investigate the effects of readiness levels on AV operations. To achieve this comprehensive aim, the study is designed to explore several dimensions, including the physical road environment and associated policy and operational challenges. A mixed-methods approach is employed to assess the critical infrastructure elements necessary for the safe operation of Level 4 AVs. Additionally, empirical research has been conducted to evaluate the preparedness levels of road sections and examine the impact of potential heterogeneity in road readiness on the usefulness and performance of Level 4 AVs. In summary, to achieve the overall aim, the thesis seeks to address the following specific research questions (RQs) that align with the gaps identified in the literature:

1. What will be the likely implications of automated vehicles for the road infrastructure?
2. What infrastructure-related challenges are involved in integrating automated driving into urban road networks?
3. What are the critical infrastructure elements necessary for the safe operation of Level 4 AVs?
4. How prepared is the current urban road infrastructure for the deployment of Level 4 AVs?
5. How does the (potential) heterogeneity in road infrastructure quality affect the usefulness of Level 4 AVs in an urban setting?

1.4 Scope of the thesis

The research approach addresses the various dimensions associated with the safe driving of automated vehicles and their usability. Level 4 AVs, in particular, hold the potential for transformative changes in transportation and urban landscapes (Milakis et al., 2017b), as they can operate autonomously in various scenarios and geographic areas while still offering the option for human control in exceptional circumstances (Tafidis et al., 2021). Accordingly, this thesis mainly focuses on Level 4 automated driving, which will probably be introduced to roads within the coming decade (ERTRAC, 2019), and uses "automated driving" to describe the technology where automation of the driving task, vehicle connectivity and the data are brought together (Shladover, 2018).

Moreover, a long transition period is expected in which transportation networks will likely encounter a mix of vehicles with different levels of automation and degrees of cooperation (Milakis, et al., 2017a), but the study focuses on the near future to assess the readiness of road infrastructure during the initial stages of Level 4 automated driving implementations. Additionally, different use-cases and mobility models might require different infrastructure requirements, including different functionalities and services. Therefore, it is not possible to foresee all configurations of road infrastructure that AVs will have in the future. For this reason, the main part of the thesis concentrates on the generic driving task capabilities of highly automated vehicles equipped with automated driving systems rather than focusing on specific use-case scenarios. This approach allowed the study to gain a broader perspective on understanding the requirements of these technologies.

1.5 Thesis outline

This section presents the outline of this thesis. As outlined in the **Figure 1.6**, this thesis consists of seven chapters:

Chapter 2 presents a paper entitled "Implications of automated vehicles for physical road environment: A comprehensive review". This paper examines the potential implications of vehicles equipped with advanced driving assistance systems (ADAS) and automated driving systems (ADS) for the physical road environment. It accomplishes this through an extensive review of the current literature, aiming to pinpoint infrastructure-related requirements essential for the integration of automated vehicles. The chapter identifies thirteen critical infrastructure-related topics from the literature on vehicle automation, that need to be considered during either the initial phase of deployment or the transition to full automation. The chapter also provides an analysis of the current state of research in these areas and offers insights into future directions. The findings from this Chapter form the basis for the stakeholder questionnaire designed in **Chapters 3** and **4**.

Beyond what the existing literature offers in terms of insights into the role of infrastructure in automated driving, there are a number of critical areas that need to be uncovered through the views of experts. **Chapter 3** presents a paper entitled "Infrastructure-related challenges in implementing connected and automated vehicles on urban roads: Insights from experts and stakeholders". This chapter details the results of an online questionnaire targeting the multi-faceted challenges of integrating automated vehicles into urban road networks. It offers an in-depth analysis of expert and stakeholder views on the barriers and challenges associated with deploying AVs in urban contexts, alongside discussing potential improvements for shared models of AVs. Moreover, the chapter presents opinions on possible strategies for maintenance and financial models for necessary investments to facilitate safe and efficient AV operation. Despite these insights, the chapter highlights a lack of consensus among stakeholders on the priorities for achieving the societal benefits of AVs. The study finds that the proposed requirements for AVs are still in a premature stage and not yet operational, due to numerous uncertainties surrounding their capabilities and limitations.

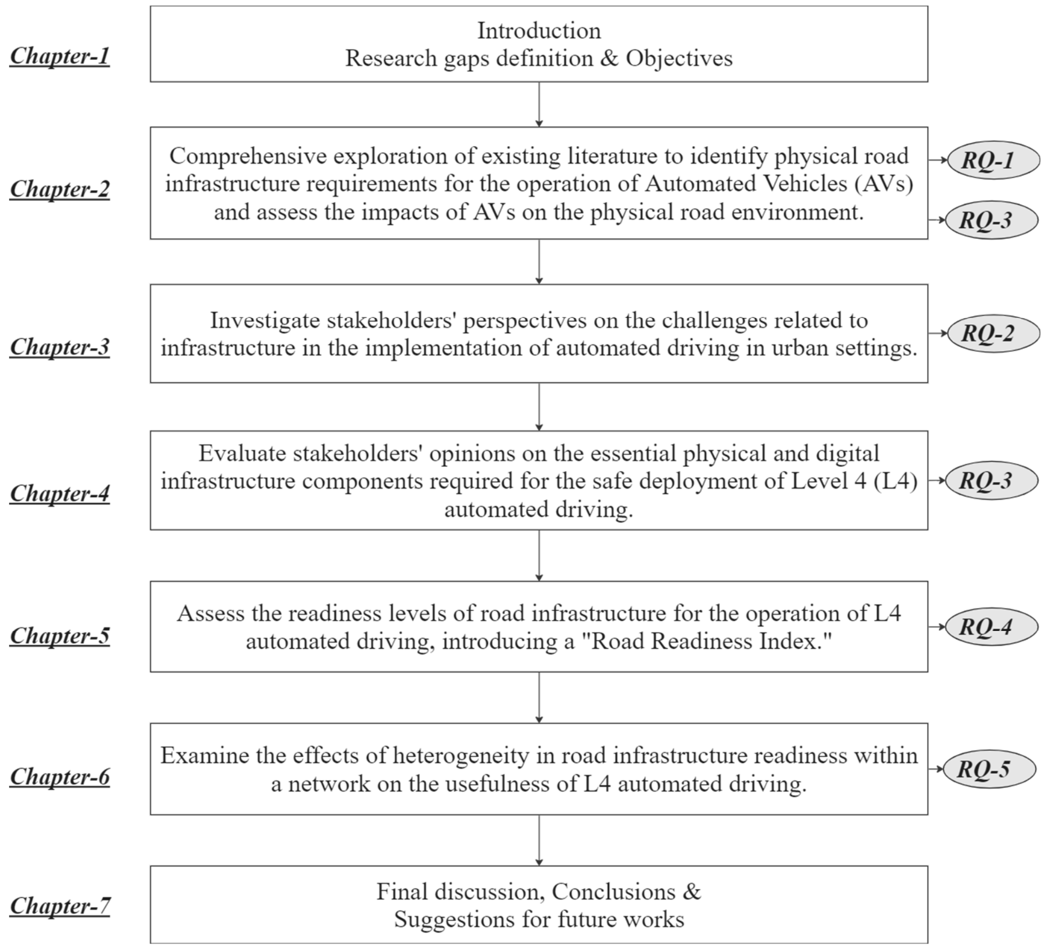

Figure 1.6 The sequential order of the thesis chapters and link to the outlined research questions.

Chapter 4 introduces a paper titled "Infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders". This chapter builds on the critical pillars of road elements identified in **Chapter 2** but focuses here on both the physical and digital infrastructure support required for SAE Level 4 automated driving. It synthesises stakeholder opinions to outline the vital infrastructure components necessary for the safe operation of Level 4 AVs, rather than focusing on their specific use case. The survey encompasses a broad spectrum of experts from various countries, who evaluate factors drawn from existing literature. The chapter also explores the concept of road certification for emerging on-road vehicle automation. Overall, the research provides extensive insights to aid decision-makers and transport planners in crafting policies, regulations, and guidelines for the imminent deployment of AVs, particularly in the pre-commercialisation phase. Furthermore, this chapter lays the foundational groundwork for the practical application of the road assessment framework, which will be elaborated on in **Chapter 5**

Chapter 5 presents a paper entitled "Are current roads ready for highly automated driving? A conceptual model for road readiness for AVs applied to the UK city of Leeds". This paper addresses a critical gap by introducing a novel and practical assessment framework, termed the "Road Readiness Index" which is designed to evaluate the readiness of road infrastructure for highly automated vehicles operation (Level 4 AVs). The chapter consists of two main tasks. The initial phase focuses on identifying the components of the framework based on the opinions of experts obtained in **Chapter 4** and insights obtained from the literature review in **Chapter 2**. This process includes pinpointing specific subcomponents within the assessment framework and assigning performance grades to measurement variables using a designated scoring system. In response to the uncertainties associated with automated driving technologies, the study embraces a holistic approach to future scenarios. It categorises two distinct levels of AV capabilities and introduces three potential network scenarios to assess the impact of technological advancements on the current road network's suitability for AV deployment.

In the second part, the proposed framework is empirically applied in a specific area within the city of Leeds, United Kingdom, demonstrating its practical applicability. Despite the study being centred on the UK, its findings have broad implications, offering valuable insights for policymakers globally. The results indicate significant heterogeneity in infrastructure readiness, suggesting that without significant interventions, certain potential benefits of AVs, such as improved mobility for the disabled or reduced reliance on personal vehicles, might remain unrealised. Furthermore, this methodological approach provides preliminary insights about the road network without the immediate need for costly AV trials, making it a useful tool for city authorities. The findings of this research offer vital insights that contribute to the understanding of AV integration into road networks and support decision-makers and transport planners in developing informed and future-oriented policies.

Chapter 6 presents a paper entitled "The effects of infrastructure quality on the usefulness of automated vehicles: A case study for Leeds, UK". This chapter extends the discussion of requisite physical and digital infrastructure for SAE Level 4 automated driving from **Chapter 5**, concentrating on the heterogeneity in road environments. This study conducts the first exploratory analysis of the impact of heterogeneity in road infrastructure readiness on the utility of AVs for urban commuting, with a focus on Leeds, UK. Concentrating on a hypothetical scenario where current car commuters have access to AVs for their daily trips, this research explores the potential effects of AV deployment on commuting trip completion, given the existing levels of infrastructure readiness. Through the evaluation of various road network configurations and AV capabilities, it evaluates the implications in a broader context. The findings reveal that infrastructure readiness levels significantly impact AV performance and utility, necessitating infrastructure upgrades and optimisations to accommodate future AV deployment. The analysis indicates that relatively less challenging paths for AVs tend to be longer than those typically used by human-driven vehicles. Additionally, it identifies a substantial number of commuting trips as currently infeasible for AV navigation, attributed to several particularly challenging road sections within the network.

Finally, in **Chapter 7**, the thesis culminates in a summary that synthesises conclusions drawn from the entire spectrum of studies conducted. This chapter elaborates on the practical implications of the research findings, providing insights into how they can influence real-world applications in the domain of automated vehicles and infrastructure planning. It highlights how the outcome of this thesis could impact policymaking, urban development, and technological advancements in the field. Additionally, the chapter identifies and outlines potential areas for future research, inspired by the findings and gaps identified during the study. It suggests directions for further investigation that could address unresolved questions, refine existing models, or explore new aspects of AV deployment and infrastructure readiness.

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CHAPTER 2

Implications of automated vehicles for physical road environment: A comprehensive review

Abstract: Automated vehicles (AVs) have received intense attention in academia and industry around the world in recent years, but the imminent introduction of AVs brings new challenges and opportunities for transportation networks and built environments. It is important to understand the potential infrastructure-related requirements of AVs and their impact on road infrastructure in order to assess the readiness of the existing road network and prepare plans for future roads. This paper seeks to address what the implications of automated vehicles will likely be for the road infrastructure based on a comprehensive literature review. To investigate this issue, two broad questions were framed: What are the potential effects of AVs on physical road infrastructure; and What do AVs require from road infrastructure for safe driving. A total of thirteen key topics around infrastructure have been identified from the existing literature regarding vehicle automation that needs to be considered during either the initial phase of deployment or transition to full automation. In the light of the identified topics, the paper presents potential changes and challenges, making recommendations for future research directions to ensure a safe and efficient operation.

Keywords: Autonomous vehicles, Automated driving, Road infrastructure, Physical infrastructure, Challenges

2.1 Introduction

In recent years, research and developments in automated driving technologies (e.g., sensing and artificial intelligence), as well as regulatory reforms around the world, have enabled rapid progress in the development of automated vehicles (AVs) (Campbell et al., 2010; Bagloee et al., 2016; Eskandarian et al., 2021). Simply defined, automated driving technologies allow for the transfer of some or all driving responsibilities from a human driver to a computer-based system (SAE International, 2021). Automated driving, together with electrification and shared mobility, is currently recognised as one of the three ongoing revolutions in road transportation (Huggins et al., 2017; Jaller et al., 2020), although there is some controversy. AVs have the potential to enhance people's lives in a variety of ways, including increasing accessibility of people with limited ability of transportation provisional, reducing parking demand, reducing travel time and transportation costs, and reducing fuel and emissions consumption (KPMG and CAR, 2012; Shladover and Bishop, 2015; Fagnant and Kockelman, 2015; Bagloee et al., 2016; Gavanas, 2019; Eskandarian et al., 2021). More importantly, AVs have the potential to improve road safety by eliminating some accidents caused by human error such as driving too fast, driver distraction and fatigue, although their expected benefits are essentially untested (W. Ye et al., 2021) and are largely speculative as new types of accidents may emerge from this huge paradigm shift (Robinson et al., 2017). On the other hand, the literature points out some of the potential negative impacts of AVs, such as security and privacy concerns due to the risk of cyberattacks, or congestion due to the increased vehicle miles travelled caused by the attractiveness of vehicle use and empty trips (Bagloee et al., 2016; Currie, 2018; Makridis et al., 2018; Soteropoulos et al., 2019; Litman, 2020; Tengilimoglu and Wadud, 2022).

In short, advances in vehicle and information technology has increased research into impacts of AVs on many aspects: e.g. travel behaviour (Gruel and Stanford, 2016; Zmud and Sener, 2017; Wadud, 2017; Ashkrof et al., 2019; Wadud and Huda, 2019; Harb et al., 2021), traffic flow and operation (Mahmassani, 2016; Do et al., 2019; Mesionis et al., 2020), urban form and land use (Chapin et al., 2016; Gavanas, 2019; Stead and Vaddadi, 2019; Malysheva, 2020), emission and energy use (Wadud et al., 2016; Kopelias et al., 2020), policy and legislation (Fagnant and Kockelman, 2015; Milakis et al., 2017b; Litman, 2020), safety (Robinson et al., 2017; Peiris et al., 2020) etc. However, the implications of AVs for road infrastructure have not yet been studied adequately and rigorously (Cavoli et al., 2017; Engholm et al., 2018; Rashidi et al., 2020). In particular, scientific study into the impacts of vehicle automation on physical infrastructure (Farah et al., 2018) and road design concepts is still in its infancy (Washburn and Washburn, 2018; Intini et al., 2019; Khoury et al., 2019; Saeed, 2019; Rana and Hossain, 2021). Most of the research on AVs to date has concentrated on vehicle technology itself or digital infrastructure (Farah, 2016), and the issues related to safety and reliability are mainly seen from a vehicle standpoint (Ehrlich et al., 2016; Carreras et al., 2018). This vehicle-centric vision also poses difficulties for vehicle and information technology industries and infrastructure owner-operators (IOOs)[3] in communicating with each other and sharing expectations (Carreras et al., 2018). Thus, the infrastructure requirements to facilitate AVs have not been clearly defined so far (Nitsche et al., 2014; Transport Systems Catapult, 2017; Lawson, 2018; Lu et al., 2019).

However, current road infrastructure is designed for human drivers and may not be able to integrate vehicles with high levels of automation (Liu et al., 2019; Lengyel et al., 2020). In other words, it is not known whether existing road infrastructure and the surrounding environment are ready for the safe and efficient operation of AVs during the nascent stages of implementation (Johnson, 2017). Human drivers have a good ability to adapt in situations where road markings and traffic signs are absent, and they can make complex inferences in real-time and exhibit acceptable behaviour even when they cannot consistently see the road scene, for example when they are blocked by a large truck (Farah, 2016). On the other hand, current sensor technologies and software adopted in AVs rely heavily on the presence of specific road environments and infrastructure (Van Brummelen et al., 2018; Soteropoulos et al., 2020). On-road testing points to worrying evidence that existing urban and particularly rural roads may struggle to support automated driving (Peiris et al., 2020).

Contrary to limited interest in the past decade, there has been growing attention to the physical road environment and its influence on the safe operation of AVs (SMMT, 2019; KPMG International, 2020). A number of recent research projects and action plans on road infrastructure for automated vehicles have acknowledged the need for comprehensive infrastructure planning for AVs (Gill et al., 2015; Ehrlich et al., 2016; Huggins et al., 2017; Johnson, 2017; Gyergyay et al., 2019; Amelink et al., 2020; Erhart et al., 2020). A recent report for the European Parliament, for example, points out that the quality of road infrastructure is vital for the effective adoption of artificial intelligence applications for transport and infrastructure must meet much higher quality standards, especially as the level of vehicle automation rises (Evas and Heflich, 2021). Also, many efforts have been made in recent years to develop new risk assessment and safety verification methods for automated driving systems as their launch to market without proof of safety would be unacceptable neither to society nor to legislators. Among these efforts, scenario-based approaches, in which individual traffic situations are tested through virtual simulation, highlight that the road environment and infrastructure are important parameters for testing the safety of AVs (Riedmaier et al., 2020; Khastgir et al., 2021).

[3] IOOs include agencies, such as state and local departments of transportation, toll operators, and transit authorities, that own and operate infrastructure used for transportation (Gopalakrishna et al., 2021).

In this regard, examining the infrastructure-related requirements of AVs will play an important role in assessing the readiness of the existing road network and preparing the plans to help facilitate the seamless integration of AVs into the future road network. Although automated driving technologies are still under development, some of their basic requirements on the physical and digital infrastructure are already clear. To assess these requirements and present them to decision makers as a whole, a few review papers (e.g. Farah et al., 2018; Liu et al., 2019) and expert opinion-based exploratory research (e.g. Nitsche et al., 2014; Lu, 2018) were conducted. Nonetheless, given the rapid growth in AV-related publications in recent years, some knowledge gaps presented in previously limited research are closed partially. In addition, technological development and field studies have brought additional criteria to be considered in the transition period for AVs or reduced the importance of some requirements for automated driving. Therefore, additional reviews are needed to capture the new knowledge produced in this growing field and complement the findings of the previous studies on infrastructure requirements of AVs.

From this motivation, this research seeks to address what the implications of automated vehicles will likely be for the physical road environment by comprehensively reviewing the current literature. Unlike previous studies (e.g. Farah et al., 2018; Liu et al., 2019; Rana and Hossain, 2021), this issue was investigated by framing two broad questions: 1) What are the potential impacts of automated vehicles (AVs) on road infrastructure and 2) What do AVs require from road infrastructure for safe driving. Although different, these two questions are often discussed together in the literature and are highly interrelated. Indeed, Amelink et al. (2020) emphasise that AVs will have an infrastructure impact in two ways. First, AVs themselves may differ in their characteristics and behave differently than human-operated vehicles, causing changes in the vehicle's impact on infrastructure. The second way is that IOOs and other stakeholders can make changes to road infrastructure due to their need to provide operational design domains (ODD)[4] for automated vehicles. According to some researchers, the impacts on the physical road environment associated with ODDs are expected to be much more significant than the effects of the first type (Ulrich et al., 2020). Therefore, this study can be considered as a supplement to reports identifying the infrastructure-related requirements of AVs for safe and efficient operation, or research identifying the potential effects of AVs adoption on the physical road environment. The study has several target audiences, which are summarised as: researchers who are new to the field; the authorities who own, maintain, and operate the infrastructure; policymakers; and organisations engaged in national or international

[4] ODD is the set of driving conditions for a given automated driving system under which it is designed to operate. These driving conditions may include weather conditions, road infrastructure components, and vehicle-related conditions (SAE International, 2021).

activities to define the road infrastructure requirements for successful implementation of AVs.

The rest of the paper is laid out as follows. **Section 2.2** provides an overview of the vehicle automation and deployment paths, and road classification efforts for automated driving. **Section 2.3** presents the review technique adopted in this study. **Section 2.4** illustrates the general findings on the implications of AVs for the physical infrastructure-related attributes and interpretation of the current literature. **Section 2.5** provides a discussion and summary of the issues identified and their practical implications for further research. Finally, **section 2.6** presents conclusions.

2.2 Background

2.2.1 Levels of on-road vehicle automation

Several classification schemes have been defined to distinguish between automation levels to guide industry and consumers in establishing safe operating principles for fully automated vehicles. The German Federal Highway Research Institute (BASt) and the German Association of the Automotive Industry (VDA), the U.S. National Highway Traffic Safety Administration (NHTSA) and the International Society of Automotive Engineers (SAE) in the United States have introduced levels of automation that differ based on the extent of human driver involvement. The six-level SAE classification (SAE J3016) has the most comprehensive and precise descriptions (SAE International, 2021), and the European industry has agreed to use this classification for a common understanding of automated driving (Mocanu et al., 2015).

The five levels of automation reflect the gradual process of vehicle automation, beyond Level 0 where the driver performs all the direct driving tasks (see **Figure 2.1**). At Levels 1-2, the driving assistance systems provide the driver with longitudinal or/and lateral vehicle motion control in the form of adaptive cruise control and lane-keeping assistance. However, at these levels, the driver must supervise the driving system continuously and is responsible for monitoring the environment. For automation Levels 3, 4 and 5, an automated driving system (ADS) performs the entire dynamic driving task (DDT) while the system is engaged. Level 3 is defined as *"the sustained and ODD-specific performance by an ADS of the entire DDT under routine/normal operation with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately"*. The difference between Level 3 and Level 4 automated driving is whether the driver (DDT fallback-ready user) is expected to be available for the takeover of the vehicle or not. At Level 4, ADS is expected to handle the fail-safe situation autonomously, but the ODD would still be limited. When an automated vehicle is able to drive in all driving modes which means that its ODD is unlimited, it will be defined as a Level 5 vehicle – this level is often referred to as "*autonomous*" or "*self-driving*" in the media (SAE International, 2018).

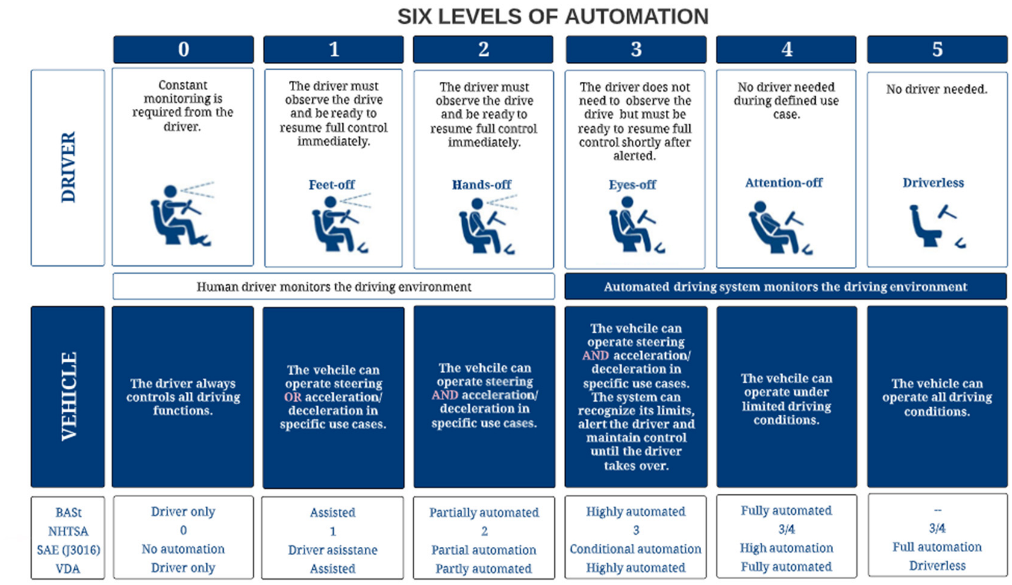

Figure 2.1 Levels of on-road vehicle automation, adapted from SAE International (SAE J3016).

Apart from the automation capability levels, the distinction between automated and connected implementations is another important dimension of the classification of these emerging systems (Shladover, 2018). When integrated with connectivity, automated driving systems give rise to the connected and automated vehicle (CAV). Although connection and automation technologies have been developed independently initially, they now seem to be converging (Timmer et al., 2015; Shladover, 2018) as in combination they offer many advantages that cannot be achieved on their own (Schoettle, 2017; He et al., 2019). Connected vehicle (CV) technologies allow a vehicle to communicate wirelessly with the surrounding road infrastructure (V2I), vehicles (V2V), other road users such as pedestrians and cyclists (V2P), or many elements in the vehicle's surroundings (V2X), see **Figure 2.2**. The limitation of CV technology is that it relies entirely on message exchange for mutual awareness (He et al., 2019). On the other hand, AVs rely on their onboard sensors, embedded software and artificial intelligence in vehicles so that they do not need additional external infrastructure or communications. However, AD technologies are not fully reliable yet and face problems in situations such as extreme weather or unpredicted road conditions (Favarò et al., 2018; Zang et al., 2019). Over the longer term as higher levels of automation is developed, it will be increasingly important for the automation systems to be connected to overcome some of the limitations of AD technologies and, more importantly, to gain transportation system benefits through cooperation (Shladover, 2018). But some argue that it will probably not be possible for all road networks to meet the infrastructure required for connectivity (Madadi, 2021). Reviews of these communication and AD technologies are given in many studies such as (Coppola and Morisio, 2016; Huggins et al., 2017; Shladover, 2018; Sarker et al., 2020; Wevolver, 2020).

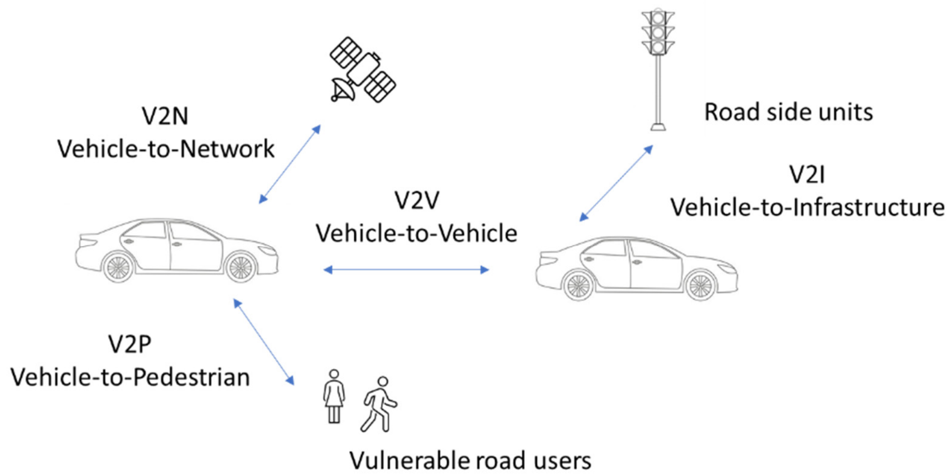

Figure 2.2 Vehicle communication types.

2.2.2 Role of infrastructure on deployment paths of automated driving

While automated driving is expected to provide various benefits for mobility, safety and the environment beyond those possible with manual driving (Bagloee et al., 2016), there are many uncertainties regarding the path of transition to full automation (Aigner et al., 2019). The European road transport research advisory council (ERTRAC) has introduced to *"Automated Driving Roadmap"* which provides descriptions of the automation systems and the expected date of their possible deployment, considering differing use cases and mobility models (ERTRAC, 2019). The report estimates that Level 4 AVs will be on the road in the next decade. Similarly, several studies have attempted to explore the market introduction and evolution of penetration rates for AVs through questionnaire surveys or interviews with experts (Saeed, 2019), but the actual rate of development of AVs and the precise nature of the transition path remains unclear (Milakis et al., 2017a). The International Transport Forum (2015) points out that two incremental paths toward full automation are being followed by the industry. These two approaches are simply described as *"something everywhere"* and *"everything somewhere"*.

The first path "*something everywhere*" strategy is generally embraced by traditional vehicle manufacturers and is largely consistent with SAE automation levels (International Transport Forum, 2015). The goal here is to gradually improve the capabilities of ADS in existing conventional vehicles and shift more dynamic driving tasks from drivers to ADS over time with the maturity of technological progress. Currently, most automakers use automated technology as a support for the driving task, resulting in Level 1 and 2 systems being widespread in the existing vehicle fleet (Robinson et al., 2017). However, driving automation Level 3 (e.g. traffic jam pilot), where responsibility can be exchanged between human and vehicle, can be particularly difficult to implement in terms of the timing of the transition (Lücken et al., 2019) and may require significant user experience for design and engineering. This is because when faced with a situation that the system cannot cope with, the driver is expected to be ready to take control of the vehicle control shortly after the alerted (Merat et al., 2014; Calvi et al., 2020). Although Level 3 has been recently regulated by authorities (e.g., UNECE Regulation No. 157), it raises many controversial questions about how the process can be managed if drivers do not respond. Another criticised point is that in the case of a failure or out-of-ODD, the number of vehicles making a minimal risk condition can be quite large, and their stopping would practically put the whole road to a standstill. Therefore, some studies have noted that stopping in a lane as the minimal risk manoeuvre should be strongly avoided (Transport Systems Catapult, 2017; Ulrich et al., 2020).

To avoid operational challenges in Level 3, technology companies (e.g. Waymo) are making significant progress and focusing on designing and manufacturing self-driving vehicles by completely bypassing intermediate automation levels. Also, some traditional automakers support a similar pattern and have announced that they will not follow the development of Level 3 systems (Bigelow, 2019; Martinez, 2019). This strategy refers to the second path *"everything somewhere"* which involves deploying vehicles without a human driver and gradually expanding vehicle operation to more contexts (International Transport Forum, 2015). In other words, this path is aiming at full automation within a limited ODD (e.g., a specific geofence or defined road types) and makes an effort to expand this domain with more complex driving situations (Madadi, 2021). However, it does not seem possible in the short term to engineer automated driving technology that can operate on all existing roads without requiring any infrastructure upgrades (ERTRAC, 2019). Therefore, reliance on AD technology alone without infrastructure support may jeopardize the potential safety and efficiency gains of AVs.

From the above discussion, it can be concluded that road infrastructure is a determining factor for both approaches and can either facilitate or prevent higher automation capabilities (Madadi, 2021). For the transition period to full automation, many studies highlight that the safe operation of levels 3-4 at full capacity will largely depend on the condition and type of infrastructure they encounter (Huggins et al., 2017; Madadi et al., 2019). It is therefore important for road authorities and agencies to know how ready road infrastructure is for safe automated driving.

2.2.3 The concept of road classification for automated driving

The idea of road certification for automated driving has been specified by some researchers (Cheon, 2003; Zhang, 2013; Issac, 2016; Huggins et al., 2017) to achieve the maximum benefits of AVs and get safer roads for all users. In this context, many initiatives are investigating cost-effective ways to prepare road infrastructure to enable the transition process in which conventional and automated vehicles coexist, and they are putting out significant effort to produce collaborative and complementary approaches (ERTRAC, 2019). Among these efforts, a recent project in Europe (INFRAMIX) has proposed a simple classification scheme to classify and harmonize the capabilities of a road infrastructure to support and guide AVs (Carreras et al., 2018). Within this framework, five levels (A-E) of infrastructure support for automated driving (ISAD) are defined and suggest that these levels can be assigned to parts of the network to guide AVs and their operator on the "readiness" of the road network for these emerging technologies.[5]

However, the idea is mostly based on digital infrastructure for roads, and connectivity alone might not enough to define how ready a road section is to host automation. Physical infrastructure, environmental conditions and other relevant aspects of dynamic elements should be considered in detail. For this reason, some organisations have focused on the concept of road classification and proposed alternative frameworks for service level classification for automated vehicles, considering the ODD and ISAD requirements (Poe, 2020; FTIA, 2021; García et al., 2021). On the other hand, some argue that the requirements of these concepts can be idealistic, expensive, and difficult to meet for all roads. In other words, large investments may be unnecessary, especially for low-volume road types such as rural roads and small city streets that serve primarily to provide access to origin and destination points (Madadi, 2021). Therefore, in the early stage of deployment, these concepts will likely be important for sections of highways rather than entire road networks to configure the various support that the infrastructure can provide to automated vehicles.

2.3 Materials and method

The study undertakes a comprehensive review of the literature on automated vehicles to address the key research questions: (1) what are the potential impacts of AVs on physical road infrastructure and road design concept, and (2) what do AVs require from road infrastructure? To address these questions, a semi-systematic approach was followed in the literature acquisition process. Studies were identified from academic databases (TRID, Scopus and Web of Science) by searching the following keywords

[5] Levels E and D are called conventional infrastructures and Levels C–A are termed as digital infrastructures. Simply, the classification is based on the availability and types of digital information provided to the AVs.

and terms: (“safety assessment” OR “road safety” OR “road infrastructure” OR “road design” OR “physical infrastructure”) AN D (autonomous OR automated OR driverless OR self-driving) AND (vehicle OR car). The reviewed documents include scientific journals, conference proceedings, book sections, technical reports, and white papers. Only documents in English published until 2022 were included. The obtained studies' titles and abstracts were screened based on their relevance to the research aim. For the eligibility part, full-text papers were skimmed and evaluated for whether they were relevant to the research question. The general criteria adopted for the document selection were that the studies focused on both the field of AVs and had at least one of the following contents:

- Discussion on potential physical infrastructure requirements or upgrades needed for the introduction of AVs;
- Presenting any challenges or limitations of automated driving caused by road infrastructure or road environments;
- Discussion of possible impacts of vehicle automation on existing road infrastructure and/or possible change in road geometric design.

Then, additional papers were identified and included through the cross-referencing of selected studies and other sources (e.g. organisations' web pages, Google Scholar, etc.). However, the findings of this study may be influenced by the following limitations. The methodology was undertaken based on the qualitative methods without any automated analysis technique and selected keywords may not cover all studies relevant to the research objective. Moreover, the combination and integration of physical and digital infrastructure are necessary for the safe operation of AVs and road traffic. However, within the scope of this literature review, digital infrastructures such as traffic management and control systems and localisation systems are not covered in this study. An overview of the digital infrastructure side of vehicle automation can be found in various studies such as (Coppola and Morisio, 2016; Huggins et al., 2017; Shladover, 2018; Amelink et al., 2020; Eskandarian et al., 2021).

2.4 Findings and interpretation of the identified literature

In the light of the eligibility criteria mentioned in the previous section, a total of 57 studies were identified from the existing literature (see **Appendix A**). The descriptive analysis of these studies regarding their year of publication revealed an increasing interest in this field due to technological advances and legislative changes around the world. These figures demonstrate similar trends to previous review studies (Farah et al., 2018; Liu et al., 2019) which confirm the growing interest in understanding the role of road infrastructure in the AVs deployments over the past few years. In the next sections, it will be seen that the available information comes not only from research, but also from grey literature, including government and industry reports, and online articles from technological institutes and websites. However, the findings of the existing studies are mainly based on subjective stakeholder opinions and literature review. The number of studies based on empirical data is quite limited. While studies have generally focused on the effects and requirements of the Level 4 or 5 automated driving system, approximately 37% of the studies identified did not clearly specify which level AVs were focused on in their research. Europe and the USA are the leading regions of origin of these studies, reflecting the fact that academic institutions and researchers from these two continents have significant interests in this topic.

Regarding physical road infrastructure, a total of thirteen key features of infrastructure have been identified in the existing literature regarding vehicle automation operation that should be considered either in the initial phase of deployment or during the transitional phase to full automation (see **Figure 2.3)**. In determining infrastructure attributes, the study sought to answer the question of which elements of road infrastructure are relevant to vehicles while travelling on a particular road segment. The following sections summarise these critical attributes briefly.

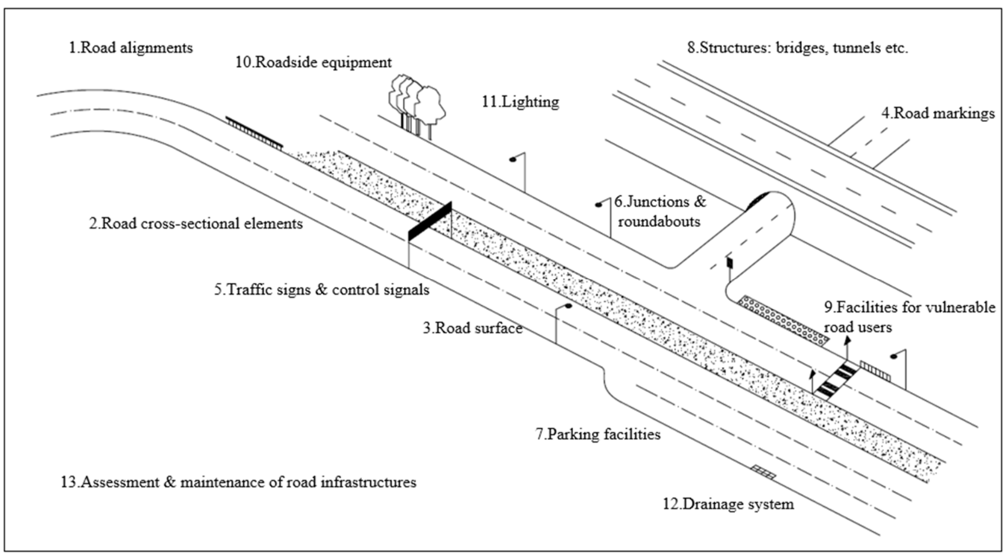

Figure 2.3 Examples of physical road infrastructure considerations discussed in the study for AVs, adapted from (Lyon et al., 2017).

2.4.1 Road alignments

Geometric design principles for roads have evolved through years of research and practical experience. Organizations such as the American Association of State Highway and Transportation Officials (AASHTO) are constantly updating their models and recommendations, taking into account newer evidence and data (AASHTO, 2011). However, most of the design manuals are based on the characteristics of human drivers. For instance, the driver's perception-reaction time, eye height, and other human-related behaviours are the major factors that influence the design of road geometric elements (Othman, 2021). One of the views in the literature is that current road geometric standards may still apply to AVs if they can recognize the risks of driving faster than or equal to conventional users through sensors, scanning, and connectivity systems (Colonna et al., 2018; Intini et al., 2019). On the other hand, many researchers emphasize that as the penetration level of AVs increases in the market, road design parameters involving a direct relationship with the characteristics of human drivers need to be reconsidered (Washburn and Washburn, 2018; Khoury et al., 2019). In other words, the road geometric design philosophy and related specifications and guidelines should be revised as some driver-based requirements may lose their importance by shifting from conventional driving to automated driving (AASHTO, 2017). Parallel to this change, the impact of AVs on highway design is an emerging area of research. However, few studies have so far investigated the impact of AV on highway geometric design elements (Intini et al., 2019; Khoury et al., 2019; Othman, 2021) since current literature mainly focuses on effects on traffic flow and road capacity. The identified literature on this subject is summarised in **Table 2.1**, including their main findings and focused design elements.

Studies have mainly explored possible changes in geometric design elements in response to full Level 4-5 AV fleet penetration and evaluated these changes in comparison to traditional design outputs. Due to differences in perception abilities between human drivers and AVs, studies have mainly focused on stopping sight distance (SSD) and decision sight distance (DSD) criteria, which are key elements in designing road alignments. While human drivers mainly use their eyes to perceive their surroundings, AVs are expected to have a wider sensing range and a shorter perception and reaction time than human drivers as AVs use data from more sensitive and diverse sensors (e.g. lidar, radar and camera) to extract useful information specific to their purpose (X. Ye et al., 2021). Therefore, AVs will have significantly lower SSD (see **Figure 2.4**) and DSD. The SSD is the main factor influencing the lateral clearance on horizontal curves, so AVs can significantly reduce the required lateral clearance (Khoury et al., 2019; Othman, 2021). Furthermore, the drivers' characteristics such as eye height and reaction time are the main factors that affect the required vertical sag and crest curve length (Aryal, 2020; X. Ye et al., 2021). Studies underline that AVs can significantly reduce the required curve length.

Table 2.1 A summary of the identified literature on the impact of AVs on road geometric design

References	Considered design elements or criteria	Design guidelines	Comments / findings
Washburn and Washburn (2018)	Vehicle performance (acceleration and deceleration rate), Sight distance (crest of vertical curve, horizontal curve, and gap acceptance at two-way stop-controlled intersection).	N/A	An exploratory approach to the subject. As safety and comfort will still be decisive factors, the authors do not expect a tremendous change in roadway design based on the vehicle performance assessment. Considering the sight distance, V2X connectivity will promote economic design for new roads.
Khoury et al. (2019)	Stopping sight distance (SSD), Decision sight distance (DSD), Length of crest vertical curve, Length of sag vertical curve.	AASHTO	Potential economic and environmental improvements through the reduced cut and fill volumes of the new design (based on the elimination of human driving) and the flexibility to use shorter vertical curves. The length controls for sag and crest vertical curves would need to be revised to accommodate the AV's required SSD.
Saeed (2019)	SSD, Acceleration lengths for entrance terminals with flat grades.	AASHTO	The road geometry design will not undergo any drastic revisions that could make the ride uncomfortable for the AV occupants. Regarding the acceleration lengths, reducing the merging manoeuvre length is only possible if the AVs are electric as they can accelerate faster than a gas combustion engine vehicle.
Intini et al. (2019)	Length of tangents and curves, Radius of circular curves, Transition curves, Road design consistency, Grades, Radius of vertical curves, Consistency of horizontal and vertical alignments, Sight distance, Speed concepts, Road friction, Lane and shoulder width.	Focus on internationally valid design concepts	Human-based requirements can greatly change in the case of the roads used only by AVs, but other requirements may still apply. Compared to current design standards, they suggest more relaxation would be expected for the design of alignments, speeds, and sight distance.
Welde and Qiao (2020)	SSD, Length of crest vertical curve, Length of sag vertical curve.	AASHTO	A significant reduction in SSD is due to changing design elements related to human characteristics and vehicle performance (e.g. perception and reaction time, deceleration rate and height of sensors), hence the minimum length of the crest and sag curves is expected for both scenarios (human drivers with a level 3 vehicle automation, and AVs without a human driver). This results in shorter curves that are more economical.

(continued on next page)

Table 2.1 (continued)

References	Considered design elements or criteria	Design guidelines	Comments / findings
García et al. (2019)	SSD, Crest vertical curves, Speed concepts	AASHTO & Spanish guidelines	International standardization is needed for related parameters as the findings might significantly change depending on the considered design guideline as well as the used AVs because each design guideline assumes specific values of the height of the eye and object above the roadway surface, and the deceleration rate is different among vehicles.
Aryal (2020)	SSD, Passing sight distance (PSD), Intersection sight distance (ISD), Length of crest vertical curve, Length of sag vertical curve, Lane width.	AASHTO	The geometric design parameters could be optimized, and this brings a reduction in the minimum required geometric design value for the AVs along with the reduction in net earthwork volume, pavement material volumes, and environmental impacts.
McDonald (2021)	SSD, Length of crest vertical curve, At-grade rail crossings, Ramp terminals.	AASHTO	The author emphasizes that as long as human-driven and controlled vehicles are part of road traffic, roads should continue to follow traditional design guidance for human-guided vehicles.
Guerrieri et al. (2021)	SSD, Maximum straight length, Horizontal circular curve design, transition curve: design criteria for the clothoid, Gradients, Crest vertical curve design, Sag vertical curve design	Italian guidelines (D.M. n. 6792. 5/11/2001)	AVs proved to need much shorter SSD (calculated in function of the design speed and the slope) than those today required by manually guided vehicles. This may eliminate many speed limits along with some motorway segments, due to visibility obstacles (e.g. small radius curves and the presence of safety barriers).
X. Ye et al. (2021)	SSD, Length of crest vertical curve, Length of sag vertical curve, Complex combined horizontal and vertical alignments.	AASHTO	AV-based design controls on vertical curves are more tolerant than those based on human drivers; and the dominating criterion of sag vertical curve design control is comfort for AVs, versus required SSD for human drivers.
Othman (2021)	SSD, DSD, Lateral clearance on horizontal curves, Length of crest vertical curve, Length of sage vertical curve, Lane width, Horizontal curve design, Spiral curve design, Maximum length of straight segments on horizontal alignments.	AASHTO	AVs can substantially reduce: 1) the required lateral clearance due to having lower SSD and DSD, 2) the required vertical curve length because of having faster reaction time and the differences in sensor height.

However, García et al. (2019) point out that findings can vary significantly depending on the design guideline being considered, as each design guideline assumes certain values of eye and object height above the roadway surface and deceleration rate. Also, since the height of the sensors' positions differs between vehicles, the characteristics of the AVs affect the results (García et al., 2019; Khoury et al., 2019). Therefore, international standardisation of these parameters is needed. On the other hand, studies suggest that most of the geometric elements will not change in the era of AVs, especially those related to physics and comfort-based parameters. For example, the required curve radius or ramp terminals will be similar for both human-guided vehicles and AVs, as it depends on the driving dynamics and passenger comfort, not the characteristics of human drivers (Aryal, 2020).

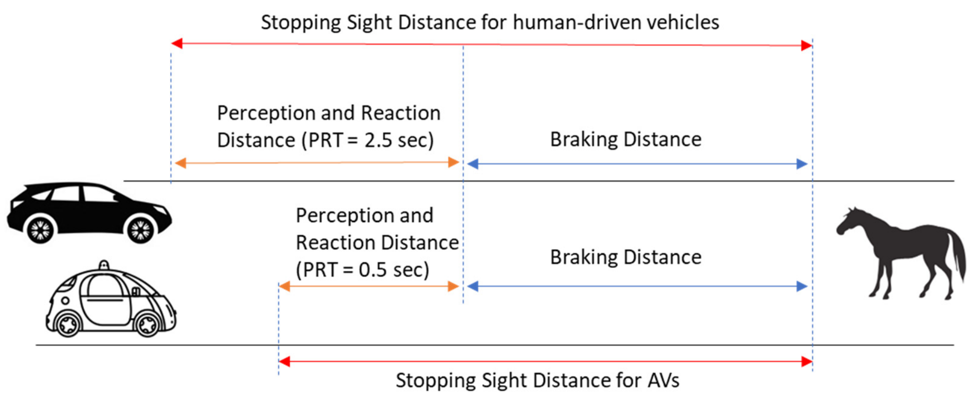

Figure 2.4 The stopping sight distance for human-driven vehicles and AVs, adapted from (Othman, 2021).

Moreover, some authors believe that without connectivity, AVs will not outperform humans in situations where the sightline is limited such as detecting objects behind a vertical crest curve (Washburn and Washburn, 2018). Regarding the effect of road alignments on AV operation, studies reveal that both horizontal and vertical curvatures of the road have an effect on the operation of automated driving systems, such as the ability to detect lane markings (Tao, 2016; Marr et al., 2020), precise localisation of vehicles (Reid et al., 2019), and path planning control (Xu and Peng, 2020; Eskandarian et al., 2021). An experimental study on the market-available (Level-2) vehicles emphasises that the driver assistance function is often disengaged or causes drivers to feel unsafe in sharp curves (Taylor et al., 2018; García et al., 2021). Similarly, experts have noted that sharp curves influence the safe operating of ADS such as lane assistance systems, collision avoidance systems and speed control systems (Nitsche et al., 2014). Mainly, sharp horizontal curves and crest vertical curves pose challenging situations for AVs as the visibility range of the machine-vision sensors is limited. To mitigate the possible risks of this challenge, some studies proposed a new speed concept, automated speed, as the maximum speed that an AV can achieve at a specific road element such as horizontal curves (García et al., 2020) and vertical curvature (Gouda et al., 2021). Therefore, it is not expected any change in road alignments during the initial phase of AVs, but revision can be seen on dedicated roads or lanes for safe operation.

2.4.2 Road cross-sectional elements

2.4.2.1 Lane width

The dimensions of the cross-sectional elements (e.g. lanes and shoulders) are generally defined in standards based on road type, importance, traffic volume and context (Intini et al., 2019). Current road design standards specify the width of roadway and lanes depending on the width and length of the vehicles, while also providing a tolerance for driver behaviour. The tolerance for driver behaviour takes into account the change in the horizontal position of the vehicle in the lane and the space required to make any turn on the road without entering the opposite lane (Amelink et al., 2020; García and Camacho-Torregrosa, 2020). Typically, cars are about 2 m wide and trucks about 2.5 m, while standard lane widths can range from 2.5 to 3.7 m (Amelink et al., 2020). With the development of positioning technology, one of the common ideas is that AVs will likely have accurate steering control and track more precisely within a lane, which could allow lanes to be narrowed (Lyon et al., 2017). If this could result in fitting an additional lane to be placed in the carriageway, the efficiency of the road will increase without the construction of a new lane. The paved width of current carriageways can be easily retrofitted to achieve this by reconfiguring the lane markings significantly (Saeed, 2019; Amelink et al., 2020).

Besides, when designing new roads, the total road width could be likely reduced for AVs than in the case of traditional roads (Intini et al., 2019). This is generally positive, among the other reasons, for saving land and agency funds for construction and maintenance of the paved surface. Considering the urban street where the speed limits are low, AVs can potentially help to promote more efficient use of land in cities and facilitate new forms of streetscaping. Reduced lane widths for AVs result in more space for vulnerable road users so these spaces could be used for better pedestrian and bicycle facilities or emerging new transport modes (Johnson, 2017). Thus, this can create new opportunities to increase urban attractiveness (Chapin et al., 2016; Stead and Vaddadi, 2019).

As with other road design features, lane width has been found to affect the operation of current vehicles equipped with lane keeping assist (LKA) systems (Reid et al., 2019; Reddy et al., 2020). García and Camacho-Torregrosa (2020) conducted an experimental study to understand the effect of lane width on partially automated vehicle (Level 2) performance and revealed that the LKA system tends to fail in narrow lanes. The test results showed that the threshold value for the safe operation of the automatic lateral control is a 2.75 m lane width. Similarly, Marr et al. (2020) underline that lane width narrower than 2.8 m is challenging for the machine vision systems of vehicles, especially in the absence of edge lines. On the other hand, several studies in the literature conclude that AVs have the potential to reduce the required lane width to 2.4 m with high communication between AVs (Othman, 2021).

However, the configuration of lane widths on curves will need to be handled more carefully due to vehicle turning paths and vehicle overhangs (Saeed, 2019). Sight distance would also be affected by lane reconfiguration. Therefore, it is not clear yet how the narrow lane width will affect road safety. Given mixed fleet conditions with different levels of automation on the same road, lane width reduction during the transition period may not be possible unless a dedicated lane is allocated for high-level AVs. This is because recent experimental studies on partially automated vehicles (Level 2) currently on the market have revealed that the positioning stability of the vehicles differs significantly (Russell et al., 2018; Taylor et al., 2018). This variation between vehicles may pose an issue for driver confidence and safe function within narrow lanes. Taylor et al. (2018) emphasize that either certified vehicles must prove capable of remaining within a minimum given lane width, or roads must only be certified as suitable for vehicles when a safe minimum lane width is met.

2.4.2.2 Shoulders and emergency bays

Shoulders are important design considerations for roads and provide additional space for visibility or, in emergencies, for recovering after lane departure or manoeuvring to avoid collisions. Furthermore, emergency vehicles need shoulders to reach incident sites to bypass the traffic congestion. More importantly, shoulders and emergency bays are used by all vehicles in case of vehicle breakdowns for the safety of road users and the prevention of traffic jams. In a recent survey with road agencies in the USA, 35% of respondents expect reduced shoulder widths in AV operations due to more precise driving and better handling of road conditions than human-driven vehicles (Saeed, 2019). However, it is mentioned in multiple studies that AVs will need shoulder and frequent safe harbours during the transitional period to full automation (Transport Systems Catapult, 2017; Gopalakrishna et al., 2021; PIARC, 2021). According to some, with the prevalence of AVs on the roads, shoulders will be needed more than ever in order for vehicles experiencing software or hardware failures to have a safe harbour (Saeed, 2019).

Regarding vehicle automation, Level 4 systems can operate without any driver involvement within a specific ODD, but once the vehicle leaves that ODD (e.g. due to adverse weather conditions, work zones etc.), drivers need to take control. It is possible that the driver is not ready to take control of the vehicle, in this situation the vehicle needs a safe area to stop/park and wait for the driver to be ready, or wait for conditions to improve to the extent where the automated control system is able to proceed (Transport Systems Catapult, 2017). Therefore, there is likely a need to have wider shoulders and emergency bays at regular distances to act as safe harbours to stop AVs in case of the temporary ending of the ODD. Emergency refuge areas and wide enough shoulders for stopping a vehicle safely are widely available already on most highways. However, there is no shoulder available in many locations, such as bridges, tunnels, or many two-lane highways, so additional requirements will need to be considered at these locations (Nowakowski et al., 2016). Furthermore, on some highways, paved shoulders have been modified so that all lanes are running or open to traffic at peak times via indicators on overhead signage (Transport Systems Catapult, 2017). Therefore, the suitability of using the shoulder as a safe harbour needs to be carefully assessed depending on the road situation (Amelink et al., 2020).

2.4.2.3 Median (central reservation) and barriers

Median refers to the road infrastructure that separates the opposite directions of the travelled way and it is highly desirable for high-speed carriageways (AASHTO, 2011) as it helps prevent head-on crashes across the entire road segment and provides a recovery area for out-of-control vehicles (Kim et al., 2017). In addition, median barriers and side guardrails mitigate the negative consequences of road departure of human-driven vehicles (Konstantinopoulou and Ljubotina, 2020). In urban areas with low-speed roads, the function of the median is also to provide an open green space, a refuge area for pedestrians crossing the street, and control the location of intersection traffic conflicts (AASHTO, 2011). In the long term, many studies suggest that medians could be removed or narrowed since a safety buffer between traffic in opposing directions may no longer be needed for L4-5 AVs. The space saved can be used to accommodate additional lanes or other modes of travel (serving as sidewalks or bike lanes), or even converted into parking space (McDonald and Rodier, 2015; PSC and CAR, 2017; NACTO, 2020).

In the transition period, the mixed traffic era, it is likely that medians and barriers will still be needed for road safety due to the availability of human-driven vehicles. In addition, many studies point to the importance of dedicated lanes to ensure safe and efficient operation during the initial phase of implementation (Ye and Yamamoto, 2018). However, it is unclear how much buffer would be adequate for separating AVs from human-driven vehicles (Saeed, 2019), and extra efforts will be required to design and operate dedicated lanes in terms of safety and efficiency (Guhathakurta and Kumar, 2019; Rad et al., 2020). An experimental study revealed that the proximity of the line-markings to concrete safety barriers, which have similar properties to lines from a machine learning perspective made it harder for AV systems to identify them (Konstantinopoulou et al., 2020). Similarly, Kim et al. (2017) stated that flexible median barriers such as wire rope barriers can present difficulties, as AVs may have difficulty detecting smaller objects. Therefore, it is asserted that the design requirements of barriers and their types would be different for AVs (Pape and Habtemichael, 2018). Besides, design loads for barriers may need to be reconsidered due to the effect of truck platooning (Huggins et al., 2017; Lawson, 2018).

2.4.3 Pavement/road surface

As previously stated, AVs are likely to have more precise steering control allowing them to maintain a lateral position in the centre of the lane (Lyon et al., 2017). However, the more precise positioning enabled by lane-keeping technology results in reduced wheel wander distance, so repeated single-point loading can significantly affect pavement condition and cause rapid pavement deterioration (Lutin et al., 2013; Chen et al., 2016; Zhou et al., 2019; Yeganeh et al., 2022). Rutting, the permanent load-induced deformation on a flexible pavement surface, is one of the potential effects of this and needs to be carefully considered in the pavement design as it can cause vehicles to skid and drivers to lose control of the vehicle (Yeganeh et al., 2022). Chen et al. (2016) investigated the potential effects of AV deployment on the long-term service performance of asphalt pavement using large-scale finite element modelling. Specifically, the pavement rutting performance by the possibly changed behaviours, such as the vehicle’s wheel wander, lane capacity, and traffic speed were examined. The study showed that there are varying influencing factors that will counterbalance AVs' effects on the pavement. While the decreased wheel wanders and increased lane capacity could bring an accelerated rutting potential, the increase in traffic speed would negate this effect. Therefore, whether the net effect is positive or negative depends on the practical road and traffic conditions.

On the other hand, Carsten and Kulmala (2015) stated that AVs could be programmed to drive more evenly across the whole width of the driving lane to reduce pavement wear. Besides, there are some more “radical” ideas that there is no need for vehicle lanes on the roads in a fully automated environment (Malekzadeh et al., 2021). AVs can adjust the distances among them intelligently without following vehicle lanes. These ideas could prevent increased damage from precise positioning, but it also means that the lane width could not be narrowed. Zhou et al. (2019) investigated the different lateral wandering pattern impacts on the pavement by modelling with the Texas Mechanistic-Empirical Flexible Pavement Design System (TxME). Results showed that the AVs with smaller lateral wandering (compared with human-driven vehicles) would shorten pavement fatigue life by 22% and increase pavement rut depth by 30%, which leads to a much higher risk of hydroplaning (Zhou et al., 2019). On the other hand, they estimated that the use of AV optimal pattern – designed for wider wheel wander with uniformly distributed traffic loads - can be beneficial and decrease the rutting depth by 24% and extend the pavement life cycle by 16%.

Similarly, Noorvand et al. (2017) suggested that if properly controlled, automated trucks can be quite useful for pavement design and will be most effective when the penetration of automated trucks is larger than 50%. The potential benefits stemmed from the ability to control the positioning of automated trucks more systematically and more uniformly using the available pavement surface. On the other side, in the absence of proper control, especially by repositioning trucks in the same location, the amount of damage can be quite harmful and noticeable effects can occur at automated truck volumes as low as 10% (Noorvand et al., 2017). Unlike previous research, Yeganeh et al. (2022) estimated the impacts of dedicating a reduced lane width to AVs on pavement rutting performance using finite elements. The study finds that dedicating a narrower lane for AVs could significantly influence the flexible pavement's rutting performance. Using dedicated lane widths of 3 m and 3.25 m for AVs with uniform-wander distribution would increase the total rutting depth of the pavement by 20.48% and 7.31%, respectively, compared to the lane width of 3.5 m.

Given the reported discussions, the net impact of vehicle automation on pavement structure is difficult to predict precisely as it depends on many variables (e.g. traffic speed, road capacity, lane width etc.). However, in urban areas with low-speed limits and narrow lane widths, the negative impact of AVs on the pavement is expected to be greater, so certain areas below the AV operation track may need to be strengthened (Johnson, 2017). Additionally, more efforts will likely need to focus on the balance between thresholds (e.g. speed limit, lane width, uniform wandering strategy etc.) and a detailed cost-benefit analysis should be done to examine the optimum solutions.

2.4.3.1 Skid resistance on the road surface

Skid resistance relates to the force developed when a tyre that is prevented from rotating slides along the pavement surface (Konstantinopoulou and Ljubotina, 2020; Zhao et al., 2021). Although many vehicles today have electronic stability control, which is a system designed to help drivers to avoid crashes by detecting and reducing skidding or loss of traction as a result of over-steering, drivers are normally unaware that a skid will occur until it starts (Weeratunga and Somers, 2015). Several car accidents on rural roads are currently caused by a loss of friction. Therefore, vehicle automation shows great potential for reducing this accident type since AVs will likely be able to forecast the skidding before it happens, based on friction estimations (Colonna et al., 2018; Montanaro et al., 2019). However, the failure to estimate friction on the road might result in roadway departure crashes. This would need to research not only the requirement for the coefficient of friction skid resistance but also speed and maximum values of acceleration and deceleration of AVs. Zhao et al. (2021) evaluated the driving safety of AVs concerning pavement friction and suggested that there is no urgent need to increase pavement friction requirements concerning rear-end crashes involving AVs. In addition, AVs can adjust their speed more predictively through communications with roadside units (V2I) or vehicles (V2V) to avoid sharp braking (Johnson, 2017). The requirement for the coefficient of friction, so materials with less skid-resistance in the surface layer can be used in the future (Liu et al., 2019). Nonetheless, AVs will continue to use rubber wheels and drive on paved or concrete surfaces, so friction is still a crucial factor in design (Washburn and Washburn, 2018). Apart from that, Zhou et al. (2019) stated that significant efforts are necessary to evaluate how pavement skid resistance decreases with the applications of multiple AVs under different lateral wandering widths and various distribution patterns.

2.4.4 Road markings

Road markings are one of the most prominent research areas among physical road attributes since current and near-future advanced driver assistance systems (e.g. LKA) highly rely on road markings in order for positioning the vehicle within the section of the road (Gupta and Choudhary, 2018). AVs use sensors, cameras, and artificial intelligence to detect the edges of the roads and identify lane markings on the roads to complete the tasks of driving and navigation (Kuutti et al., 2018; Meneguette et al., 2018; Easa et al., 2021). However, improper delineation of road markings poses challenges for vision sensors of AVs to predict where the vehicle is in the lane (Konstantinopoulou et al., 2020). Many trials of automated driving have failed or been disengaged due to the poorly marked and inconsistent road markings (Favarò et al., 2018). As such various studies have been conducted in order to develop algorithms that allow for real-time recognition of lane boundaries and vehicle guiding (Xing et al., 2018; Eskandarian et al., 2021). However, most of the research has concentrated on the phenomena from a hardware and software standpoint (i.e. image recording devices and detection algorithms). The infrastructural component, on the other hand, plays an important part in this phenomenon (García et al., 2021).

In the last few years, there has been a growing interest in scientific committees to evaluate the optimum requirements and conditions of road markings (see **Figure 2.5**) for the safe operation of AVs (Ambrosius, 2018). In this context, studies have attempted to identify performance characteristics of road markings that could affect the ability of machine-vision systems to recognise markings (Konstantinopoulou et al., 2020; Marr et al., 2020). However, as sensor technology and software capabilities evolve, the minimum requirements for road marking conditions for AVs will likely change as well. For example, findings of a recent project, using 360-degree imagery and computer vision techniques showed that the width of lines was as not as important as the condition of the line itself (Konstantinopoulou et al., 2020). On the other hand, optimum requirements of road markings for vehicle automation are difficult to determine precisely as it depends on many variables (e.g. operating speed, road surface condition, lane width etc.). A recent experimental study highlights these factors and outlines the desired conditions and configurations of road markings for AVs (Marr et al., 2020).

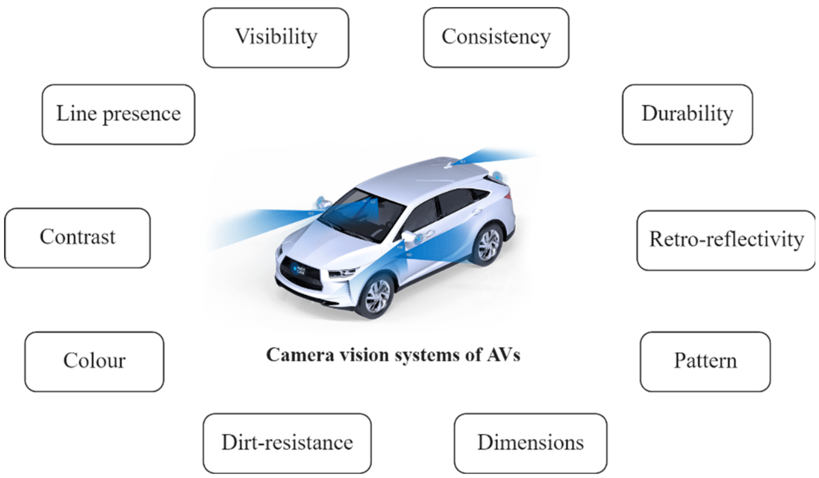

Figure 2.5 Requirements and conditions of road markings for camera vision systems of AVs.[6]

In general, research points out that ideal road marking should be "readable" by both human drivers and machine-vision systems (Nitsche et al., 2014; Huggins et al., 2017; Transport Systems Catapult, 2017; Lawson, 2018). In Europe, it is recommended that a good road marking should have a minimum performance level of 150 mcd/lux/m² in dry conditions and have 150 mm width for all roads, while it should be 35 mcd/lux/m² for wet conditions (EuroRAP and Euro NCAP, 2013; ERF, 2013). Also, it is widely accepted in the literature that high-quality and frequent maintenance of road marking can help overcome the challenges of camera vision technology. However, road markings are not always clear in natural environments, numerous factors such as shadows from trees affect their clarity (Ye et al., 2018). Moreover, the most frequently cited issue from the AV industry regarding road infrastructure opportunities to support AV deployment is the lack of uniform implementation of markings and signs around the world. In Europe, for example, non-standard road markings are cited as a major

[6] Picture of the vehicle is taken from: https://www.mobileye.com/solutions/super-vision/.

problem facing current drivers and confuse AVs (EuroRAP and Euro NCAP, 2013; Johnson, 2017; PIARC, 2021). To deal with non-standard, damaged, or poor-quality markings, AVs may need to use other sensors or systems or supplementary information via high-definition maps that provide a better position estimate (Van Brummelen et al., 2018; Marr et al., 2020). Additionally, there are various road layouts and situations (e.g. road works) where lane marking is not available. The development of the V2I communication technologies might become the key solution for these marking issues. Furthermore, new applications such as magnetic materials, which have been embedded on the road to improve the navigation and positioning of the AVs, might be potential solutions for AVs (PIARC, 2021).

According to the Transport Systems Catapult (2017), it is possible that as vehicles use digital infrastructure and mapping to localise and navigate, the issue of road markings will become less critical; however, current technologies rely on road markings, and at least some highly automated systems are expected to rely on them for some time. Furthermore, physical markings will be required as part of the road infrastructure until human-driven vehicles are completely removed from the road network. Apart from this, AVs can benefit from a “hybrid” combination of both physical road markings/signs and their digital twins in digital maps, thereby increasing the robustness of their operational capabilities (Ulrich et al., 2020). Also, some argue that HD maps will likely not be available for many cities during the early stage of implementation. Briefly, as human drivers will be able to take control of the vehicles until fully AVs are commonly adopted, road markings will continue to represent an important infrastructure element (Ambrosius, 2018) and will play a vital role for the foreseeable future (Department for Transport, 2015).

2.4.4.1 Rumble strips and road studs

Rumble strips are important physical road attributes for road users’ safety due to having the potential to reduce road accidents. Rumble strips are commonly used to delineate the centre and shoulders of paved roads (Department for Transport, 2019) and take a few different forms. For example, they can be produced by cutting grooves within the pavement surface, or by adding plastic ribs to the road. Research has shown that shoulder and centre rumble strips can significantly reduce serious run-off-road and head-on crashes on single carriageways (Biehler et al., 2009). Also, the profile of the marking within the rumble increases the night-time visibility of markings, particularly under dark and wet conditions (see **Figure 2.6**). However, considering the current literature, the role and effectiveness of rumble strips on AVs and their potential impact on the operation of machine vision systems are not clear yet.

Figure 2.6 Night-time visibility of line marking within the rumble strip, taken from (FHWA, 2015).

Another important road attribute for the delineation of the lane boundary is the application of road studs. Road studs provide visibility for drivers to keep the vehicle in the lane and prevent it from running off the roads. Retroreflective road studs, also known as cat's eyes are significantly important for drivers, particularly in wet and rainy conditions where puddles and fog inhibit vision (Pike et al., 2019). The presence of cat's eyes on a road has the potential to improve the readability of lane markings by providing a reference point with a much higher reflectance. This may enable more robust detection and classification of pavement markings by machine vision systems (Shahar et al., 2018). Recently, solar-powered, connected road stud sensors have been launched as part of the Internet of Things (IoT) to support autonomous traffic management systems. These wireless sensors collect data about vehicle movement, physical objects and road surface conditions (Browne, 2020). Similarly, Singh and Islam (2020) propose to use raised pavement markers with a chip installed inside to provide the smooth movement of AVs in work zones.

2.4.5 Traffic signs and control signals

Traffic signs and control signals are also well-researched topics among road features because AVs, like human drivers, need to detect, read and understand traffic rules in order to navigate safely. Current traffic sign recognition technology works through built-in cameras that see and interpret the traffic sign's colour, shape, message etc. (Bruno et al., 2018). However, this technology has not yet reached the desired level (Nowakowski et al., 2016). For example, false positives and false negatives are both a problem for the safe operation of vehicles (Shladover and Bishop, 2015; Koopman, 2019). For this reason, scientific committees show great effort to develop more robust and reliable traffic signs and signal recognition systems (Chen and Huang, 2016; Jensen et al., 2016). However, for this to be successful, the traffic signs have to be visible to both the human eye and the machine vision technology that is reading them

(Lyon et al., 2017). While there are standards for signs and signals, many road features, including traffic signs, differ from jurisdiction to jurisdiction (EuroRAP and Euro NCAP, 2013; Huggins et al., 2017). This variability will likely be challenging for automated driving, so there is a need to understand what types of signs, markings, and devices are currently “easy” for AVs. For example, variable message signs (VMS) are often difficult to read with cameras because they are using technologies and control systems designed for the human eye (Roper al., 2018; PIARC, 2021). Moreover, rural and remote areas might pose significant challenges to the functionality of AVs, as they often lack the necessary infrastructure and communications network for road operation. There is a need for low-cost machine-readable static signage that can fill the gaps in the infrastructure. For example, markings such as “QR codes” may be intelligible to machines, but they would be challenging for humans (Ozan, 2019). Therefore, the collaboration between industry and authorities is becoming urgent to develop standards that could assist both AV and human drivers.

A recent project in Europe analysed approximately 1000 km of roads across Croatia and Greece to assess the readability of traffic signs for AVs by using 360-degree imagery and mobile lidar (Konstantinopoulou et al., 2020). According to the assessment carried out as part of this study, about 11% of the five main types of signs (predominantly speed signs) in Croatia were not detected using computer vision techniques on undivided roads. On the other hand, this was nearly 25% on divided roads. In Greece, these were around 5.4% and 4.1%, respectively. Based on the initial findings, the project points out that the adoption of harmonised regulation and standardisation of sign types, symbols used, shapes, heights, locations, and orientations are required to increase the readability of traffic signs (Konstantinopoulou et al., 2020). Moreover, the need for regular and consistent maintenance is particularly important for AVs as they rely on delineation and signs (Huggins et al., 2017).

In the future, although most of the safety-critical information for AV navigation is expected to be able to be sent wirelessly, in the absence of a connection, traffic signs will still play a prominent role in informing the decisions an AV needs to make (Transport Systems Catapult, 2017). In addition, there is still no guarantee that the information transmitted by temporary signs, such as those used in road works or temporary deviations, will be wirelessly transmitted to the vehicle or and therefore they remain necessary. Apart from that, some infrastructure requirements can be relaxed by using a high-definition (HD) map that can assist the vehicle with a safe motion plan (Ulrich et al., 2020). But some researchers believe that all road networks will not be covered in the geographical database in the early stage (Mocanu et al., 2015). Nonetheless, the need for traffic signals and signs is expected to potentially decrease gradually with the maturity of digital support (Liu et al., 2019).

2.4.6 Junctions and roundabouts

Junctions are complex traffic situations and represent bottlenecks in the traffic flow (Montanaro et al., 2019). They can be classified into two groups: intersections and interchanges. The main distinction is that interchanges are two roads that cross over and under one other, whereas intersections are two roads that meet at the same level. Interchanges use ramps to connect the roads for often seamless traffic flow, while intersections usually employ a set of rules or a system (e.g. traffic lights) to direct traffic flow and prevent crossing paths (Paulsen, 2018). AVs are expected to improve these bottlenecks significantly with the help of new connectivity technologies that allow cooperation between vehicles or infrastructure. In line with this motivation, extensive research has been conducted on the effects of connected and automated vehicles on traffic flow at intersections to date (Elliott et al., 2019). Simulations have shown that AVs contribute to increasing the efficiency of traffic flow, thereby increasing junction capacity and reducing fuel consumption and waiting time at intersections (Atkins, 2016). However, many articles have highlighted that AVs without connectivity may not provide these benefits.

From a safety perspective, although junctions represent a small part of the road system, a significant amount of fatalities occur in the area shared by crossing streets, and these fatalities are in part due to human error (Montanaro et al., 2019). For example, statistics show that during the 10 years from 2007 to 2016, over 35% of the fatalities on UK roads occurred at junctions (European Commission, 2018). Similarly, current AV trials in mixed traffic conditions show that intersections are the most challenging road sections for AVs since 89% of the reported AV accidents (mostly rear-end crashes involving manually driving vehicles) happened at intersections (Favarò et al., 2017). Problems arise for AVs in these areas as traffic conditions are complex and there are many things to detect and monitor. Also, high speeds and sensor range limitations can cause problems at intersections. Much of the research focuses on digital infrastructure and how V2V and V2I can address these challenges. In this context, vehicle-to-network communication has also gained momentum in recent years (Martínez-Díaz et al., 2019). However, the solution does not just come from vehicle automation and connectivity, but the serious effort is also needed to upgrade infrastructure during the transitional period. Particularly, it is necessary to understand which types of intersections are safe to facilitate automated driving, and what special rules and physical requirements must be considered for intersection types to ensure AVs can safely accommodate, including platooning of vehicles. According to expert opinions, motorway exit/entrance, unsignalised intersections and roundabouts with bicycle lanes are the most dangerous and challenging road situations for AVs (Lu et al., 2019) because they are considered a complicated areas for AVs in terms of dimensions, visibility, and other issues (Amelink et al., 2020).

While few studies suggest that as the number of AVs on roads increases, signalised intersections will gradually be replaced by roundabouts as they are likely more efficient for AVs (Gill et al., 2015), many studies point out that signal-controlled junctions and crossings might be easier for AVs to handle than other forms of junctions (Transport Systems Catapult, 2017; Lawson, 2018). It is suggested that signalised intersections may be safer for AVs than roundabouts, mainly because they provide the more predictable elements of a stop-and-go manoeuvre and provide more closely defined turning manoeuvres. A recent simulation-based study by Morando et al. (2018) shows that AVs might reduce the number of conflicts by 20% to 47% with penetration rates of between 50% and 100% at signalised intersections, while for the roundabout the number of conflicts is reduced by 29% to 32% with the 100% AV. Consequently, solutions for junctions are an area of active research, and will primarily need connectivity with likely minor changes to the physical infrastructure. In the long term, considerable changes can be expected at intersections thanks to vehicle coordination. For example, intersections could be made more compact (Huggins et al., 2017). However, in this case, the intersection sight distance (visibility) models should be checked for safety, and design specifications may need to be revised as they are based on driver behaviour rather than vehicle and road capacity (Aryal, 2020; Wang et al., 2021). In addition, some studies reveal the necessity of redesigning the geometry of intersections in order to implement seamless flow (Chen et al., 2021; Lin et al., 2021).

2.4.7 Parking facilities: pick-up and drop-off locations, service stations

The impacts of Level 4-5 AVs on parking demand and related effects on urban forms have been extensively studied in the literature, particularly in the context of shared AVs (Stead and Vaddadi, 2019). It is widely accepted that as AVs become widespread, there is a potential that private car ownership will decrease, so parking space requirements will decrease significantly (Gill et al., 2015; Johnson, 2017; Litman, 2020). However, this scenario will likely be possible when the adoption of shared mobility models is high (Currie, 2018), otherwise, the need for parking will continue and or even increase (Duarte and Ratti, 2018).

Regarding automated driving, parking assist systems are already available on the market, but with the automated valet parking (AVP) systems, cars will park in parking lots or garages after the driver or passenger leaves the vehicle (Shladover, 2018), which will bring both challenges and opportunities (Transport Systems Catapult, 2017). For the opportunities, many researchers point out that in areas where land is expensive, parking spaces can be redesigned to be more compact, making it possible to use other purposes (e.g. recreational), or placed further away from the buildings they serve (Shladover and Bishop, 2015; Stead and Vaddadi, 2019). On the other hand, it is predicted that curb frontage loading areas need to be expanded to accommodate pick-up and drop-off points (Lutin et al., 2013). These points in urban areas will likely become increasingly valuable, especially those within walking distance of transport links (Huggins et al., 2017). Also, existing car parks are not designed to support self-parking facilities (Liu et al., 2019), so their infrastructure needs to be improved in many aspects. The majority of parking spaces in urban areas are located underground where GPS signals are not strong, which will cause difficulties in navigating the vehicle (UK Autodrive and Gowling, 2018). Moreover, the Transport Systems Catapult (2017) has stated that many car parks do not use standard road markings because they are privately operated, making the markings difficult to read by onboard sensors. In short, a serious effort will be required in many aspects such as the implementation of proper toll systems, standardization of lane markings and traffic signs to design AV-compatible parking lots.

2.4.7.1 On-street parking

Street parking is popular in many countries, but this imposes a huge restriction on traffic flow. In fact, this situation may leave insufficient space for two-way traffic in many places. In this case, drivers can decide among themselves who goes first, and this can often be communicated by a hand gesture or a flash of the headlights (Transport Systems Catapult, 2017). However, during the transitional phase, AVs may have trouble on these roads to operate. To enable AVs to operate on these roads, several options may need to be considered, such as removing street parks or converting streets into one-way operations (Transport Systems Catapult, 2017). According to current guidelines on traffic signs (e.g. in the UK (Department for Transport, 2019)), centreline marking is not required on roads with a carriageway width of 5.5 m or less – most residential roads are in this category. This might cause a significant challenge for AVs to navigate and localise on these roads with the presence of on-street parking. Current lidar and camera integrated L4 AV trials with HD mapping in the USA show that parking on the street may not be a major problem for AVs navigation, even in the absence of road signs. However, it is not yet clear how AVs will operate safely in countries with narrower roads such as the UK.

2.4.8 Structural elements

2.4.8.1 Bridge design

Many studies suggest that AVs will have an impact on existing bridges and may require revision of design standards in light of the potential future scenarios (Huggins et al., 2017; UK Autodrive and Gowling, 2018; Liu et al., 2019). This is because the current bridge load models and bearing capacity guidelines have not considered the possibility of additional lanes and vehicle platooning. Contemporary bridge design standards make assumptions about the number of vehicles likely to be on the bridge at any given time, as well as other physical characteristics such as vehicle mix, axle spacing and loadings (Ulrich et al., 2020). However, the potential impacts of AV platooning, particularly groupings of heavy goods vehicles (with small headways and little lateral offset) on these design standards need to be explored further (Paulsen, 2018; Yarnold and Weidner, 2019; Thulaseedharan, 2020; Tohme and Yarnold, 2020; Sayed et al., 2020). Platooning of AVs can change the loading on the bridge deck, and this poses a great risk, especially for existing bridges with long spans. Therefore, on routes for heavy truck platoons, structural recalculation of bridges needs to be carried out, potentially resulting in the need for strengthening measures (Amelink et al., 2020). Additionally, if the lane width decreases due to the precise movement of vehicles and the right of way are sufficient for reconstruction, the total lanes on the bridge might be increased (see **Figure 2.7**). It should be considered whether this effect will be significant and whether the load models used in the design of the structures will be sufficient for this change.

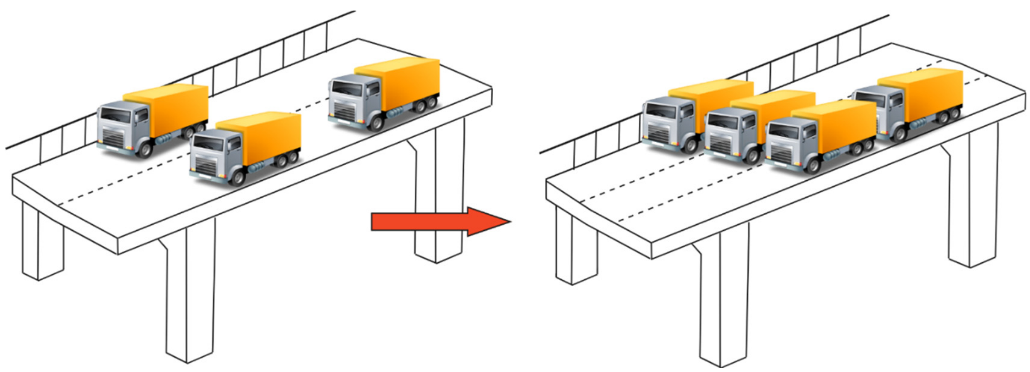

Figure 2.7 The capacity of the bridges will likely need to be rechecked according to new driving scenarios (e.g. platooning or lane width reconfigurations).

Previous research has found that the spacing between trucks in a platoon is a crucial factor that has a significant impact on bridge safety (Thulaseedharan, 2020; Tohme and Yarnold, 2020). As a result, increasing the spacing between vehicles in platoons before reaching might be a strategy for managing or mitigating the impact of platoons on existing bridges. However, traffic volume will be affected in this case. There is no research in the literature to explore how the load capacity limit of bridges that can allow the maximum number of vehicles in a platoon will affect road capacity. On the other hand, to prepare for the future, newly constructed bridges must take truck platooning into account, and new bridge design standards must be created. A recent report of an EU-funded project covers this issue extensively, and the effects of automated freight vehicles are thought to depend on future load capacities rather than automation (Ulrich et al., 2020). Also, bridge design standards/guidelines are different in each country, thus standardization on future platooning scenarios might be required globally.

2.4.8.2 Tunnels and underpasses

Similar to underground parks, tunnels and underpasses might be an obstacle to the safe operation of AVs in two ways. The first is that satellite signals may be weak or blocked, making location accuracy problematic within these road sections (Wevolver, 2020). As a result, specialised positioning infrastructure for the functioning of AVs will be required (Huggins et al., 2017), such as roadside beacons or landmarks for positioning assistance (Kulmala et al., 2020a; PIARC, 2021). The second is that illumination might be an issue for AV vision-based systems. Roads around underpasses and tunnels may require more or different lighting than they currently do, as a recent project found that image-based line recognition cannot detect lines in tunnels due to low light levels (Konstantinopoulou et al., 2020). Another potential issue is that AV vision-based systems may fail to detect approaching tunnel entrances or exits or may become completely blind as a result of rapid changes in surrounding illumination (see **Figure 2.8**) (Taylor et al., 2018; Rosique et al., 2019). However, this might be mitigated by mapping and real-time information may also be needed to support AVs at these critical points. Briefly, lighting and positioning are two topics discussed in the literature for the safe operation of AVs in tunnels.

Figure 2.8 An example of the limitation in vision-based systems on near the exit of the underpasses and tunnels (Google Street View).

2.4.9 Facilities for vulnerable road users

Vulnerable road users (VRUs) such as pedestrians, pedal cyclists, motorcyclists, or users of new micro-mobility modes such as e-scooters are the biggest obstacle to the success of collision avoidance systems due to the high risk of injury and fatality when involved in vehicular accidents. For example, VRUs have the highest accident rate in terms of casualty rate per billion passenger miles by road user type in the UK (Department for Transport, 2018). Interestingly, pedestrian fatalities have increased recently in many countries such as the USA, although vehicles are increasingly equipped with more sophisticated safety and anti-collision technology (Elliott et al., 2019). Despite this, advances in AD technology are expected to substantially reduce the fatalities of VRUs by eliminating accidents caused by human error (Lawson, 2018).

However, before AVs can be widely accepted for use in urban environments, convincing demonstrations must be made that AD technology can detect and safely respond to the VRUs (Shladover and Bishop, 2015; Parkin et al., 2016). For this reason, this issue is receiving increasing attention from researchers, OEMs and road agencies (Vissers et al., 2016; McDonald et al., 2018). In this context, there are many crucial issues to examine such as how pedestrians and cyclists interact with AVs that have no human driver or to what extent AVs will be able to detect a cyclist on the road ahead when lighting and weather conditions are adverse (Vissers et al., 2016; Stanciu et al., 2018). A recent study finds that current detection technologies vary widely in their potential to detect and avoid fatal collisions with pedestrians, from less than 30% (visible-light cameras alone) to over 90% (combination of cameras, lidar and radar) of preventable fatalities (Combs et al., 2019). This means that cameras, the most affordable detection technology, are unlikely to be effective alone in substantially reducing pedestrian fatality. Nonetheless, it is believed that advancements in artificial intelligence will help increase the onboard scene recognition capabilities of AVs (Gwak et al., 2019). So better scene recognition leads to safer decisions on the part of the automated driving system (International Transport Forum, 2018).

Clearly, the road infrastructure should enable and support AVs to make safe progress on roads with VRUs (Johnson, 2017). In the transitional period, physical road design changes will likely be needed for junctions and crossing to better accommodate AVs among human-driven vehicles (Kulmala et al., 2020a). However, care will need to be taken to consider pedestrian and cyclist movements in any innovative design (Huggins et al., 2017). Johnson (2017) states that unless AVs are to operate on completely separate, dedicated infrastructure, other road users will need to be separated from or educated in and adapt to the behaviour of AVs in different ways. Based on expert opinion, Nitsche et al. (2014) suggest that pedestrian and bicyclist protection and shielding at urban intersections are needed for the safe operation of AVs. In addition, the Transport Systems Catapult (2017) points out that infrastructure-mounted sensors and V2I communication to AVs can help, but must be developed to provide robust, mission-critical, fault-proof information rather than advisory information. Pedestrian crossings also are one of the most challenging locations for operating AVs in urban areas. The report also suggests that zebra crossings may need to be replaced with signalled crossings that are much more deterministic for pedestrians (Transport Systems Catapult, 2017). Road markings at pedestrian crossings are also well maintained and be good service quality to easily detected by on-boar sensors (Lawson, 2018).

2.4.9.1 Speed limit adaptation

Speed has been identified as a key risk factor for road users and greatly affects both the risk of traffic accidents and the severity of injuries from accidents (Konstantinopoulou and Ljubotina, 2020). With the introduction of AVs, it is expected that accidents caused by unsafe speed will be eliminated or significantly reduced. This is because AVs will likely travel at a safe speed under harsh conditions with the help of their onboard sensors as well as I2V communication and accurate map data with speed limits (Nitsche et al., 2014). There is a potential for to AVs dynamically adapt their speed based on the legal speed limit or external factors such as road alignment, congestion and weather conditions to reduce accidents caused by unsafe speed. Therefore, speed ranges will be within the permitted speed limits for each road category as AVs are expected to follow the rules (Amelink et al., 2020).

From the road infrastructure point of view, a revision or necessity of speed-related infrastructure measures needs to be reconsidered for a fully automated environment. For example, traffic calming, speed bumps, radar-imposed speed restrictions, and related engineering measures, primarily concerned with reducing the negative impact of motor vehicles in built-up areas, will likely lose their importance with the deployment of AVs. In addition, since AVs have the potential to adapt vehicle speed according to road design characteristics, relevant design parameters in the specifications need to be reconsidered (Intini et al., 2019).

Given the operating aspect of AVs, current automated driving systems are not yet ready to safely perform all driving tasks at high speeds (Schwall et al., 2020). While sensors normally see better than people, and a human cannot match a computer's response, humans are often considerably better at reading traffic and detecting potentially dangerous situations. High-speed traffic is difficult for computers to understand and predict situations happing driving environment (Pendleton et al., 2017). At higher operating speeds, automated vehicles need to perceive and react more quickly – e.g. detection of the environment by the sensors, the processing of the sensor data by the software or the achievement of a control decision (Campbell et al., 2010). Higher speeds and therefore less response time increase the complexity of ADSs as they require much faster computation time and higher computational resources (Soteropoulos et al., 2020). Therefore, different speed limits will likely be vital for the functional use of different AVs during the transition period. For example, some AV use cases such as low-speed shuttles and robotaxis may not be operated safely on high-speed roads based on the current sensor and software solutions. Additionally, depending on weather conditions, the operation speed of AVs can be changed according to their capabilities. So different speed limits may be considered for different use cases of AVs, but the effects on the traffic and management side should be considered. However, it is unclear in the current literature how different speed limits can be applied on the same roads according to different use cases or capabilities of AVs.

2.4.10 Roadside equipment or street furniture

Automated driving systems not only detect and respond to dynamic objects such as pedestrians, cyclists and animals but also need to perceive the static objects and obstacles across the road like bushes, trees, safety fences, pedestrian barriers, street nameplates, bins, bollards, hydrants, post boxes, bus shelters, grit bins, seating, verge marker posts etc. Soteropoulos et al. (2020) emphasize that the complexity for automated driving systems increases as the number of objects increases due to the necessity of detecting, identifying and determining the behaviour of such objects. Thus, the more such objects mean the more complex environment for ADS. Therefore, the vehicle and information technology industries must demonstrate that their systems operate safely in complex road environments. In addition, roadside objects constitute a physical obstacle to the detection task of an automated driving system (Koopman and Fratrik, 2019). Road authorities will likely need to check the roadside frequently and take precautions for objects that may pose a risk to AVs. On the other hand, studies suggest that AVs should have a detailed prior knowledge of the traffic infrastructure and surrounding environments on the planned route before the journey starts (Huggins et al., 2017; Ulrich et al., 2020; PIARC, 2021).

2.4.11 Road lighting

Adequate illumination of roads especially urban roads during night hours is essential to ensure road safety for all road users (Department for Transport, 2009). According to Shladover and Bishop (2015), improving the visibility of road markings, signals, and signs enabling AVs to operate successfully may require enhanced road lighting, either through greater illumination or more closely placed lights. In particular, critical road sections such as road underpasses and tunnels may require more illumination than they do now, as a recent project shows that image-based line detection is unable to detect lines in tunnels due to low light levels (Konstantinopoulou et al., 2020). Similarly, Reddy et al. (2020) conducted experimental research on LKA-enabled vehicles to estimate the impact of driving environment components on vehicle performance and discovered that driving at night with streetlights and rain resulted in the lowest detection performance for vehicles when compared to other visibility conditions. Lastly, W. Ye et al. (2021) investigated the patterns and associated factors of AV trials-related road traffic injuries in California and discovered that crashes in poor lighting, even with streetlights turned on, resulted in a much higher number of victims than those in daylight. Consequently, further investment and maintenance in lightning circumstances are required in their operational regions until the AVs can operate safely at night.

2.4.12 Drainage systems

Drainage systems are one of the main road features that significantly affect road safety, especially in areas with intense rainfall. Insufficient drainage allows water to accumulate on the pavement surface, leading to the phenomenon of partial hydroplaning on curves at higher speeds and also reducing the skid resistance of the surface (AASHTO, 2011). Although the response of AVs to events such as skidding and hydroplaning is expected to be better than that of human drivers, it is unclear how AVs will safely perceive and respond to the environment when the road surface covers water (Johnson, 2017). Regardless of lane marking quality, the ability to read road markings and surface edges is also affected by the amount of water on the road. Inadequate drainage and muddy-filled surface cause difficulties for AVs in detecting road markings (Lawson, 2018). This is a major issue, particularly at night when there is less ambient lighting, and vehicle headlights can produce high-intensity reflections from wet road surfaces (Reddy et al., 2020). Therefore, higher priority should be given to the design and maintenance of the drainage infrastructure (Johnson, 2017). However, the expectation of suitable drainage systems covering all road networks may not be realistic. Many residential roads, low-flow roads, and even parking lots do not have good drainage systems. Therefore, ADSs need to prove their capabilities under such harsh conditions.

2.4.13 Assessment and maintenance of road infrastructures

Maintenance of the infrastructure is important not only to meet the needs of AV development but also to meet the safety requirements of all road users. Studies point out that the maintenance of road infrastructure will play a key role at an early stage of AVs, rather than dramatically changing infrastructure (Liu et al., 2019). It is mentioned in multiple studies in the literature that AVs are likely to require road infrastructure (e.g. road markings, traffic signs, drainage, roadside, etc.) to be maintained at a much higher level and a higher standard than is currently the case (Johnson, 2017; Lawson, 2018; Liu et al., 2019). Particularly heavy vehicle platooning will require a different consideration of maintenance regimes for structures and pavements (Huggins et al., 2017). For this reason, to achieve the desired level of safety, inspection and repair of road infrastructures are important. Therefore, road and city authorities need to start coordinating with the vehicle and information technology industry to develop new asset and maintenance strategies for emerging technology.

However, current road maintenance and inspection methods entail a significant amount of manual surveying effort by transportation agencies. Manual surveying is time-consuming, labour-intensive, inefficient, and prone to errors and traffic interruptions (Konstantinopoulou and Ljubotina, 2020; Gouda et al., 2021). Recently, new technologies have emerged for automated road assessment that can provide high-accuracy data at traffic speed without interrupting the current traffic flow (Osichenko and Spielhofer, 2018; Urano et al., 2019). However, while highways and trunk roads are periodically inspected with specialized vehicles (Department for Transport, 2021), roads maintained by local authorities are relatively less inspected because of a lack of budget and workforce (Urano et al., 2019). This will likely limit the road infrastructure that allows AVs to operate and will trigger several problems in terms of automated driving safety. Improving vertical and horizontal coordination between government levels is needed to foster stronger collaboration in order for improving road safety performance (International Transport Forum, 2019).

In addition, road agencies and operators will need to be allocated sufficient funds to prepare roads for AVs, but it is still unclear how they will be able to meet their infrastructure financing needs. Also, parameters of maintenance and current asset management strategies might be changed as digital infrastructure equipment (e.g. landmarks, roadside beacons, etc.) are also needed to be maintained regularly. So the type and frequency of maintenance efforts necessary for various technologies should be reconsidered. Moreover, AVs are likely to require different winter maintenance strategies (Ødegård and Klein-Paste, 2021).

On the other hand, AVs also have cameras and sensors that can collect inventory and condition data for the road (Osichenko and Spielhofer, 2018). In other words, road maintenance can also benefit from new data sources on road conditions made possible through additional vehicle sensors and V2X communication. The collection of road condition data like potholes, cracks, rutting or skid resistance facilitating sensor technology of AVs through V2X communication would greatly benefit road maintenance (Ehrlich et al., 2016). The application of this technique will allow automated inspection, geolocation and prioritization of roads or areas that may require maintenance and repair, as well as inform drivers or AVs about road safety conditions to prevent accidents. Additionally, road condition data should be made available to service and map providers to increase automated driving safety (Kulmala, et al., 2020b). However, so far it remains unclear whether AV sensors will be suitable for providing road condition data. In addition, the correlation between road data from measurement systems and vehicles with ADS is under question. It is not clear whether this data will be of the same quality and usability as data from measurement devices. Also, AVs can provide this information in real time, raising questions about how this big data can be managed and how barriers to providing such data can be overcome without compromising cybersecurity and data privacy (Ehrlich et al., 2016; Osichenko and Spielhofer, 2018). The answers to these questions are important for the further development of road asset management.

2.5 Summary of findings and recommendations

Technological developments and regulatory reforms are accelerating the adoption of automated driving systems on the roads. However, many uncertainties remain regarding the potential impacts of AVs on physical road infrastructure. As such this research has sought to understand what the implications of AVs will likely be for the physical road environment based on a comprehensive literature review. A total of thirteen features related to physical infrastructure have been identified in the existing literature regarding vehicle automation that should be considered during either the initial phase of deployment or transition to full automation. Based on these features, the following key findings can be highlighted:

- Although horizontal and vertical alignments of roads have been found to affect the operation of existing automated driving systems, no changes are expected in the current road design philosophy for the transition period. In the long term, there are potential economic and environmental improvements for new roadway design due to the elimination of human-based driving characteristics. However, requirements will vary by AV models and types, therefore international standardisation is needed in geometric road design parameters such as the height of the sensor positions in vehicles.

- Cross-section elements of roads such as lane widths, shoulders, medians and safety barriers are also found to affect the functioning of existing automated driving systems. However, further research is needed to evaluate and validate the effects of the type and configuration of these elements on the operation of AVs. Also, their design needs to be re-evaluated for future scenarios, including vehicle platooning. For example, no studies were found on the impact of AVs on barrier capacity, considering the re-configuration of lane width, shoulder etc. Additionally, there are no empirical studies regarding the implications of reducing the cross-section elements on traffic safety performance.

- Wider shoulders and emergency bays at regular distances will likely be needed for L3-L4 AVs to stop/park in the event of temporary termination of ODD. However, many places, such as bridges, tunnels, or some two-lane highways, do not have shoulders, so additional requirements should be considered from a safety and traffic efficiency perspective at these locations. However, the current literature is scarce on this subject. Therefore, more experimental, and simulation-based research will likely need to investigate possible scenarios and present solutions.

- The effect of vehicle automation on the road surface structure depends on many variables e.g. speed limit, lane width, uniform wandering strategy etc. In urban areas where the speed limits are low and lane width is narrow, the negative impact of AVs on the pavement such as rutting will likely be more pronounced. More field and laboratory research are needed to focus on the balance between thresholds and detailed cost-benefit analyses should be conducted to examine the optimum solutions.

- Road markings and traffic signs are key road features that affect the operation of AVs, but there is presently no formal standard or benchmark to be used by authorities to assess the quality of their markings/signs to support automated driving. It is necessary to set minimum criteria for their conditions and configurations as well as international standardisation. For this, studies are needed to determine their optimum design conditions (e.g. width, location, size, shape etc.) under different road environment conditions. Future research should include evaluating the role and effectiveness of road studs and rumble strips for AVs. Also, one of the questions yet to be unanswered is whether road marking/signs will still be important with the digitalisation of the road environment. Therefore, it is important to start questioning their role and minimum requirements of these elements with the transition to the digitalisation of the road environment.

- With the redesign of intersection layouts and the help of connectivity, there is a potential for achieving seamless traffic on intersections in a fully automated environment. However, available data on accidents involving AVs indicate that intersections are one of the most challenging road segments for the early phase of AV deployment due to the complexity of traffic conditions. For this reason, more research is needed to understand which types of intersections are safe for automated driving, and what special rules and physical requirements must be considered for intersection types to ensure AVs can perform safely, including in the special case of platooning of heavy vehicles.

- AVs will likely present new risks and challenges for existing road structures such as bridges and tunnels. Any new design should consider the impact of the heavy vehicle platoon. More importantly, existing bridge capacities need to be rechecked according to possible scenarios. Also, tunnels and underpasses are likely to need additional investment in positioning and lighting infrastructure for AVs to operate. However, more empirical findings and applications are needed on how AVs can operate safely in these critical locations and what infrastructure support will be needed.

- The transition to full automation will likely be dominated by human factors, so much research focuses on ways to reduce risks for vulnerable road users through technology. However, this may not be possible without additional precautions in physical road environments. Also, it is possible to consider different speed limits for different use cases of AVs or based on the ODD changes, but the effects on the traffic and management side have not yet been studied adequately and rigorously. Simulation-based research is needed to explore how different speed limits can be applied on the same roads according to different use cases or capabilities of AVs.

- More research is needed to clarify how automated driving can operate in improper road drainage systems and what its limitations are. Also, it is not clear whether the current standards on gradient level of roads need to be revised for future road design. This has not been systematically investigated in the literature or practice.

- Road lighting factors such as illumination colour, intensity and location of light can also affect the operation of automated driving performance. However, the available literature on this topic is limited, so further research is required to examine what the main factors are on the operation limitations of AVs and whether standardisation of these elements is necessary.

- Last but not least, it is clear that new asset and maintenance strategies are required for the safe operation of AVs. However, there is currently no official standard or benchmark to be used by transport agencies to assess the quality of their infrastructure that can support both driver assistance systems and automated driving functions. Therefore, government officials need to start coordinating with the vehicle and information technology industry to produce policies and strategies for emerging technology.

2.6 Conclusions

This study has gathered and interpreted the perspectives of the existing vehicle automation and infrastructure literature on the potential impacts of AVs on the physical road environment and infrastructure-related requirements for safe operation. The main implication from the identified literature is that many researchers recognise that improved road maintenance and enhanced and harmonised physical road infrastructure, in addition to digital infrastructure, have the potential to improve both driving assist systems and automated driving operations. However, given the uncertainty regarding automation capabilities and requirements, many are concerned about making long-term infrastructure investments. The main reason for this is that there are some unclear points regarding the necessary infrastructure changes, as discussed in the previous section, due to the speed and state of technological development of AVs and the rate of user adoption after commercial deployment of AVs. Also, some argue that AVs are still in the development and testing phase, so it is difficult to predict in advance which technologies will be successful and therefore what infrastructure will be needed.

Another reason is that vehicle and information technology industries are often reluctant to share what they expect from road infrastructure as they are in serious competition for a dominant position in the emerging market, which naturally leads to close protection of industry knowledge. This highlights the value of research, field testing and deployment pilots as well as organised discussion among stakeholders. Particularly, road authorities and policymakers need to start coordinating with the vehicle and information technology industries to evaluate their requirements and expectations and prepare their roads for this emerging technology. They also need to start making changes to the infrastructure where there is enough evidence of benefits. Thus, achieving readiness for automated driving will require a combination of high-level AV capabilities, upgrades to infrastructure, and improved operations and maintenance practices of infrastructure (Somers, 2019).

Otherwise, although it is not mentioned in the literature, the equity gap between societies caused by differences in the quality of infrastructure is inevitable. For example, there is potential for a gap in access to AV services among people living in the same cities due to the variability of the road environment. Therefore, instead of waiting for AVs to be ready for the roads, authorities need to focus on the question of when the driving environment will be ready to permit the use of AVs and where will this disruptive technology work best during the transition period. Also, there will likely be different types of deployments that operate in different areas of the network. Activities should begin by investigating prospective applications and their impact on cost structures, transport, and the environment.

In addition to infrastructure and technological issues, other key issues such as the lack of policies and regulations regarding the implementation of AVs, the uncertainty of societal benefits, and public trust and acceptance of AVs are frequently raised in multiple studies. The impacts of AVs on road transport, especially at high levels of automation, will be diverse, complex, and highly uncertain as it will affect many aspects of transport system performance (Milakis et al., 2017b). For this reason, some believe that the most important question of AV implementation is the assessment of whether it would be beneficial for each particular society and place of implementation. Therefore, there appears to be widespread agreement that the necessity of policies mitigating negative impacts and promoting socially beneficial models of AVs that can provide safe, equitable, and sustainable mobility throughout a community.

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CHAPTER 3

Infrastructure-related challenges in implementing connected and automated vehicles on urban roads: Insights from experts and stakeholders

Abstract: The introduction of connected and automated vehicles (CAVs) has potential to bring numerous advantages to urban mobility. However, many challenges for road infrastructure need to be overcome before those benefits can be achieved. This study addressed multiple dimensions of the implications of CAV deployment for road infrastructure through a comprehensive survey with 168 experts from different sectors and regions around the world. The issues are grouped into five categories: (1) key challenges of accommodating CAVs in existing urban transport networks; (2) infrastructure improvement required for shared CAV models; (3) maintenance aspect of infrastructure for CAVs; (4) implementation time of infrastructure support for CAVs; and (5) financing infrastructure upgrades to facilitate CAVs on the roads. The outcomes of the research show that there is still no consensus among the stakeholders on what should be considered to maximise CAV benefits for society as a whole. This indicates the necessity for cooperation between stakeholders to achieve the safe and efficient operation of CAVs. Overall, this study provides in-depth insights for decision-makers and transport planners to form policies, regulations, and guidelines regarding the future implementations of CAVs for roads before their commercialisation phase.

Keywords: Connected and automated vehicles, Automated driving, Urban network, Road infrastructure, Challenges, Financial requirements.

3.1 Introduction

Recent advancements in software, hardware, and information and communication technologies have propelled the development of automated vehicles (AVs), which are no longer mere hype or science fiction but a gradually introduced technology in the automotive market (Saeed, 2019; Litman, 2020). The classification of AVs based on their capabilities has been subject to various schemes (Mocanu et al., 2015), with the widely used six-level classification by the International Society of Automotive Engineers (SAE J3016) reflecting the progressive transfer of driving responsibilities from humans to vehicles (SAE International, 2021).[7] Level 4 AVs, in particular, hold the potential for transformative changes in transportation and urban landscapes (Milakis et al., 2017), as they can operate autonomously in various scenarios and geographic areas while still offering the option for human control in exceptional circumstances (Tafidis et al., 2021). Beyond automation, the connectivity aspect of vehicles plays a vital role (Engholm et al., 2018; Shladover, 2018), enabling the exchange of safety and mobility information[8], overcoming limitations of onboard sensors and improving reliability in challenging conditions (Favarò et al., 2018; Zang et al., 2019; PIARC, 2021). The integration of connectivity and automation, known as connected and automated vehicles (CAV)[9], offers unique advantages that cannot be achieved independently (Schoettle, 2017; He et al., 2019).

It is a common view that in the early stages of deployment, the safe operation of CAVs at full capacity will mainly depend on the quality and consistency of road infrastructure (Huggins et al., 2017; Madadi et al., 2018; Evas and Heflich, 2021). Several aspects of road infrastructure such as the positioning, height, and size of traffic signs, physical characteristics of road markings, variable sign message systems, warning message systems for work zones, curb areas, and maintenance strategies will likely undergo reassessment based on the capabilities of CAVs. For example, the current automation industry consistently emphasises the significance of well-maintained road surfaces and clearly visible signs and road markings, although a definitive standard has not yet been established. However, as the deployment of CAVs becomes more imminent, addressing these needs is increasingly important (Manivasakan et al., 2021; Mihalj et al., 2022; Wang et al., 2022). Moreover, the variety of road facilities and connectivity

[7] No Automation (Level 0; hereafter, L0), Driver Assistance (L1), Partial Automation (L2), Conditional Automation (L3), High Automation (L4), and Full Automation (L5).

[8] Connected vehicle technology enables wireless communication between vehicles (V2V), road infrastructure (I2V), and other components (V2X), facilitating the exchange of safety and mobility information.

[9] In this study, the term 'automated driving' is used to describe the technology where automation of the driving task, vehicle connectivity, and data are brought together. Also, the term automated driving and connected and automated vehicles (CAVs) are used interchangeably.

capabilities brings new challenges for transport authorities and legislators looking to embed CAVs into road networks. Therefore, the relationship between automated driving and both the physical and digital road infrastructure is an area of active research (Mihalj et al., 2022). Road authorities and road safety organisations around the world are actively investigating potential infrastructure modifications to facilitate CAV operation (e.g. Huggins et al., 2017; Somers, 2019; Marr et al., 2020; PIARC, 2021; Gopalakrishna et al., 2021). Additionally, few research projects (Carreras et al., 2018; Poe, 2020; García et al., 2021) have been dedicated to developing classification schemes that categorise the capabilities of road infrastructure to support and inform CAVs and users about the functionalities offered by different road facilities. These efforts aim to enhance the compatibility and interaction between CAVs and the surrounding infrastructure, promoting a safer and more efficient integration of CAVs on public roads.

In parallel, regulatory bodies and organisations worldwide have been actively engaged in formulating and implementing legislation to facilitate the integration and safe deployment of CAVs (Lee and Hess, 2020). Notably, the European Commission has taken a leading role in developing policies and regulations within the European Union to promote CAV deployment. Initiatives such as the European Strategy on Cooperative Intelligent Transport Systems and the European Framework for the Deployment of Intelligent Transport Systems aim to harmonize legal requirements and foster cross-border collaboration. In addition, the United Nations Economic Commission for Europe (UNECE) has played a crucial role in shaping international legislation for CAVs. The UNECE's Working Party on Automated/Autonomous and Connected Vehicles has developed standards and regulations, including the influential UNECE regulation on automated vehicles (e.g. Regulation No. 157). Also, countries such as the United States of America (USA) and the United Kingdom have taken proactive measures to support CAV innovation and deployment. The USA, through entities like the National Highway Traffic Safety Administration (NHTSA), has issued guidelines and regulatory frameworks at the federal and state levels. Similarly, the UK has established legislation and initiatives to encourage CAV testing and development, such as the Centre for Connected and Autonomous Vehicles (CCAV) and the Code of Practice for Testing.

However, automated driving technology and automation-enabled mobility services are evolving at a more rapid pace than the understanding of the infrastructure required for them to be efficiently and safely implemented (Manivasakan et al., 2021). As such, the number of studies addressing potential infrastructure-related requirements to facilitate CAVs, or challenges associated with infrastructure adoption for CAVs is limited. Moreover, existing research on CAV implementation has mainly focused on the consumer or end-user perspective. These studies primarily examine how attitudes and perceptions can influence the intention to adopt or use CAV technology (e.g. Liljamo et al., 2018; Nordhoff et al., 2018; Thomas et al., 2020; Stoma et al., 2021). However, the implementation and adoption of new technology are not solely driven by consumer demand. It is crucial to acknowledge the involvement of other key stakeholders, such as policymakers, vehicle manufacturers, and academia (Hamadneh et al., 2022; Lim et al., 2023).

On the other side, as noted in Shladover (2022), the literature on software and hardware technologies that support CAVs is vast and growing rapidly and becoming obsolete rapidly, too. This rapid development in automation and information and communication technologies has prompted researchers who want to gather information about the latest developments in the field to seek opinions from experts (e.g. Nitsche et al., 2014; Huggins et al., 2017; Transport Systems Catapult, 2017; Lawson, 2018; Lu et al., 2019). Among these studies, for example, Saeed (2019) explored the types of changes that may be needed for road infrastructure at the two stages of AV operations (transition phase and fully autonomous phase), based on expert feedback from technology developers and highway agencies in the USA. Similarly, Gopalakrishna et al. (2021) have investigated the impact of AVs on highway infrastructure through engagement with highway agencies and interviews with industry members in the USA. In another study, Wang et al. (2022) conducted an online survey and follow-up interviews with AV industry members alone in California, USA, to evaluate the transportation infrastructure improvement requirements that can improve AV performance. In Australia, Lim et al. (2023) conducted in-depth interviews with experts from the public and private sectors who had direct experience with AVs, exploring various micro and macro environmental factors that could either impede or facilitate AV adoption.

In a similar strategy, but on a global scale, this study aims to gather insights and perspectives from experts and key stakeholders to gain a better understanding of critical factors and challenges related to urban road infrastructure for the successful implementation of CAVs. Through a large survey encompassing various sectors and regions, the study explores the multifaceted dimensions of CAV deployment implications and challenges for road infrastructure that authorities will need to consider both in the early stages of their implementation and the transition phase. The main research questions addressed in this study are as follows:

1. What are the key challenges of accommodating CAVs in existing urban transport networks?

2. How does infrastructure improvement support the shared mobility model of CAVs?

3. What additional maintenance for infrastructure will be required for CAV operation?

4. When should infrastructure improvement for CAVs be initiated?

5. How will the CAV infrastructure be funded?

The main contribution of this paper is to provide an overview of the opinions of members of different stakeholder groups that may affect or be affected by the deployment of CAVs, on several issues that are contested or lacking in the literature. Particularly, it provides an understanding of priority issues that need to be considered for the successful implementation of CAVs on public roads by identifying the points of convergence and divergence of stakeholders. These insights inform the formulation of policy recommendations to guide decision-makers in navigating the complex landscape of CAV implementation. To the best of the authors' knowledge, while there exist some reports that address the challenges associated with infrastructure adoption for CAVs based on stakeholder engagements, no other study has examined or compared the views of various stakeholder groups internationally on the multiple dimensions of the CAV deployment implications for road networks. Another contribution is to examine the issues that need to be considered for the readiness of the current road infrastructure to accommodate emerging technologies. In this regard, this study can be considered as an addition to reports that identify infrastructure-related requirements of CAVs for safe and efficient operation or research that identify challenges and opportunities for CAVs adoption in road networks.

The organisation of the remaining paper is structured as follows: **Section 3.2** presents the methodology adopted in this study and provides information about the participants. **Section 3.3** illustrates the descriptive results of survey responses and the main interpretation of findings, including the comparison between grouping variables. Finally, **Section 3.4** concludes the paper with recommendations for transport authorities and policymakers toward to integration of automated driving in cities.

3.2 Methods

3.2.1 Survey content and participants

Given the sheer diversity of stakeholders involved in the implementation of forthcoming CAV technology, this study narrowed its focus to three distinct categories of supply-side stakeholders (for a detailed examination of stakeholders, refer to (Hamadneh et al., 2022)). These stakeholder groups can be briefly classified as follows:

1) Agency: This group comprises organisations responsible for road networks, including national, regional, and local government entities, and policymakers who make crucial decisions regarding the regulation of technology, road networks and users and the allocation of funding. Additionally, it includes infrastructure owners and operators who bear direct responsibility for the management and maintenance of roads and engineering companies providing consultancy services.

2) Technology and vehicle industry players: This group encompasses a wide range of companies operating in the automotive and technology sectors. These companies are involved in various aspects such as vehicle manufacturing, the development of artificial intelligence and sensors, the provision of vehicle components, or the sale of data related to connected and automated driving.

3) Academia: This group represents universities, research institutes, and other educational organisations involved in conducting research and providing expertise in the field of connected and automated mobility.

To get the opinions of these key stakeholders, the research employed a semi-structured online survey consisting of a mixture of closed (e.g. multiple-choice and scaling) and open-ended questions. The questionnaire was developed based on an extensive literature review (Tengilimoglu et al., 2023a). The methodology adopted in this study are briefly illustrated in **Figure 3.1**. While there are other methods that can be effective for gathering such views, such as stakeholder interviews or focus groups, surveying experts on an international scale is more cost-effective and practical to obtain quantifiable data that can be analysed. Another advantage of conducting a survey is that it is anonymous, making respondents feel more confident and secure in sharing their views and expectations about the questions (Van Selm and Jankowski, 2006; Lefever et al., 2007). This is especially important for industry participants because they may not wish to share information publicly about the capabilities and limitations of their products. In addition, such expert surveys give respondents time flexibility so they can respond at any time and pick up where they left off. In the scope of this research, the topics discussed are grouped into five categories: (1) key challenges of accommodating CAVs in existing urban transport networks; (2) infrastructure improvement required for shared CAV models; (3) maintenance dimension of infrastructure for CAVs; (4) implementation time of infrastructure support for CAVs; and (5) financing of infrastructure upgrades to facilitate CAVs on the roads. However, this study is part of a large survey including other research questions related to Level 4 automated driving (Tengilimoglu et al., 2023b).[10]

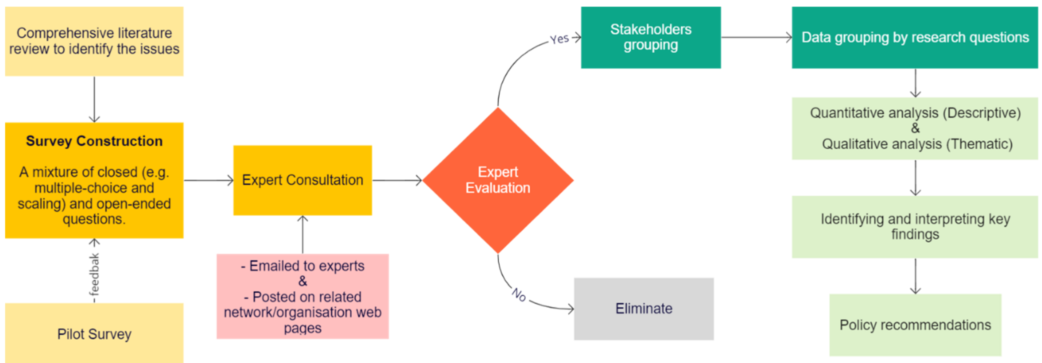

Figure 3.1 The steps of methodology adopted in this study.

The recruitment process involved the distribution of the survey link to potential experts who were identified through various channels, including relevant past conferences, seminars, and research. For this purpose, the link was sent to the e-mail address of more than 800 individuals, also shared on social networking sites dedicated to topics such as vehicle automation, automotive industry, and transportation groups. Additionally, participants were encouraged to forward the survey link to other potential respondents within their organisations through emails and newsletters, which resulted in several successful referrals. The data collection process began in mid-October 2021 and concluded by the end of November 2021. During this period, the survey was distributed to a wide audience, reaching approximately 4,600 individuals. To assess the eligibility of respondents, the first part of the survey focused on the type of respondents' organisation, area of expertise, work experience, the relevance of their work content to CAVs, and country of residence to gain insight into the profile of the participant. After this step, 168 valid responses were obtained. This limited number of responses can be attributed to the specific expertise required in the field of automated driving and the nature of a comprehensive survey, encompassing numerous questions from diverse topics. Despite this, it is worth noting that the number of experts surveyed in this study represents one of the largest samples of its kind compared to previous research in the literature.

Responses were collected from a diverse range of sectors, and were grouped into three main stakeholder groups as delineated earlier: ***Agency*** (comprising local/regional authorities (9), national authorities (12), road agency/administration/operators (27), consultancy/engineering (24)); ***Industry*** (consisting of vehicle industry (15),

[10] The survey was conducted as part of the first author's PhD research on the road readiness index for automated vehicles and only a relevant part of the data obtained from the survey was used in this research (Ethical approval protocol no: LTTRAN-142).

technology developers (9), service providers & suppliers (4), R&D companies (3), insurance companies (1)); and ***Academia*** (encompassing universities (39), research institutes and organisations (25)). The composition indicates that the survey respondents well represented the key actors of automated driving. **Figure 3.2** illustrates the proportion of respondents by type of organisation they represent and place of residence.

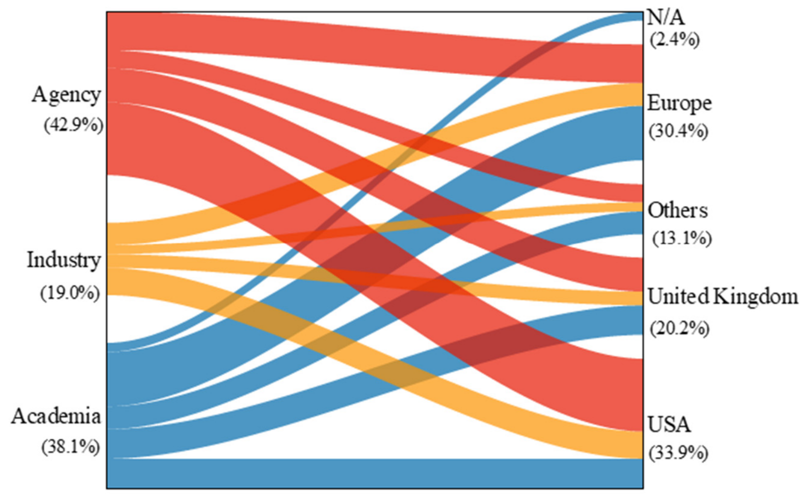

Figure 3.2 Schematic distribution of participants by organisations they represent and place of residence.

The study included participants from a diverse range of twenty-nine countries[11], with a notable majority (54.1%) originating from two countries: the UK and the USA. In addition, the respondents have an average of 17 years of work experience, with over 70% of participants possessing a minimum of 10 years of professional experience in their fields. Predominantly, the respondents belonged to the agency and academy groups, accounting for 81% of the total participants. This trend may be attributed to the inherent reluctance of the vehicle and information technology industries to disclose their existing operational and capability constraints, given the highly competitive nature of the industry (García et al., 2021).

3.2.2 Data analysis

This study used a mixture of quantitative and qualitative methodological approaches for the analysis of the responses. For the quantitative data gathered, descriptive

[11] Number of participants by country of residence - USA: (57), United Kingdom: (34), Germany: (9), Italy and Australia: (6), The Netherland and Turkey: (5), Canada, Finland, and Ireland: (4), France and Korea: (3), Albania, Austria, Japan, and Switzerland: (2), Brazil, Croatia, Denmark, Greece, India, Indonesia, Israel, New Zealand, Poland, Singapore, Slovenia, and South Africa (1), Prefer not to state (4).

statistics were displayed graphically. In response to the open-ended questions, a range of responses from experts and stakeholders was elicited. The thematic analysis of these responses was done using the qualitative data analysis software NVivo. First, word clouds were generated to identify the most frequently used words in the responses. This allowed us to identify emergent themes against the question (Santos and Davies, 2020). After repeated reading of the responses, we coded these verbatim responses into a relatively small set of meaningful categories in order to examine key issues and check how often respondents refer to a particular issue (Feng and Behar-Horenstein, 2019). Lastly, results were tabulated based on the groups by using the crosstab feature in the software. Some missing responses in the survey were acceptable since we expressly requested participants to skip topics that they did not want to answer or those where they believed they did not have the technical expertise to comment on. So, the total number of responses may not reach 168 for some questions.

3.3 Results and Findings

This section summarises the findings and interpretation of the opinions of experts and stakeholders on five topics presented in the introduction, including the rationale of the research questions.

3.3.1 What are the key challenges of accommodating CAVs in existing urban transport networks?

3.3.1.1 Rationale

The imminent introduction of CAVs presents new challenges and opportunities for transport authorities and decision-makers looking to incorporate these technologies into the built environment. In general, studies (e.g. J. A. Khan et al., 2019; Alawadhi et al., 2020; KPMG International, 2020) emphasise that four primary pillars play a crucial role in assessing the readiness of countries or jurisdictions for CAV operation: policy and legislation, technology and innovation, infrastructure, and user adoption. While all these aspects are vital in establishing a conducive road environment for emerging vehicle automation, the relative difficulty of achieving each pillar has not been extensively discussed. Therefore, the survey posed a question to stakeholders regarding the perceived difficulty of each key aspect and identified major barriers in accelerating CAV deployment in urban networks. Additionally, there are numerous challenges associated with CAVs within the mentioned pillars and other essential factors in adopting this emerging technology (Shladover and Bishop, 2015; Anderson et al., 2016; Alawadhi et al., 2020). For this reason, the survey also asked stakeholders for their views on the main challenges of accommodating CAVs in existing urban transport networks[12] and how road authorities and policymakers can meet these challenges.

The research specifically focused on the urban road network for several reasons. Firstly, previous studies have mainly concentrated on highway automation, as controlled and well-maintained road environments are seen as potential early operational areas for CAVs. Therefore, by shifting the focus to the urban road network, the study aimed to contribute to the understanding of the unique challenges and their potential countermeasures specific to urban areas. Secondly, CAVs are expected to have significant and multifaceted impacts on urban areas, which encompass diverse environments, land uses, road types, and road users (Joint Research Centre, 2019; Rahman and Thill, 2023). The complexity and variation in urban road networks present specific challenges that need to be addressed before the commercialisation of CAVs. Additionally, since the survey also focuses on the shared mobility service of CAVs, concentrating on the urban road network can be seen as a logical approach for acquiring comprehensive interpretations.

3.3.1.2 Findings and interpretation of responses

The responses (N=166) show that policy and legislation option is the relatively dominant choice among the options. About one-third of respondents (34.3%) stated that policy and legislation regarding CAVs is the most difficult milestone to accomplish to accelerate the deployment of these technologies in urban networks. The second most frequently mentioned option by respondents was vehicle technology and innovation, corresponding to 22.9% of responses. These are followed by physical road infrastructure (14.5%) and consumer acceptance (13.3%), with almost a similar ratio. On the other hand, a minority of participants (6.0%) believe that digital infrastructure will be the most difficult turning point for accelerating the CAV deployment in urban networks.

Figure 3.3 highlights a consensus among stakeholders regarding the significance of policy and legislation as the primary bottleneck in the adoption of CAVs. This alignment reflects the recognition that automated driving will bring and/or require substantial transformations in policy and legislative strategies. Policymakers and legislators are faced with the challenge of regulating complex CAV technology, including sensors, AI, and communication networks. Furthermore, safety assurance, liability considerations, ethical dilemmas, interoperability, standardisation among

[12] The urban road network refers to the interconnected system of roads and streets within urban areas or cities, facilitating transportation within the urban environment. It includes various types of roads, intersections, and infrastructure designed for vehicles, pedestrians, bicycles, and public transit.

manufacturers, and the adaptation of existing laws add further complexity to this milestone.

However, other factors show some variation among stakeholder groups and regions. For instance, the academy group prioritise physical infrastructure as the second most challenging milestone after policy and legislation, whereas the agency group assigns it relatively less importance. The role of stakeholders and their country's current level of infrastructure, technology and legislation also influence responses. For instance, those in the UK believe that vehicle technology and innovation will likely be a less important issues compared to other regions.

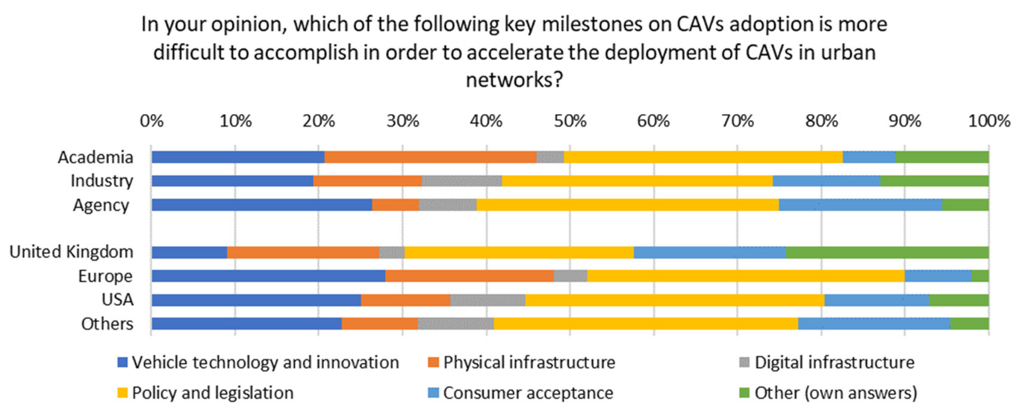

Figure 3.3 Responses to the question about the key milestones that should be accomplished for the acceleration of CAVs deployment by type of organisation and place of residence (%).

Notably, respondents (predominantly UK respondents) selecting the "other" option emphasise the interdependence of all the milestones, highlighting the need for coordination between technology, infrastructure, and policy timelines. They stress that these milestones are interconnected and crucial for accelerating CAV deployment in urban networks. Some respondents underscore the importance of societal desirability and the need for proper discussion in addressing these challenges.

Table 3.1 presents the heatmap of responses regarding the challenges for accommodating CAVs in urban networks and ways to overcome these. The main challenges cited by experts surveyed are safe and efficient management of mixed traffic, consisting of both CAVs and human-driven vehicles, and interactions between CAVs and Vulnerable Road Users (VRUs) such as pedestrians, cyclists, and e-scooter users. Another major issue mentioned is the environmental complexity and conflicts in the urban road network. Some respondents point out that the road network is becoming more and more diversified at the urban, thus increasing the complexity that

CAVs must cope with. This is due to various factors such as dense traffic, unpredictable pedestrian behaviour, complex road geometries, and the need to interpret and respond to a wide range of dynamic situations. In this context, technological reliability, as well as infrastructure, are key components that need to be addressed. On the infrastructure side, participants also point out the necessity of regulatory guidance to ensure consistency across all jurisdictions and uniformity.

It is a common expression among many responses that current CAV capabilities and technological developments are insufficient in terms of safety and reliability for societal acceptance. Further evolution of CAV technology is necessary to effectively integrate it into existing urban road networks. A group of participants advocates for the maturation of CAV technologies to prove they are safe enough before large-scale commercialisation. In this context, they highlight the significance of paving the way for CAV trials as a means to develop reliable technology over time. Respondents also note that the physical and digital infrastructure that supports the CAV operation on a large scale today does not exist or that existing provision is not suited to the needs. Limited investment budgets in CAV-focused infrastructure are stated as the main barrier to deployment. Therefore, many experts surveyed, particularly from the industry groups, emphasise the need for funding and incentives to provide the facilities that CAVs require on physical and digital road infrastructure (e.g. digital mapping and communication systems). Suggestions include implementing access-controlled lanes or roads for CAVs during initial deployment stages and establishing low-speed zones in urban areas to address safety concerns in mixed traffic environments. However, some participants argue that CAVs should operate on existing road networks without requiring additional support beyond conventional vehicles.

Clearly defining the operational constraints of CAVs is another measure often cited by respondents to reduce the potential risks from the limitations of technological capabilities. However, this will be possible by establishing safety testing protocols for CAVs, including both software and hardware systems of vehicles. As noted in Shladover and Bishop (2015), this issue has two dimensions, each with different challenges: determining the safety requirement and verifying that the particular vehicle system meets the safety requirement. To address these challenges, there is widespread agreement that collaboration between stakeholders (e.g. legislators, transport authorities, telecommunication, OEMs etc.) is vital and essential to achieving success in this area. This is also important for the standardisation and harmonisation of regulation activities such as registration, licensing, and testing of CAVs.

Also, the reliance of CAVs on data and technology raises a wide range of new legal issues such as data protection, cyber-security, and privacy. In addition, there is a lack of evidence on how the technology is ethically appropriate, and the moral hazard side of CAVs is seen as a main concern. Lastly, liability and insurance issues regarding

CAVs are seen as one of the main challenges by many participants. Regarding this issue, there are many questions that need to be addressed. For example, where a vehicle is highly or fully automated, how will liability for road accidents be shared between the manufacturer and the driver, or what if a design flaw, a cyberattack on digital hardware or software, or an internet outage causes an accident? In short, the main challenge is to clearly define who will be responsible for what. To address the liability and insurance challenges arising from CAVs, there is a need for new regulations and insurance systems for both these emerging technology and related infrastructure. Despite this, some experts surveyed mentioned that regulators are generally under-skilled in technology to be able to meaningfully regulate the technology companies developing CAVs. Therefore, they suggest that road authorities and policymakers need first to be educated on what is CAV.

Briefly, all these challenges can be seen as major obstacles to public trust and acceptance. This is also the main reason for the reluctance of decision-makers to take the initiative in the commissioning of CAVs, as can be interpreted from the quote: *"Without a large public drive/need, why would a politician take the risk and legislate in this area? And where is the public push to move away from current (human-driven) taxi/bus models?"* (agency respondent). Therefore, as some respondents have pointed out, gradual (a process that is carried out incrementally with implementation planning from year to year) and integrated (a process that includes various aspects and cross-field expertise) planning is required for CAV implementation. Road authorities and policymakers can overcome these challenges by following a roadmap describing the proposed activities to be undertaken in terms of technology, infrastructure, policies and socioeconomics.

Table 3.1 Thematic representation of responses on key challenges of CAVs adaptation in urban road network and potential countermeasures.

	Survey Respondent				Survey Respondent				
	Agency (72)	**Academia (64)**	**Industry (32)**	**Total (168)**	**UK (34)**	**Europe (51)**	**USA (57)**	**Others (22)**	**Total (164)**
Key Challenges									
• Environmental complexity and conflicts in the urban road network	8	5	0	13	3	6	3	1	13
• Inadequacy of technological developments (Limitations on CAVs capabilities)	10	10	3	23	10	5	6	2	23
• Interaction between CAVs and VRUs (e.g. Pedestrians, cyclists)	9	14	3	26	4	13	6	3	26
• Lack of physical and digital road infrastructure to support CAV operation	12	12	5	29	8	11	9	1	29
• Liability and insurance of CAVs	15	6	5	26	5	6	11	4	26
• Limited investment budget in CAV focused infrastructure	4	2	1	7	2	1	3	1	7
• Management of mixed traffic situation (CAVs and human-driven vehicles)	11	15	4	30	6	13	6	5	30
• Policy and legislation barriers	11	4	2	17	2	4	8	3	17
• Societal, economic, and environmental challenges in the adoption CAVs	4	7	2	13	5	2	2	3	12
• Trust, acceptance, and willingness to use CAVs	15	4	1	20	6	6	6	2	20
Ways to overcome barriers/challenges									
• Access controlled lanes & roads for CAVs (Segregation)	6	1	3	10	2	4	2	2	10
• Addressing data management and privacy issues (Data protection & Cyber-security)	5	2	0	7	1	1	4	1	7
• Clearly define operational constraints of CAVs (Attributes of ODDs)	4	1	1	6	2	2	2	0	6
• Collaboration between stakeholders (Legislators, IOOs, OEMs etc.)	12	4	5	21	4	4	8	5	21
• Education of the public on automated driving technologies	5	2	0	7	0	3	3	1	7
• Establishing safety test protocols for CAVs (Proof of safety)	8	4	3	15	5	5	2	3	15

(continued on next page)

Table 3.1 (Continued)

	Survey Respondent				Survey Respondent				
	Agency (72)	**Academia (64)**	**Industry (32)**	**Total (168)**	**UK (34)**	**Europe (51)**	**USA (57)**	**Others (22)**	**Total (164)**
Ways to overcome barriers/challenges									
• Introduction of urban low-speed zones for CAVs operation	4	1	2	7	3	2	2	0	7
• Investments to support road infrastructures for CAVs (Digital & Physical)	9	12	9	30	5	11	10	4	30
• Maturation of automated driving technologies	3	4	3	10	2	2	4	2	10
• Paving the way for CAV trials	7	2	0	9	0	4	3	2	9
• Policies mitigating negative impacts and promoting socially benefit models of CAVs	5	1	0	6	3	2	1	0	6
• Registration, licensing, and testing of CAVs	5	2	2	9	2	2	4	1	9
• Standardisation and harmonisation of activities related to CAVs	6	8	1	15	2	7	6	0	15
• CAVs must be developed to operate on existing road networks without any support.	3	2	3	8	1	1	5	1	8
Total number of respondents (unique)	**70**	**56**	**29**	**155**	**33**	**44**	**57**	**20**	**154**

3.3.2 How does infrastructure improvement support the shared mobility model of CAVs?

3.3.2.1 Rationale

Existing studies (Narayanan et al., 2020) reveal that, despite some negative consequences that may arise with shared CAV services (e.g. increasing vehicle miles travelled and security or privacy concerns of users), it has the potential to bring many benefits to the whole community (e.g. increasing accessibility and complementing mass transit systems). Therefore, the transition to automated driving must be carefully managed with policies that will promote the most sustainable forms of travel (Fagnant and Kockelman, 2015). Activities for shared mobility models of CAV need to be supported by local and government authorities and preparing proactive plans for these technologies will likely have a key role in public acceptance. Among these activities, supporting CAV-compatible infrastructure will likely be a key factor for the safe introduction of CAV mobility services by operators in cities. However, the public knowledge and academic literature available on the infrastructure side of vehicle automation are lacking. So, the opinions and suggestions of experts in the field on this subject are important in terms of giving a preliminary idea to the decision-makers and transport authorises. The survey, therefore, asked stakeholders a question about what infrastructure improvements could support the shared use model of CAVs in urban areas without compromising the needs of human drivers.

3.3.2.2 Findings and interpretation of responses

In the survey, a range of responses from stakeholders (N=129) regarding the actions on infrastructure that could support the shared models of CAV was elicited. **Table 3.2** summarizes the responses thematically by stakeholder groups and the frequency of responses. As shown in the table, most of the requirements are not only for shared models but also crucial for the safe operation of many CAV use cases. The most mentioned physical infrastructure improvement is the necessity of the standardisation, investment and maintenance of machine-readable road markings and traffic signs. This is because current CAV deployments, either vision-based or sensor fusion-based systems, depend heavily on clear, uniform, and visible road markings and traffic signs to safely perform driving tasks. Participants claim that high contrast, reflective, and well-painted lane markers and road edges are the most effective infrastructure technology that universally benefits CAVs, regardless of the manufacturer. In this regard, some experts surveyed have emphasized the importance of the consistency of these road characteristics between jurisdictions. Therefore, it is underlined that international harmonisation and standardisation on road markings and traffic signs are needed, including relative to the location of the roadway.

Table 3.2 Thematic representation of responses on infrastructure improvement for shared CAVs adaptation in urban road network.

	Survey Respondent				Survey Respondent				
	Agency (72)	**Academia (64)**	**Industry (32)**	**Total (168)**	**UK (34)**	**Europe (51)**	**USA (57)**	**Others (22)**	**Total (164)**
Expectations of infrastructure improvement for shared mobility models of CAVs									
• Access controlled dedicated lanes or roads for CAVs operation	8	13	3	24	4	6	9	5	24
• Facilities and measures for vulnerable road users to reduce interaction and conflict with CAVs	5	3	0	8	1	1	6	0	8
• Implementation of cameras and sensors for traffic control and management system	3	3	1	7	0	2	2	3	7
• Initiatives for consumer acceptance of sharing and integrating CAV into the Mobility as a Service platform	3	4	0	7	2	2	3	0	7
• Maintenance of physical infrastructure features and reconsideration of roadway design for safety improvements	2	3	3	8	0	3	4	1	8
• Parking facilities for CAVs e.g. pick-up and drop-off points, parking lots	11	6	4	21	7	1	11	2	21
• Providing high-definition mapping service – digital twin	6	8	1	15	2	8	3	2	15
• Reconsideration of lane width and speed limit for CAVs operation	3	2	0	5	0	3	2	0	5
• Reducing complexity in junctions and providing connected traffic light control systems for CAVs	7	9	3	19	2	7	6	4	19
• Regular checks and measures on and surrounding the roadway to improve visibility	2	1	1	4	1	2	1	0	4
• Standardisation, investment and maintenance on machine-readable road markings and traffic signs	20	10	9	39	8	8	15	8	39
• Supporting communication infrastructure (DSRC, Cellular network etc.)	21	13	10	44	5	17	18	4	44
• Supporting the localisation function of CAVs	2	3	1	6	1	3	1	1	6
• No need to significant changes in infrastructure for CAVs	5	0	6	11	2	3	5	1	11
Total number of respondents (unique)	**59**	**45**	**25**	**129**	**22**	**36**	**53**	**18**	**129**

Another frequently cited improvement on physical infrastructure is the implementation of dedicated lanes that could help to realize the full benefits in specific locations while operations remain in the mixed-use case. Regarding this, some respondents suggested that dedicated lanes for public transport vehicles can be allowed during the transition period. Additionally, a few participants mentioned that special lane markings such as magnetic markers can be considered for these lanes in dense urban zones to support the basic operation of CAVs. In connection with this improvement, facilities and measures should also be taken into account for VRUs to reduce interaction and conflict with CAVs. Pedestrian fences along the sidewalks and physically separated lanes for bicycles or micro-mobility users such as e-scooter are some of the examples stated by respondents for this improvement in dense urban zones.

In addition, the accommodation of shared mobility models of CAV in the urban network will require the reconsideration of parking facilities. There was a wide consensus among stakeholders that the dedicated curb area for passenger pick-up and drop-off and CAV-compatible parking lots will support the efficient operation of CAVs. There were also some radical ideas for parking practices, such as removing on-street parking from all commercial corridors and replacing them with pick-up and drop-off zones, and introducing high-cost or limited parking for private single-occupant vehicles. This will also encourage the potential users to accept shared mobility by providing a more convenient service. This seems to be important because some experts surveyed point to the necessity of initiatives for consumer acceptance of sharing CAVs. Moreover, maintenance of physical infrastructure features, reconsideration of roadway design for safety improvements, and regular checks and measures on and surrounding the roadway to improve visibility are less frequently mentioned than other previously stated physical infrastructure improvements.

Concerning the digital features of road infrastructure, the importance of supporting short-range and long-range communication infrastructures for the efficient and safe operation CAVs is stated mainly by respondents. Therefore, uninterrupted telecommunication networks (i.e. good cellular network coverage) or implementation of roadside units (e.g. dedicated short-range communication) at critical locations along the road network will likely play an important role for CAVs in receiving critical operational information such as road conditions, work zones, incidents, or lane closures. However, their effectiveness relies on the availability of traffic control and management centres, and information systems that provide up-to-date data by road agencies or city authorities. Road condition sensors and cameras need to be implemented to provide continuous data from the road environment. Some participants stressed the need to allocate space for retrofitting the physical components of digital infrastructures. Additionally, some participants expressed that internet-based cloud systems for sharing such data in real-time or in advance (e.g. information about work zone plans) will be important for the safe operation of CAVs. Another frequently mentioned support for connectivity is the implementation of traffic light control systems that can communicate with CAVs to share traffic signal information (e.g. Signal Phase and Timing and Green Light Optimal Speed Advisory). This can be crucial not only from a traffic efficiency perspective, but also for safe operation, especially where traffic signals are difficult to detect by AD technologies. More information on facilities of these communication service for automated driving can be found in the reports (European Commission, 2017; 5GAA, 2020; PIARC, 2021). Besides, standardisation of intersection layouts or adjustment of traffic rules such as some restrictions on CAV manoeuvres to reduce complexity is mentioned by participants to be able to support CAVs in urban networks. Lastly, according to some the most helpful infrastructural improvements would be high-definition digital twins of city areas and road networks.

On the other hand, some agency participants expressed concerns about uncertainties in CAV deployments and technology capabilities, making it challenging to determine common requirements for authorities in their investment plans. For example, one of these participants emphasised this uncertainty by stating, *"We do not know yet exactly what CAV will actually require."* Another participant explained the industry's diversity by stating that different CAVs under development require various roadway features for operation. This includes preferences for high reflective striping, reliance on signage or base mapping, and the need for communication systems. Agencies face a significant dilemma in preparing for the wide variety of CAVs due to the lack of standardisation in their operation. Also, *s*ome participants claim that no significant physical infrastructure changes should be made until the market is more mature, and the focus should be on the digital side until the new business models for CAV's matures. This is because for CAVs to become mainstream, they must be able to share roads with human-driven vehicles - and most are being developed to do so. Therefore, infrastructure improvements or changes should be minimal.

3.3.3 What additional maintenance for infrastructure will be required for CAV operation?

3.3.3.1 Rationale

Deployment of CAVs will likely pose new challenges in maintenance and asset management systems for cities and road authorities to ensure their roads are safe and compatible with all road users. In other words, with the adoption of CAVs instead of human-driven vehicles, different infrastructure maintenance requirements are likely to be needed (Sobanjo, 2019). Many studies in recent years have underlined the importance of road infrastructure maintenance in the initial phase of CAV deployment (Johnson, 2017; Lawson, 2018; Osichenko and Spielhofer, 2018; Gopalakrishna et al., 2021), rather than dramatically changing infrastructure (Liu et al., 2019). For example, the frequency of maintenance of road infrastructures, which may be critical to CAVs, and current winter maintenance strategies can change drastically as sensor-based vehicles hit the roads (Ødegård and Klein-Paste, 2021). A recent survey of AV industry members in California highlighted that the performance of automated driving systems will improve with well-maintained infrastructure (Wang et al., 2022). Therefore, CAVs can probably be expected to require stricter rules for maintenance. In short, a change in the approach to road maintenance and asset strategies may be required so that facilitate the safe operation of CAVs. In addition to the statements mentioned in the available literature, to understand the stakeholders' opinions on the maintenance aspects of road infrastructure, in the survey, we asked two questions: 1) Do you think the parameters of maintenance and current asset management strategies will change? 2) What additional maintenance for infrastructure will be required for CAV operation?

3.3.3.2 Findings and interpretation of responses

In the survey, about half of the participants (N=85) expressed their opinions directly regarding the change in maintenance and asset management strategies that could support the safe operation of CAV. Most of these respondents (*n=57*) believe that maintenance parameters and current asset management strategies will change drastically because the AD technology requirements from the infrastructure will be different. Regarding this, one general view is that parameters will likely expand to include additional supportive equipment (e.g. roadside devices) that will need to be maintained that is different from traditional infrastructure. Another more optimistic view is that reliance on physical infrastructure will decrease as technology advances. Some of these participants argue that anything that needs a change in current asset management strategies should be moved to digital platforms. As such, it will likely require a different maintenance approach. However, according to some experts surveyed, although change in existing procedures is needed, the funding and time necessary to develop and implement a national infrastructure with standardised traffic control devices are at least a generation away. On the contrary, a small group of respondents (*n=17*) mainly industry representatives argue that most infrastructure required for CAVs is essential and desirable for all users, so maintenance needs will likely not change dramatically. Some also point out that regardless of the CAVs, parameters for maintenance and asset management are continuously changing based on experience and knowledge. As was mentioned multiple times, some respondents argue that CAV manufacturers should be encouraged to improve capabilities within existing infrastructure provisions. According to these stakeholders, the less external infrastructure is needed outside the vehicles, the better, because they believe that all other scenarios will not become fundable. Lastly, a relatively small group of respondents (*n=11*) did not have a clear view of the subject and expressed that they are unsure until the technology is ready.

With respect to the necessity of additional maintenance on the infrastructure for CAV operation, a range of responses from stakeholders (N=128) was elicited. In general, responses of stakeholders are consistent with outlined maintenance requirements for CAVs in current literature. Many participants (*n=54*) pointed out the importance of the quality and consistency of physical infrastructure and surrounding road environment for CAV operation. It is expected that CAVs will require higher and more frequent infrastructure maintenance compared to the current maintenance schedule for human-driven vehicles. The rationale is that human drivers have a good ability to detect and react when road infrastructure deteriorates or is not up to standards. However, current automated driving systems have limited capabilities to perform driving tasks when faced with gaps in the infrastructure, thus needing data fusion from different sensors or external supporting information via connectivity. In short, the degradation of road infrastructure will pose a challenge to the safe performance of CAVs. Therefore, respondents believe that keeping infrastructure more compatible and detectable for vehicle sensors will be crucial in the transitional phase. In this context, assessing the readability of road markings and traffic signs (e.g. painting, cleaning), repairing road surface conditions (e.g. potholes, rutting), providing proper road lighting, controlling traffic loading on long-span bridges due to platooning effects, or channelisation of pedestrian crossings and intersections are some of the examples in maintenance that need to be considered. Also, roadside environments such as plants and trees that are constantly growing during the spring and summer months should be regularly maintained because onboard sensors of CAVs see them as obstacles and they affect the sight lines of vehicles. In addition, locations with extreme weather (e.g. snow, flooding) have significant impacts on the roadway system, so asset management and maintenance will be critical to ensure the safe operations of CAVs. Therefore, some respondents (n=6) underline the importance of the necessity of new adverse weather maintenance strategies for CAVs.

In fact, nearly all mentioned precautions related to physical infrastructure are also important and beneficial for human-driven vehicles in terms of safety. The main expected difference is that more frequent maintenance will play a critical role in the CAV adoption in road networks. In this context, frequently recorded road views or monitoring the road conditions with sensors might be necessary as well as some communication equipment might help CAVs learn the new road conditions. However, present road maintenance and inspection methods necessitate extensive manual surveying work on the part of agencies. According to some participants, a paradigm shift from traditional human judgment techniques to more objective tracking and assessment techniques based on the technology will be necessary for road maintenance. Additionally, there is potential to leverage the CAVs' cameras and sensors to be able to collect and share inventory and conditions data for the road. However, there are many uncertainties about whether the data provided by CAVs will be accurate and appropriate. Furthermore, CAVs can offer this information in real-time, but this raises concerns about how this data can be managed and how hurdles to supplying such data can be overcome without jeopardising cybersecurity and data privacy.

In addition to the current physical road infrastructure attributes, the maintenance and control of newly introduced digital infrastructure (e.g. communication units and sensors) and their physical components will need extra consideration from authorities or service providers (n=59). As frequently mentioned by participants, current road infrastructure uses long-cycle maintenance. However, with more electronic equipment installation on roads, the maintenance cycle will need to be much shorter and much more time-sensitive, and thus more budget will be required for more teams, more spare parts' stock etc. Some respondents (n=4) emphasise that agencies and city authorities will need personnel with higher qualifications to maintain these electronics. Lastly, digital mapping will likely be needed for road safety features and conditions to allow rapid treatment and mitigation of priority items in road networks. Furthermore, a few experts (n=3) point out that infrastructure maintenance plans and execution should be part of the certification process for roads and controlled by independent audits.

3.3.4 When should infrastructure improvement for CAVs be initiated?

3.3.4.1 Rationale

There has been a growing literature in recent years recognising the importance of the quality and consistency of road infrastructure in the safe operation of CAVs (Liu et al., 2019). Similarly, the findings of the previous section show that maintenance of road infrastructure will be crucial to maintain a high level of road quality so that CAVs can operate safely. However, there is uncertainty about when the necessary infrastructure-related improvements for automated driving and connectivity will be introduced to meet the emerging market needs (Saeed et al., 2021). This uncertainty may remain until the marketplace further matures. Therefore, to get a preliminary idea of the subject, we asked stakeholders a question: *"What is the minimum level of market penetration for road agencies and operators to start reorienting their road infrastructure to accommodate CAVs?"*

3.3.4.2 Findings and interpretation of responses

Looking at the distribution of responses, there is no dominant choice among the stakeholders (N=162). About one in four respondents (22.2%) expressed that when about less than 10% of vehicles on roads are CAVs, road agencies and operators should start to re-orient their road infrastructure for CAVs. Relatively more participants (25.3%) believe that this should be started when about 10 to 25% of vehicles on roads are CAVs. This indicates that about half of the participants (47.5%) express that when less than 25% of vehicles on the roads are CAV, necessary infrastructure improvement should be considered. Conversely, around 30% of the respondents suggested that improvements should be contemplated once the market achieves a specific threshold of penetration, such as exceeding 25%. For closer inspection, **Figure 3.4** illustrates the proportion of responses based on the grouping variables. The data in the figure clearly show that the participants from academia and industry groups have relatively more favour for infrastructure improvements in the early stage of the CAVs to accelerate the adoption. A similar trend can be seen in the respondents from Europe. On the other hand, agency participants are more in favour of waiting for the technology to mature or until it proves beneficial to overall community goals and then acting on the infrastructure needs.

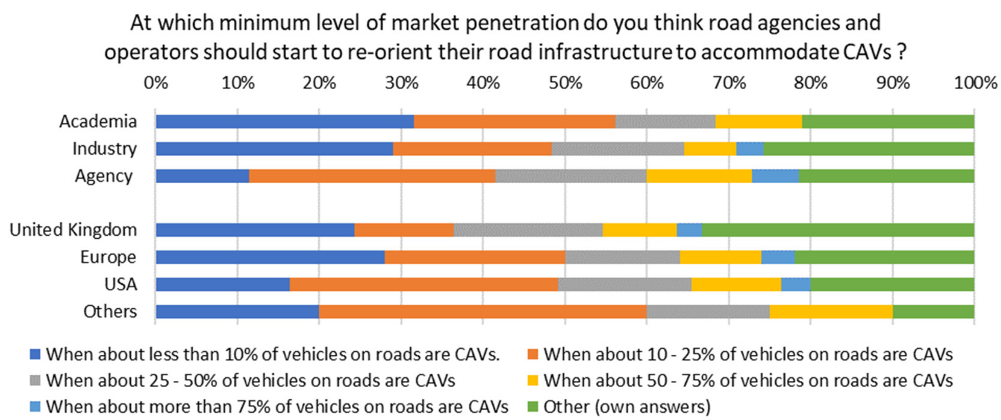

Figure 3.4 Responses to the question about the penetration rate for infrastructure improvement for CAVs, by type of organisation and place of residence (%).

Moreover, nearly one-fourth of respondents (23%) selected the “other” option to share their views regarding the question. Considering the comments expressed here, there is no distinction between stakeholder groups on views and three different views can be underlined:

- The first group is in favour of taking proactive action in advance of the widespread implementation of CAVs, recognizing the crucial role of road infrastructure in automated driving. They believe that without some upgrades to an existing roadway and higher levels of maintenance, it might not be obtained higher automation levels on roads. These respondents emphasise that many of the infrastructure improvements for CAVs will also make roads safer for all users. Therefore, national plans are required for infrastructure to facilitate automated driving.

- The second group is more cautious in this regard and favours the gradual implementation of necessary improvements as the market matures. They point out that maintaining the minimum standards on roadways (e.g. improving lane markings) will be necessary for the early stage of CAVs, but substantial maintenance needs to occur further down the track. That is, the type of infrastructure change depends highly on the degree of penetration. However, some participants argue that comprehensive orientation such as changing lane width might require nearly 100% adoption. Participants also stated that for the transition period, different areas should be zoned as CAV and non-CAV.

- The third group argues that CAVs should be designed to adapt to existing roads, so there should not be major changes in the physical road infrastructure, but rather about the digitisation of the mobility system, which is relatively inexpensive compared to the physical infrastructure. However, these respondents anticipate that there may be changes on the physical roads for use cases of CAV with societal benefit such as buses and shuttles.

3.3.5 How will the CAV infrastructure be funded?

3.3.5.1 Rationale

Numerous studies (e.g. Shladover and Bishop, 2015; Johnson, 2017; S.M. Khan et al., 2019; Zenzic, 2019) and some official reports (European Commission, 2018) indicate that new funding and incentives are needed to provide the facilities that CAVs need for physical and digital road infrastructure. However, there has been limited research in the available literature focusing on the financing requirements for infrastructure-related investments, maintenance, and operation expenses (Adler et al., 2019; Saeed et al., 2021). Government revenue, budget and financial institutions should conduct a thorough review of how revenue streams may change as a result of automation and supporting legislation (Terry and Bachmann, 2019; Litman, 2020). Krechmer et al. (2016) have discussed a set of individual scenarios with corresponding upgrade cost estimates that might be paid for by public or private organisations in the USA. However, there is a lot of uncertainty around this issue and lack of evidence on how to measure the potential impact of CAV adoption on financing plans and, more importantly, what the approach of stakeholders from different groups is. Moreover, developing new business models for financing infrastructure improvements will likely be needed for different jurisdictions. This is because, as noted in Shladover and Bishop (2015), approaches that fit well within one country's established business and legal frameworks may not fit well at all in another. In the survey, we asked stakeholders how road agencies and operators (IOOs) can meet their infrastructure financing needs to accommodate CAVs on the roads to understand the recommendations of the experts on the subject.

3.3.5.2 Findings and interpretation of responses

In the survey, a variety of responses (N=141) were received from stakeholders regarding potential actions that could contribute to financing needs for infrastructure-related investments. However, some of the answers (*n=23 respondents*) were not applicable as they either stated that they had no idea about the question or were related to their expectations and views in the context of automated driving and infrastructure. For infrastructure-related investment, a few respondents (*n*=*9*) believe that road agencies and operators, as well as local authorities, can afford their financing requirements through internal funding and budgetary allocations. However, some (*n*=*7*) point out that there is great uncertainty about the requirements, as there is currently no agreement on optimal and standard requirements that can facilitate automated driving due to a lack of knowledge. Therefore, road agencies and operators are still unsure what will be needed or how to budget. For example, an agency participant stated this as follows: "*We first need to understand what is needed and develop strategic plans to incorporate the things that will be needed and utilized by CAV technology. This will allow IOOs to spend money wisely and not on things that are not useful."*

On the other hand, a group of respondents (*n*=*13*) argues that the efforts and focus should not be on building and investing in infrastructure specifically for CAVs, but on initiatives that will be beneficial for all road users. Among these experts, as mentioned in the previous sections, some suggest that CAVs should be developed to operate on the existing infrastructure and they need to prove their safety, as well as benefit the whole society. One example of this view is that *"If CAVs need additional infrastructure to operate then the technology is not mature enough."* Therefore, proofs of concept that CAVs are safer than human drivers and finding the proper arguments for public acceptance are required before road agencies and local authorities have any motivation to make the required changes.

Contrary to previous opinions, another group of participants (*n*=*13*) believes that road agencies and operators cannot afford these investments alone, so they should not be solely responsible for them. In this regard, participants point to the current financing constraints faced by road and local authorities to keep roads maintained. One of the respondents criticises this situation by commenting: "*For basic, simple things (like painting faded road lines, cleaning road signs, etc) they often fail to do this well enough, even for human drivers, despite it being a legal requirement"*. This is because funding is a major challenge, particularly for local governments with limited infrastructure budgets. As one participant (from Academia and Europe) commented, *"with limited funding, investments specific only to CAVs might not be justifiable."* For this reason, according to some participants, CAVs that can work on the existing infrastructure will be a best fit with the current state of infrastructure funding. In other words, this view asserts that CAV technology should, at least in short term, be developed in locations where the need for extra infrastructure support is minimal.

However, considering current technological deployments, it may be unrealistic to expect maximum benefit and social value from CAVs without infrastructure improvements. According to many respondents, roads allowing CAVs to travel must have additional infrastructure elements; thus, unit investment per vehicle must be minimized by starting with major arterials and city centres where we have high traffic volumes. For intercity/rural corridors, these should be the ones with higher commercial vehicle traffic volumes as the commercial vehicle fleet transformation to CAVs can be faster and more fundable. The key consideration is that road agencies and local authorities should not be obliged to invest simply to enable CAVs to get started: the private sector such as technology companies and service providers need to contribute to fund any necessary infrastructure. Therefore, many participants (*n=20*) believe that public private partnerships will be key to moving forward with ubiquitous infrastructure distribution. Particularly, when it comes to funding large-scale transportation projects that involve design, build, financing, operation and maintenance in one package for CAV related facilities, incentives for the private sector by regulatory bodies will likely be critical.

In addition, given the current financial situation of local authorities and road agencies, there will need to be significant government policies in place to better support the use of CAVs before they become mainstream. Many respondents (*n=34*) emphasise that new business models and strategies need to be identified for CAV-oriented investments. For instance, it requires a large shift to funding maintenance of traffic control devices and new connected technology from pavement management and construction budgets. This will take a paradigm change in legislation and policy (*n=8*). As commented by one of the respondents these changes should be implemented incrementally, aligning with the advancements in vehicle technology. Moreover, one of the main challenges the authorities will face is that different levels of vehicle automation and use cases can require different infrastructure support and therefore different business investment models will need to be considered. For this reason, participants point out that multilateral cooperation at the levels of producers and road authorities needs to make a decision to use public and international funding.

To date, roadway infrastructure has been designed based on the average human driver criteria. For this reason, identifying the variation between the average human driver and the developing CAVs, and then determining where design standards may need to be adapted to accommodate both will allow agencies and authorities to focus funds in areas that will create a longer infrastructure life for the least cost. It is also worth noting that, some of the investments in improving current road infrastructure will be beneficial for both the CAVs and human-driven vehicles, such as well-painted road markings, clear and consistent traffic signs, frequent maintenance of road surface etc. Therefore, the realisation of these improvement investments needs to be made by using public funds that mainly come from the taxation of the car-buying public, fuel taxes, licencing etc (*n=16*). This may not be an issue until vehicle technology reaches Level 4 automation, as human drivers will still be required for safe use (i.e. traditional car buying will continue, and revenue streams may not significantly change). But the main challenges begin with Level 4 services where a driver may not be needed in certain operational areas. In this context, the policy options could be around a charging model to provide further funding, but this is a politically tricky thing to do and requires getting the public on board and showing all the potential positive and negative aspects regarding safety, the environment, and accessibility etc. Some respondents (*n=6*) believe that the cost of infrastructure-related investment can be compensated by the direct and indirect benefits of CAV adoption. However, this will be difficult to handle from the existing budgets of authorities because the initial investment cost will be high and the savings offered are a long way in the future, making the business case hard to predict. According to a group of experts (*n=19*), a special tax can be issued for certain transportation services for funding purposes. Regarding this, stakeholders mentioned many options of user-based charging, such as tolls of roads, vehicle miles travelled (VMT) fees, congestion fees, additional registration fees for privately owned CAV etc. Among these options, some participants believe that mileage-based user fees may be an equitable approach to funding considering the connected direction vehicles are progressing as well as the likely reduction in gas revenue (due to electrification in the vehicle industry). One of the respondents explain this situation by commenting: "*VMT is the only way to make the needed funding possible. The decline in collected funds is affecting the authorises and change needs to be made to include all of the forms of users. The funding currently does not keep up with maintenance let alone the new infrastructure to be implemented*." However, some argue that introducing a toll system may not be successful since during the transitional phase most vehicles will not be CAV and thus will not pay. Therefore, the system can only be funded through the combination of the general exchequer funding and the collection of taxes/tolls from a certain group of taxpayers (users of automated driving services).

3.4 Conclusions and policy recommendations

This study engaged a diverse group of experts and key stakeholders to comprehensively explore the various aspects of connected and automated vehicles (CAVs) deployment on urban roads. By analysing and interpreting the feedback collected through an online survey, the research identified areas of agreement and disagreement among stakeholders, resulting in some policy recommendations.

One common conclusion emerging from the survey is that stakeholders' attitudes and perspectives on the implementation of CAVs vary based on the types of organisations they represent and their geographic regions. EU respondents, for example, prioritise challenges related to managing mixed traffic situations and interactions between CAVs and vulnerable road users (VRUs). UK respondents, on the other hand, highlight concerns about the adequacy of technological advancements. In contrast, USA respondents mainly underlined liability and insurance issues associated with CAVs. These differences can be attributed to the varying levels of infrastructure, technology, and legislation in each country (KPMG International, 2020), as well as their unique urban forms. The current state of these factors in each region shapes stakeholders' perceptions and priorities regarding the implementation of CAVs. For example, EU stakeholders commonly emphasise the use of low-speed shuttles in urban streets, reflecting their strategic focus on integrating into public transport systems. In contrast, stakeholders from the USA frequently emphasised the concept of driverless taxis, reflecting a car-focused approach in their strategies for CAV implementation.

While the priorities of each stakeholder in the deployment of CAVs may differ, there was a strong consensus regarding the main barriers to CAV adoption in urban networks. Concerns for the safety of automated driving technologies and deficiencies in the development and implementation of policy and legislation are widely recognised as significant challenges. In fact, there are two kinds of challenges awaiting authorities to facilitate the integration of CAVs: the first is the steps to be taken for the successful implementation of CAVs on the existing road network and the second is the problems arising from the implementation. There was widespread consensus that it is not possible to address many of these challenges without concerted cooperation among stakeholders. Therefore, new platforms are vital to provide continuing dialogue between stakeholders. Another commonality was the need for investment in road infrastructures that would benefit the safe deployment of CAVs. The main reason for this is the frequent mention of the lack of physical and digital infrastructure to support the CAV operation on a large scale, regardless of their mobility models.

Nevertheless, the findings of this study indicated the presence of three distinct perspectives among stakeholders regarding infrastructure improvement to support automated driving. According to the first group, mainly from industry and academia representatives, infrastructure investments need to be made "in advance" of widespread consumer adoption of vehicle technologies. The main argument is without any supportive upgrade on infrastructure maximum benefits of automated driving will not be achievable by relying on only vehicle technology. On the other hand, the second group of participants (predominantly legislators and IOOs) are in favour of a "wait to see" stance to take action on this emerging mobility option. This is mainly because uncertainties regarding technological advancement and CAV implementation pose a major challenge for authorities to plan infrastructure upgrades in their short-term agendas. More importantly, their impacts on road transport are still highly uncertain as it will affect many aspects of transport system performance. Therefore, the steps that pave the way for CAV trials will play an important role in the development of reliable technology over time and in evaluating their potential impacts. The third group, however, is more sceptical in this regard and holds that automated driving systems must be able to perform all driving tasks safely on existing road infrastructure. Their argument is that it is neither possible nor feasible to prepare all roads for CAVs. However, achieving the desired level of digital infrastructure in the urban network is commonly seen by many stakeholders as a relatively less challenging step to support the deployment of CAVs. The overall opinion is that the digital infrastructure can offer greater potential for short-term benefits compared to physical infrastructure upgrades, by providing cost-effective and adaptable solutions to improve transportation systems.

Contrary to the differences of opinion regarding CAV infrastructure improvement, another common agreement among stakeholders was that CAVs will require stricter rules for maintenance regimes of road networks. This also means that current maintenance and asset strategies will need to be changed significantly. Compared to human-driven vehicles, it is expected that CAVs will require more advanced and frequent infrastructure maintenance to keep infrastructure more compatible and detectable for onboard sensors of vehicles. While there are arguments suggesting that CAVs may collect data for the network themselves, stakeholders have expressed concerns about the quality, consistency, and sharing/storage of such data. Therefore, the development of new technologies for automated road assessment becomes increasingly important to ensure the provision of highly accurate and officially approved data for road authorities (Osichenko and Spielhofer, 2018; Konstantinopoulou and Fuller, 2021). Another consensus was that the maintenance and control of the emerging digital infrastructure (e.g. communication units, road detectors, sensors, cameras, etc.) and their physical components will require separate consideration by the authorities or service providers. With more electronic equipment installed on the roads, the maintenance cycle will need to be much shorter and time-sensitive (Sobanjo, 2019). This also brings a necessity of personnel with higher qualifications and skills in multiple fields for road agencies and city authorities to operate and maintain these electronics. An interdisciplinary approach and collaboration with other stakeholders will be key to expanding their in-house expertise (Gopalakrishna et al., 2021). Briefly, to facilitate the integration of CAVs, a more proactive approach (i.e. shifting from a repair-as-needed approach to a preventative-maintenance) is necessary for the maintenance of road infrastructure, as stated in Wang et al. (2022). Also, it is necessary to initiate direct and in-depth discussions between the public and private sectors on the standardisation on many digital infrastructure aspects and the determination of task sharing.

There was no widespread agreement among stakeholders on the financial models to meet the needs of infrastructure-related investments, maintenance and operating expenses. In particular, it remains unclear how the authorities will meet the initial infrastructure investments related to CAVs and who should be responsible for them. Moreover, there is substantial uncertainty and information complexity around the minimum and optimum requirements of CAVs. Although the need for standardisation and harmonisation in activities related to road infrastructure and maintenance of infrastructure elements has been highlighted, there are not yet official specifications or agreed guidelines for assessing the readiness of existing infrastructure. The diversity in CAV capabilities and models also poses challenges for authorities to understand and act based on the requirements of emerging mobility trends. Therefore, as a first step, it is necessary to determine the roadway characteristics that allow for a minimum performance at each automation level or mobility models. Then, starting with roadway features, which will be important for human-driven vehicles, will likely eliminate opposing noises in public.

Despite the inherent uncertainty concerning the future, it is argued that decision-makers should be aware of upcoming public finance challenges and take them into account in their agendas. With the introduction of CAVs, it is likely that the revenue streams of both local and central governments will change drastically. Currently, many countries rely mainly on revenue from fuel taxes of vehicle users for investment in road infrastructure. However, with the increasing trend of vehicle electrification due to environmental benefits and regulatory requirements, revenue streams for road authorities are declining. Therefore, CAVs (expected to be electrified) will not directly contribute to road maintenance to a major extent unless a new business model is developed for electric vehicles. The tax structure will need to be reconsidered before CAVs begin to dominate the roads, or CAVs maintenance and infrastructure demands dominate road maintenance costs. This is because there is a common argument that IOOs cannot afford the required investments alone. However, for the early stage of deployment where the operation of CAVs will be limited due to the lack of coherent road infrastructures, the integration of new business models may raise many social and equity concerns among the public. On the other hand, it is not clear how accepting CAVs users will be about paying extra for features that can only be used while driving in wealthier political jurisdictions, as stated in Shladover and Bishop (2015). Therefore, although operating environments are expected to be constrained, commercial fleets are viewed as feasible in the short term (Gopalakrishna et al., 2021), with cooperation between the public and private sectors. This seems particularly important because survey findings showed that there is a concern about whether investments in CAVs will benefit all segments of society.

There are clearly further need for research in specific areas. Firstly, while this study primarily examined experts' opinions of CAV deployment and infrastructure requirements, it is important for future investigations to also consider public opinions, which are commonly incorporated in CAV adoption research (Thomas et al., 2020). Differences in opinions between stakeholders and the public regarding CAV deployment can offer decision-makers a more comprehensive understanding of the overall landscape. This is because stakeholder opinions and public opinions can differ on the deployment of CAVs, hence the requirements and challenges (Swain et al., 2023). Although this study revealed variations in stakeholders' attitudes and perspectives towards CAV implementation, these observations were derived from qualitative analysis of open-ended responses, lacking quantitative validation. Therefore, findings of this study can be utilised in future research to compare expert opinions across diverse stakeholder groups by using multi-actors multi-criteria analysis (MAMCA). As evidenced by Kroesen et al. (2023), expert perceptions have undergone shifts as a result of increased related research in the domain and heightened awareness of CAV technology. The findings can be compared over time to track changes in stakeholders' perception of CAV deployment and its impact on infrastructure. Implementing these recommendations will contribute to a more profound comprehension of the perceptions and expectations surrounding CAV deployment and infrastructure.

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CHAPTER 4

Infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders

Abstract: The need to future-proof road transport networks is becoming increasingly urgent in order to take full advantage of automated vehicles (AVs). It is now vital to understand the basic road infrastructure requirements of AVs in order to assess the readiness of the existing road network and prepare the roads for the safe operation of these vehicles. However, current literature on this subject is limited. As such this research seeks to understand the desired infrastructure-related requirements of highly automated vehicles (SAE Level 4) for safe operation based on a survey with experts and stakeholders. On the basis of 168 expert responses from 29 countries, this study presents stakeholders' views on: (1) deployment paths of Level 4 automated driving, (2) the concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operations of Level 4 automated driving. The findings show that different types of stakeholders (e.g. academics, infrastructure owners and operators, and vehicle and information technology developers) have broadly similar views on most criteria requiring consideration in the early stages of automated driving implementation. However, there is no clear consensus on issues regarding operating constraints on road networks and some are in favour of waiting for the technology to mature or until it proves beneficial to overall community goals and then acting on the infrastructure needs.

Keywords: Automated driving, Autonomous vehicles, Road readiness, Road infrastructure, Stakeholder engagement

4.1 Introduction

Automated vehicles (AVs) along with electrification and shared mobility, are currently recognised as one of the three ongoing revolutions in road transportation (Jaller et al., 2020). However, enabling AVs to travel on public roads might require some infrastructure upgrades or adjustments based on the needs of automated driving technologies (Manivasakan et al., 2021). Current road infrastructure and the surrounding environment are designed and built for human drivers and may not be able to deal with the integration of vehicles with high levels of automation (Liu et al., 2019; Lengyel et al., 2020). In other words, it is not known whether they are ready for the safe and efficient operations of AVs during the initial phase of implementation (Johnson, 2017). Also, there are significant differences in the quality, nature, and maintenance standards of roads in the same country and between countries. This gives reason to hypothesise that some roads or zones will likely be less suitable for AVs than others, and therefore the appropriate ones should be prioritized to ensure the highest levels of safety in the early phases of deployment. Hence, with the transition from human-driven vehicles to automated vehicles, the demand for future-ready road networks will likely become more important.

The role of infrastructure in vehicle automation clearly depends on AV capabilities. The six-level classification (SAE J3016) of on-road automation capabilities of vehicles is widely used in academia: no automation (Level 0; hereafter, L0), driver assistance (L1), partial automation (L2), conditional automation (L3), high automation (L4), and full automation (L5). This driving automation spectrum (L0-L5) demonstrates the increasing automated driving capabilities based on the gradual shift of responsibility for dynamic driving tasks (DDTs) from a human driver to computer-based systems. Among these levels, L4 and L5 are the main automated stages, which are fail-safe situations where drivers have sufficient warning or do not need to concentrate on their driving tasks at all (SAE International, 2021). Major benefits of AVs are expected at these stages (e.g. increasing accessibility of people with limited ability of transportation provisional or allowing users to be engaged in other activities in vehicles etc.), therefore this study focused on L4 and beyond.

For the transition period to full automation, studies point the safe operation of L4 vehicles at full capacity will heavily depend on the type of infrastructure they encounter (Huggins et al., 2017; Madadi et al., 2018; Evas and Heflich, 2021). Automated driving trials have been disengaged many times due to factors related to the road environment and infrastructure, such as poorly marked and inconsistent road markings (Favarò et al., 2018; Ye et al., 2021). Europe's leading road safety authority (EuroRAP) highlights some potential problems that AVs are likely to encounter given the current infrastructure deficiencies (Lawson, 2018). It is therefore important for road authorities and agencies to know how ready their road infrastructure is for safe automated driving operation (Zenzic, 2019). However, current academic literature and field reports are lacking on this subject (Farah, 2016). Few studies have attempted so far to investigate the role of infrastructure in automated driving (e.g. Gill et al., 2015; Ehrlich et al., 2016; Huggins et al., 2017; Johnson, 2017; Transport Systems Catapult, 2017a; Gyergyay et al., 2019; Amelink et al., 2020;) and the number of pilot projects (e.g. Konstantinopoulou et al., 2020; Marr et al., 2020) addressing infrastructure challenges for AVs is limited. Particularly, the number of studies addressing potential infrastructural requirements to facilitate AVs remains substantially limited (Nitsche et al., 2014; Lu et al., 2019; Wang et al., 2022). In short, the literature points to the need for research to assess what infrastructure needs are to contribute to facilitating AVs in the built environment.

This research aims to fill this gap by identifying the potential infrastructure-related requirements of automated driving using a survey to get the views of experts in the field. Another key contribution is to identify (any) differences in perspective between regions and sectors from which experts come, and to provide clear directions to transport authorities based on opinions elicited. In this context, the study focused on the near future to assess the readiness of road infrastructure in the early stages of L4 automated driving applications, which will likely be introduced to roads at a remarkable level within the coming decade (ERTRAC, 2019). The term 'automated driving' is used to describe the technology where automation of the driving task, vehicle connectivity, and the data are brought together (Shladover, 2018).

The rest of the paper is organised as follows. **Section 4.2** presents the methods adopted for data collection and analysis and describes the profiles of the stakeholders surveyed. **Section 4.3** illustrates the descriptive results of survey responses and the main interpretation of findings, including a comparison of opinions between various types of stakeholders. Finally, **Section 4.4** summarises the main findings and gives future research recommendations.

4.2 Methods

Despite some recent works, there is a general lack of published material on basic road infrastructure requirements for automated driving, as noted in the introduction. The intense competition between automotive and information technology companies for gaining a dominant market position leads to the careful preservation of industry expertise, too (Shladover, 2018). Therefore, little information is available in the public domain regarding precise infrastructure-related vehicle requirements. The AV community, on the other hand, is fast evolving, and aside from highly guarded development projects, there is substantial knowledge in academia, OEMs, and public trials. Under this circumstances, expert consultation appears as an appropriate research method to understand the requirements and implications of AVs for road infrastructure. While there are several options available to seek expert opinions, such as conducting individual interviews or focus groups, these can be time-consuming and costly. On the other hand, questionnaires are more cost-effective and provide more quantifiable data that can be easily analysed. Qualitative methods are generally favoured due to their ability to gain more detail by collecting information about people's views on a given question (Taylor et al., 2015). A mixture of quantitative and qualitative methods, on the other hand, can allow for more diverse insights to be drawn from the results (Thomas et al., 2020). Therefore, this research used a semi-structured questionnaire comprised of a mixture of closed (e.g. multiple-choice and scaling) and open-ended questions to gain an insight into the opinions of experts from various backgrounds.

4.2.1 Survey instructions and questionnaire content

The draft questionnaire was created using Online surveys (onlinesurveys.ac.uk), a web-based survey tool after identifying from the literature potential factors that affect the safe operation of automated driving. It was subsequently modified and refined based on the outcome of the pilot survey with 5 researchers in the field, before being delivered to the target experts. The final version of the questionnaire consists of 27 questions divided into 5 parts, excluding the instructions for participants. These are:

- Part 1 focuses on the type of respondents' organisation, area of expertise, work experience, relevance of their work content to AVs, and country of residence to gain an insight into the profile of the participant and assess their eligibility for the study. This also allows for the evaluation of a correlation to be formed between the profile-based attributes and the attitudes towards questions.
- Part 2 covers general questions about AV deployment and its potential impacts.
- Part 3 includes a set of questions about participants' views on physical road infrastructure requirements and road evaluation for AV-specific functionality and safety, including questions regarding the concept of road certification.
- Part 4 covers questions about digital and communication infrastructure requirements for automated driving.
- Part 5 focuses on the importance level of thirty potential road safety assessment factors or infrastructure elements that can affect the safe operation of L4 automated driving.

4.2.2 Participants and data

The survey focuses on three key stakeholder groups who will affect or be affected by the infrastructure for automated driving: academia (e. g., universities and research organisations), industry (e.g., technology developers, vehicle manufacturers, and service providers), and government agencies and related institutions which are responsible for infrastructure investment, regulations, and policy formulation (e.g., national authorities, local authorities, road agencies, and consultancy firms). Although road users have been identified as one of the key stakeholders in many studies (Lu et al., 2019; Saeed, 2019; Hamadneh et al., 2022), they were not considered as we mainly focused on technology and related road infrastructure requirements. After receiving an ethical approval form the University of Leeds Ethics Committee (LITTRAN-142), the questionnaire link was e-mailed to potential experts and stakeholders identified from relevant conferences, workshops, and research. They were also asked to forward it to other possible respondents within their organisations via e-mails and newsletters and several did so. Reminders were sent out to recipients approximately three weeks after the original email date. In addition to the target contacts, the survey link was also shared on social networking sites related to vehicle automation and transportation organisations.

Data collection began in mid-October 2021 and ended at the end of November 2021. A total of 168 valid responses were received from experts and stakeholders, making it one of the largest studies of such experts to participate (compared to Nitsche et al., 2014; Farah et al., 2018; Madadi et al., 2018; Saeed, 2019; Gopalakrishna et al., 2021).[13] Participants came from twenty-nine different countries, but more than half were from two countries: the United States of America (USA) and the United Kingdom. Participants have an average of 17 years (SD 10.8) of work experience, and more than 70% of respondents have at least 10 years of experience in the field. Most are from agency (43%) and academy (38%) groups, with the rest working in the industry (19%). **Table 4.1** shows the detailed breakdown of the respondents' backgrounds.

[13] This online survey was conducted as part of the first author's PhD research on the road readiness index for automated vehicles. Only a part of the data obtained from this survey was used in this research.

Table 4.1 Number and proportion of respondents by type of organization they represent, total work experience, and place of residence. [14], [15]

			Number of Respondents	Percentage share [%]
Organisations	**Academia**	Universities	39	23.2
		Research institutes and organisations	25	14.9
		Total	**64**	**38.1**
	Industry	Vehicle industry	15	8.9
		Technology developers	9	5.4
		Service providers & suppliers	4	2.4
		R&D companies	3	1.8
		Insurance companies	1	0.6
		Total	**32**	**19.0**
	Agency	Local /regional authorities	9	5.4
		National authorities	12	7.1
		Road agency / administration /operators	27	16.1
		Consultancy / engineering	24	14.3
		Total	**72**	**42.9**
Work experience		0-9 years	45	26.8
		10-19 years	44	26.2
		20-29 years	46	27.4
		>30 years	30	17.9
		N/A	3	1.8
Place of residence		United Kingdom	34	20.2
		Europe	51	30.4
		USA	57	33.9
		Others	22	13.1
		N/A	4	2.4

4.2.3 Analysis method

A mixed methodological approach was adopted in this study. Statistical analysis of the collected quantitative data was performed using Excel and SPSS, and descriptive statistics were presented using graphics. Some missing responses were valid, as we specifically asked participants to skip questions that they did not want to answer or that they thought did not have the technical knowledge on the subject. The responses of the participants were tested with the Kruskal-Wallis H test, which is suitable for testing the statistically significant differences of the variables where preference scales

[14] Number of participants by country of residence - USA: (57), United Kingdom: (34), Germany: (9), Italy and Australia: (6), The Netherland and Turkey: (5), Canada, Finland, and Ireland: (4), France and Korea: (3), Albania, Austria, Japan, and Switzerland: (2), Brazil, Croatia, Denmark, Greece, India, Indonesia, Israel, New Zealand, Poland, Singapore, Slovenia, and South Africa (1), Prefer not to state (4).

[15] Pearson's Chi-Squared test was carried out to assess whether grouping variables are correlated. Based on the results, no association was found between groups: for organisations and work experience ($\chi 2$ (6) = 11.934, p = 0.063); for organisations and place of residence ($\chi 2$ (6) = 8.663, p = 0.193); for place of residence and work experience ($\chi 2$ (9) = 5.790, p = 0.761).

were used (Marusteri and Bacarea, 2010; Liljamo et al., 2018). Lastly, qualitative data analysis software NVivo was used for the thematic analysis of the open-ended responses to the survey questions.

4.3 Results and discussions

The research questions in this study are grouped into four main categories: (1) deployment paths of L4 AVs, (2) concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operations of L4 automated driving. In light of these four topics, the analysis and interpretation of opinions of experts and stakeholders are presented in the following sections, including the rationale of the research questions.

4.3.1 When, where and which model of Level 4 AVs are expected to be widely available?

4.3.1.1 Rationale

In recent years, most vehicle manufacturers have adopted automation technology as a support for the driving task, and as a result, L1-L2 systems have become commonplace in the existing vehicle fleet (Robinson et al., 2017). Considering the L3 systems, it raises many controversial questions about how the process can be managed if drivers (DDT fallback-ready users) do not respond when the occurrence of a failure or out of operational design domain (ODD)[16] condition – which is referred to as a minimal risk condition.[17] To avoid this challenge in L3 AVs, technology firms and some conventional automakers are focusing on developing and manufacturing L4 automated driving (Bigelow, 2019). In L4, system is expected to handle the fail-safe situation autonomously within the certain ODDs. For this reason, L4 AVs are of great interest in both academia and industry and are currently being tested on real roads in many cities around the world, albeit on a small scale (Farah, 2016; KPMG International, 2020). Several documents have been published that provide descriptions of automation systems and the expected date of their possible deployment, taking into account different use-cases and mobility models (Transport Systems Catapult, 2017b; Aigner et al., 2019; ERTRAC, 2019; Zenzic, 2019; Litman, 2020). Studies predict that, in

[16] SAE International defined the ODD as *"operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics"*.
[17] According to the BSI (CAV Vocabulary BSI Flex 1890 v4.0), "minimal risk condition" defined as: *"stable, stopped condition to which a human driver or automated driving system brings a vehicle after performing the dynamic driving task fallback in order to reduce the risk of a collision or other loss when a given trip cannot be continued"*. For example, at Level 3 if the human driver fails to respond to transition demand, a failure mitigation strategy follows, such as stop-in-lane.

general, L4 AVs will be on the road in the next decade, but the actual deployment path of AVs and the precise nature of the transition path remain unclear (Milakis et al., 2017). However, to prepare and evaluate the future-ready roads, understanding the deployment paths of L4 automated driving is essential. Therefore, this section presents the results of the questions asked to get participants' views on when, where and which models of the L4 AV will be generally available to the public.[18]

4.3.1.2 Findings and interpretation of responses

The first question in this regard concerned the deployment time of L4 automated driving, which is considered safe enough to be allowed for public use. Responses show that there is no dominant choice among the options (N=165). About one in six respondents (17.6%) were very optimistic about the deployment time and believe that L4 AVs will be available for public use in the next 5 years (starting with 2021). Relatively more participants (27.3%) stated that this technology will hit the road and be safe enough in the next 5-10 years. The second-highest proportion (19.4%) was the option of in the next 10-15 years. Only a minority of participants (7.9%) have stated that L4 AVs will not likely be considered safe enough to allow for public use before the next 20 years. To examine the differences of opinion among stakeholders, **Figure 4.1** illustrates the proportion of responses based on the type of organisation respondents represent, their total work experience in the relevant field, and their place of residence. The figure shows that the participants from the USA, and those with relatively little work experience generally have a very positive attitude towards the deployment time of AVs. More than half of the responses in both groups indicated that L4 AVs would likely be safe and on the road in the next decade.

Considering the comments stated in the "other" option (10.9% of respondents), participants generally highlighted the role of ODDs and specific controlled environments in assessing the deployment time of L4 automation. Most of these respondents expect L4 AVs with the carefully defined ODDs will likely be available for public use within the next 5-10 years and, but only on a small part of the network specifically maintained for successful operation. Most of the network will likely be suitable in more than 20 years and entirely dependent on technological advances that negate current challenges. Moreover, some stressed that deployment time largely depends on what use-cases are considered. In this context, they point out that in a very restricted ODD, L4 vehicles like robotaxi, heavy-duty trucks, shuttles, and small robot delivery services are already operating on some public roads and sidewalks by giving examples. However, many have the same opinions that current L4 AVs are still under

[18] Relevant definitions and schematic representations of vehicle automation levels in accordance with SAE J3016 were also given in the survey to evaluate similar technology and eliminate the misconception about L4 AVs among the participants.

development and not safe enough for citywide operation, therefore at-scale commercialisation of L4 AVs will take much longer.

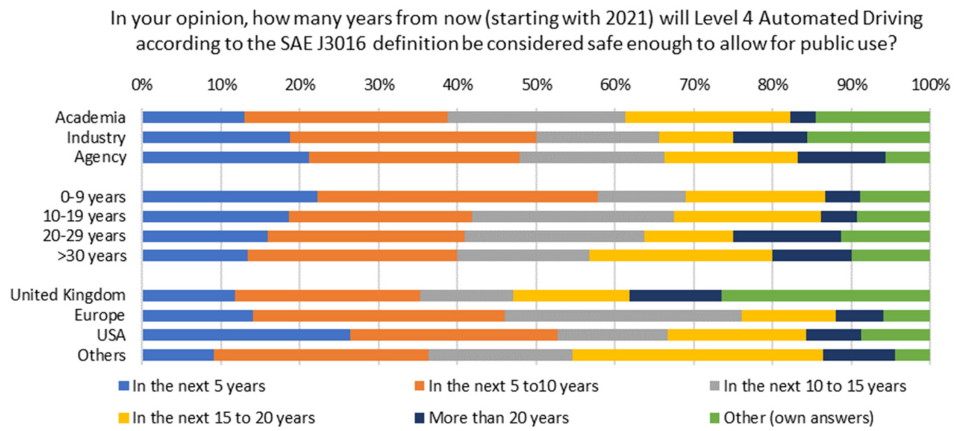

Figure 4.1 Responses to the question regarding the deployment time of L4 AVs for public use, by type of organisation, work experience, and place of residence (%).

In the next question, stakeholders were asked for their views on what types of roads should be considered safe for the operation of L4 automated driving during the initial stage of deployment. For this, by giving their definitions, respondents were asked to choose five different road types commonly adopted in the UK.[19] Multiple responses were allowed to this question, and a total of 313 responses were collected from 168 participants. The results show that over 60% of respondents believe motorways with or without active traffic management systems will likely be considered safe road types for the early operational phase of L4 AVs. The second most frequently selected option was minor roads, corresponding to 26.2% of respondents. This indicates that participants might have an opinion that minor roads will be more suitable for low-speed AVs operation from a safety point of view. Considering A and B roads, only 10% of respondents had an opinion that these roads would be safe for L4 operation. On closer inspection, the findings show that there is no remarkable difference in opinions between the groups (see **Figure 3.2)**. However, various explanations were made by the participants in the "other" option (17.3% of the total participants). These are:

[19] These are: *Motorways* that are high-traffic access-controlled roads where non-motorized vehicles and pedestrians are prohibited; *Smart Motorways* that employ active traffic management techniques to monitor and respond to fluctuating traffic conditions; *Radial roads (A-roads)* which are high-density traffic roads that connect motorways to distributor roads or urban centres; *Distributor roads (B-roads)* that connect A-roads with minor or local roads and generally have low to moderate capacity; and lastly *Minor roads (local roads)* that provide access to residential areas and other local developments.

- A group of respondents noted that the type and intended use of the L4 vehicle will be directly related to the areas in which it could safely operate, and most developers are focusing on a particular type of area for their early deployments. They commented that well-maintained protected environments such as dedicated lanes/roads and areas where pedestrians can be controlled will likely be considered safe road environments for AVs. In addition, some participants mainly from the industry highlighted the importance of the role of infrastructure and road environment in AV capabilities and stated that the initial deployment will take place on networks that prove their safety status. Some of these responses are: "*There is not a safe option, the environment needs to be built to accept these driverless vehicles. Until there is a sufficient level of control over the environment, it will not be safe. The environment also needs to be sure of an excellent standard level of maintenance"* and "*It depends less on the type of road than on the level of infrastructure development*".

- Some experts believe that AVs will only operate on limited-access motorways due to safety reasons. One respondent specifically stated that controlled long-distance motorways sections only be safe for the operation of AVs. Similarly, few respondents have a pessimistic view of AV technology on minor roads, commenting, "*We have very mixed modal traffic in the cities, which I do not think the AVs would be able to handle sufficiently well"* and *"There are unresolvable problems for the safe operation of L4 AVs in urban environments".* However, another group believe that for the early stage of deployment, low-speed models of L4 AVs will be available on private roads or geofenced areas (e.g. university campuses, theme parks, airports, manufacturing plants, etc.) rather than public roads for avoiding high risks.

- Unlike previous views, some academy participants argued that it depends on the safety assurance of the vehicles and one stated that *"If the vehicles can be assured to handle the specific hazards associated with each road type, then it may not matter. How can city authorities control which AVs might be used on their roads?".*

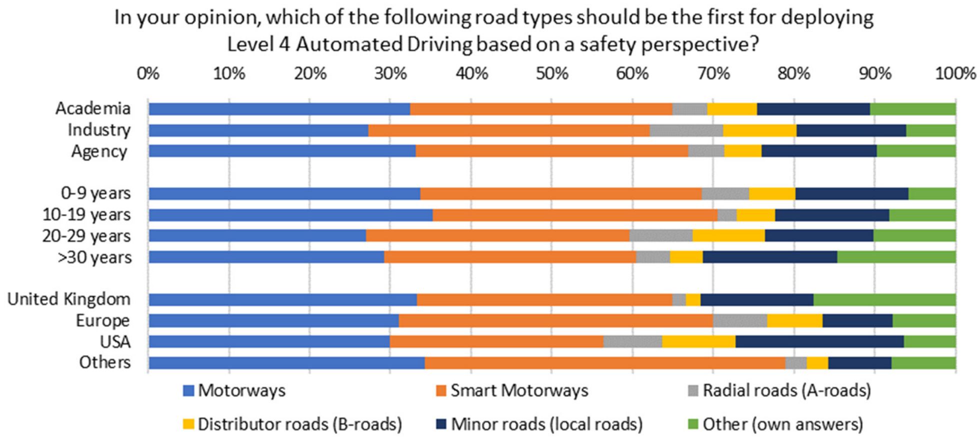

Figure 4.2 Responses to the question regarding the road types for the safe operation of L4 AVs, by type of organisation, work experience, and place of residence (%).

The last question was about the deployment model of L4 AVs. In this context, we asked the opinions of the stakeholders about three models that are likely to be encountered with the emergence of L4 automation technologies.[20] Responses (N=167) indicate a relatively dominant choice among the options. Half of the respondents (49.7%) stated that the public transport L4 AV service model will likely be available for public use firstly compared to other models. This opinion corresponds to around 60% of the UK respondents (see **Figure 4.3**). When the private (18.6%) and shared (19.2%) L4 AV models are considered, there is not any remarkable difference of opinion among the participants. However, closer inspection shows that respondents from the agency and industry groups do not have the same opinion about these two models compared to the academia group. They asserted that privately-owned L4 AVs will likely be generally available firstly compared to shared models. On the other hand, academia respondents chose the shared L4 AV model almost twice as many as the private L4 AV use model.

In addition to the use-cases given in the question, looking at the opinions expressed in the "other" option (12.6 % of respondents), respondents highlight automation in freight transport such as L4 automated freight trucks or commercial vehicles should not be overlooked. They suggested that commercial trucking owned by a company would probably be generally available first. In addition, some express that several models of L4 will likely be available on the market simultaneously.

[20] These are: 1) Privately owned L4 AV - You own the vehicle but will use the auto mode on certain road types and conditions; 2) Shared L4 AV - You do not own the vehicles, but you will/(not) share rides with strangers in certain areas; 3) Public transport L4 AV - Such as bus services on private lanes and certain routes.

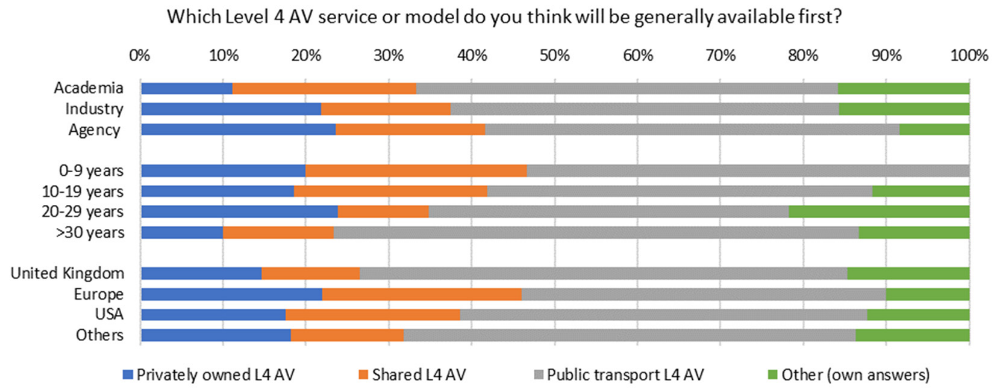

Figure 4.3 Responses to the question regarding the deployment model of L4 AVs, by type of organisation, work experience, and place of residence (%).

4.3.2 Do we need to certify roads for automated driving?

4.3.2.1 Rationale

There has been a growing literature in recent years recognising the importance of road infrastructure for the safe operation of automated driving. Many initiatives are investigating cost-effective ways to prepare road infrastructure to enable the transition process in which conventional and automated vehicles coexist, and they are putting out significant effort for collaborative and complementary approaches (ERTRAC, 2019). Among these efforts, a recent project has proposed a simple classification scheme to classify the capabilities of a road infrastructure to support and guide AVs (Carreras et al., 2018). In this context, five levels of infrastructure support for automated driving are defined and suggesting that these levels can be assigned to parts of the network to guide AVs and their operator on the "readiness" of the road network for the coming motorway automation era. Similarly, the concept of road classification (Poe, 2020; García et al., 2021) or certification (Cheon, 2003; Zhang, 2013; Issac, 2016; Huggins et al., 2017) has been specified by some researchers, however, the idea is mostly based on the digital infrastructure for motorways. Besides, the requirements of this concept can be idealistic, expensive, and difficult to meet for all roads, especially low-volume road types such as small city streets (Madadi, 2021).

Given the current ADS technologies, AVs capable of operating on all existing road networks in various environmental conditions are not expected to emerge in the short term, at least at an affordable price (Shladover and Bishop, 2015). Reliance on vehicle technology alone without infrastructure support may jeopardize the potential safety and efficiency gains of AVs. Therefore road certification or assessment of road infrastructure might play an important role in demonstrating suitable routes for the safe operation of AVs, as well as ensuring the safety of all road users in the early stages of deployment. This issue was handled in the survey by asking questions about the necessity of road assessment and the concept of road certification. This section presents the findings of the responses to these questions.

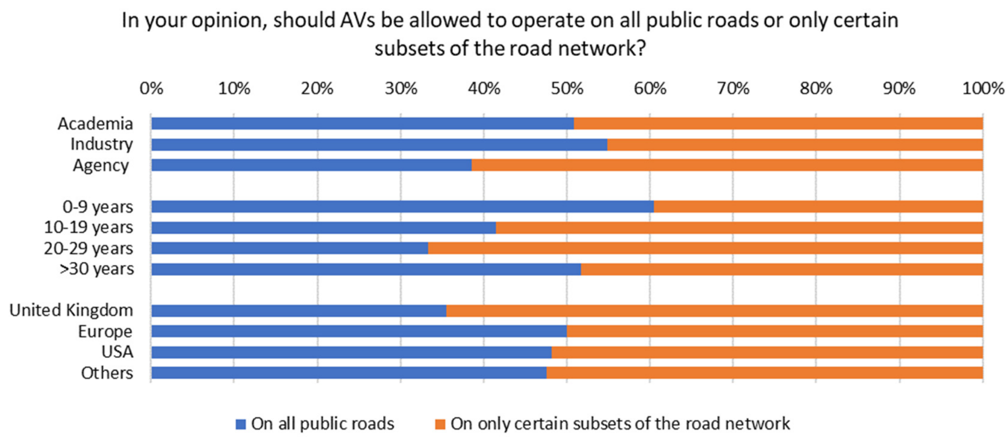

Figure 4.4 Responses to the question of allowing AV operation on road networks. by type of organisation, work experience, and place of residence (%).

4.3.2.2 Findings and interpretation of responses

The first question was whether AVs should be allowed to operate on all public roads or only certain subsets of the road network. Just over half of respondents (53.7%) stated that AVs should be allowed to operate on only certain subsets of the road network (N=162). Unlike this view, 46.3% of the participants argued that AVs should be allowed to operate on all public roads. This indicates that there is no dominant view from the participants regarding the question. **Figure 4.4** shows that only stakeholders from the agency group prominently stated that AVs should be allowed to operate on only certain subsets of the road network (61.4%). On the contrary, participants in academia (50.9%) and industry (54.8%) believe that AVs should be allowed to operate on all public roads. Also, those with relatively less work experience have the same view. Considering the residence-based grouping, around two-thirds (64.5%) of UK respondents believed AVs should only be allowed to operate on certain roads of the networks, whereas for other locations there was no clear agreement on this.

Also, we asked an additional question about what difficulties would arise in the implementation of this requirement for those who chose the option "*on only certain subsets of the road network*". Based on a review of the 81 responses to this question, the following key statements can be highlighted:

- A group of respondents mentioned that the methodology for selecting suitable road sections and subnets that can meet the requirements for the safe operation of AVs in the network will likely be very difficult and complex. Additionally, some participants emphasize the difficulties of balancing between the investment cost of required road infrastructure and meeting the user demands. Therefore, it would be difficult to support AV travel on all roads as the cost of building infrastructure for a limited number of vehicles operation might be expensive and not be feasible during their initial stages. Experts noted the challenges of how to design AV routes or catchment areas that correspond with the trips people want to make. Low consumer uptake of AV technology could be a problem if it can only be used in certain locations. They added that this would be triggered by the public perception that infrastructure would be only to support the wealthy that can afford the technology.

- Another frequently mentioned problem by participants is the requirement of effective enforcement. These respondents underline that policy development is needed for specific roadways until technology can be applied to any roadway/environment. In addition, few participants pointing out the necessity of public education about the capabilities and limitations of automated driving. Some of these responses are: "*ensuring that all users are aware of where AVs are permitted*", "*ensuring that AV operators know which roads are available to them and enforcement of those rules*", *"educating drivers about their responsibilities"*, and "*educating the public about safe operation and the boundaries required until greater acceptance"*.

- Some respondents noted that as an interim step, as automated driving technologies are not yet ready for use on all public roads, well-maintained, very accurately mapped, and controlled subsets of the network will reduce difficulties in deployment. However, according to some, this will require more advanced road quality management and maintenance than is available, and it will also be difficult to provide real-time data for road accessibility. Also they underlined that the difficulties of geofencing in practice and maintaining definitions of allowed zones, accounting for vehicles with different capabilities.

- In the context of geographic limitations, many participants pointed out the importance of clearly defining the boundaries within which the AV can operate safely. These participants mainly noted possible functional difficulties in operating L4 AVs. Some of the responses are: "*Difficulties could arise with these vehicles not being able to get to the full range of* *destinations they would like", "What happens at the edge of the ODD?*" and "*What to do if the beginning or ending of a trip is outside of the ODD?*". This is because in the period of transition, not all the networks may be AV ready, so it may be necessary for drivers to take over in areas where the road infrastructure or environmental conditions cannot support L4. For example, one expert noted that "*ODD must be clearly documented and be communicated to the vehicle owner. Violation of operations outside ODD needs to be prevented by technical means"*. However, some worry about managing the transition from automated to manual mode or manoeuvring between subsets and claim that some temporary deadlocks on roads may occur. Therefore, recognition and classification of subsets and ODDs would be difficult and segmented and differentiated driving in mixed usage areas could bring new uncertainties and risk developing new risk scenarios.

The second question in this thread concerned whether the necessity of an approach such as road certification or iRAP star rating[21] to assess the suitability of roads for the operation of AVs. More than half of the respondents either strongly agree (21.8%) or agree (32.7%) with the statement that roads need to be classified or properly evaluated for the AV operation (N=156). On the other hand, roughly one in seven respondents (14.7%) expressed a negative attitude towards the requirements of road certifications for AVs, and the proportion of those with a very negative attitude was only 4.5%. Moreover, a considerable number of participants (30.8%) have a neutral opinion regarding this subject. The proportions of the responses according to grouping variables are illustrated in **Figure 4.5**. Overall, the results were consistent across stakeholders, with no significant differences detected between grouping variables.[22] However, a prominent finding is that approximately 40% of the industry respondents strongly agree with the road assessment requirements for automated driving, while this is about 20% for academia and agency. Also, those who state that AVs should only be allowed to operate in certain subsets of the road network are more in favour of the necessity of the road certification approach. On the other hand, experts who argue that AVs should operate on all road networks are generally more neutral or negative towards the idea of road evaluation.

[21] Star ratings are based on road inspection data and provide a simple and objective measure of the level of safety which is 'built-in' to the road for vehicle occupants, motorcyclists, bicyclists, and pedestrians.
[22] According to the Kruskal Wallis H test, p value is greater than 0.05 for all grouping variables. ($\chi^2(2) = 1.948$, $p = 0.378$, with a mean rank score of 81.82 for Academia, 84.02 for Industry and 72.91 for Agency; $\chi^2(3) = 5.865$, $p = 0.118$, with a mean rank score of 73.45 for 0-9 years, 73.51 for 10-19 years, 90.67 for 20-29 years and 69.02 for >30 years; $\chi^2(3) = 0.547$, $p = 0.908$, with a mean rank score of 79.09 for United Kingdom, 80.33 for Europe, 75.80 for USA and 73.05 for Others).

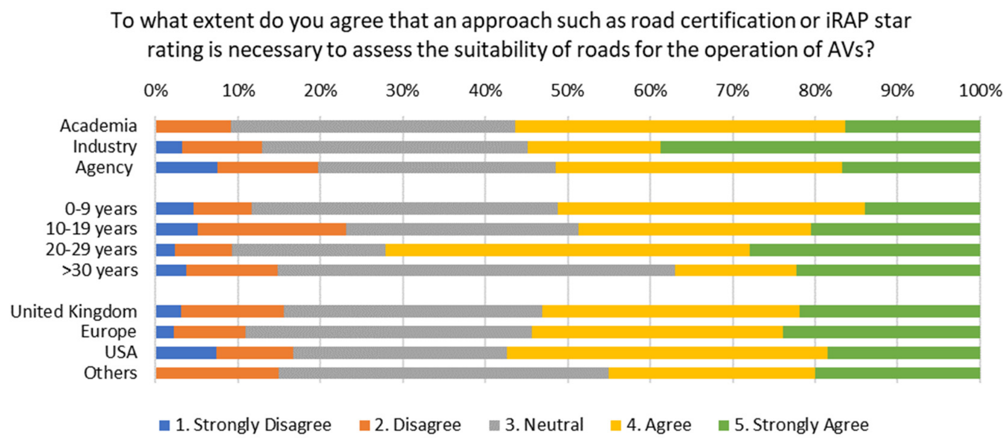

Figure 4.5 Responses to the question regarding the road evaluation approach for AVs operation, by type of organisation, work experience, and place of residence (%).

The findings of the previous questions suggest that assessing the suitability of roads for AVs is desirable among stakeholders. However, it is also important to discuss who should be responsible for this audit. Responses (N=159) indicate that the road agencies/administrations option is the relatively dominant choice among the possibilities. About half of the respondents (46.5%) suggest that road infrastructure readiness assessment for AV operation should be conducted by road agencies/administrations. This is followed by national authorities, which stated by 23.9% of respondents. On the other hand, a minority of participants stated that local authorities (6.9%) and the vehicle industry (5.0%) should be responsible for the assessment of the road infrastructure. **Figure 4.6** shows the distribution of responses according to the grouping variables for a deeper look at whether there is any difference of opinion among stakeholders. Although the results show that the most preferred option for all stakeholders is road administrations and operators, participants from the academia and industry did not have an explicit decision between the options of road agencies/administrations and national authorities. Similarly, UK and Europe respondents expressed divergent views on who should be responsible for the readiness assessment of road infrastructure, and no option is dominant.

Considering comments given the question (17.6%), most of the respondents underline the importance of collaboration between all stakeholders because they believe that one group is never going to have the funding and expertise necessary. They stated that a combination of organizations should be responsible for the readiness assessment of road infrastructure for automated driving operation. Some of these responses are: "*Should be a partnership between operators, authorities, and industry to fully understand all components of readiness*" and "*There needs to be a process that* *involves all stakeholders, including citizens (e.g. disability advisory groups). AV should be subjected to societal readiness assessment.".*

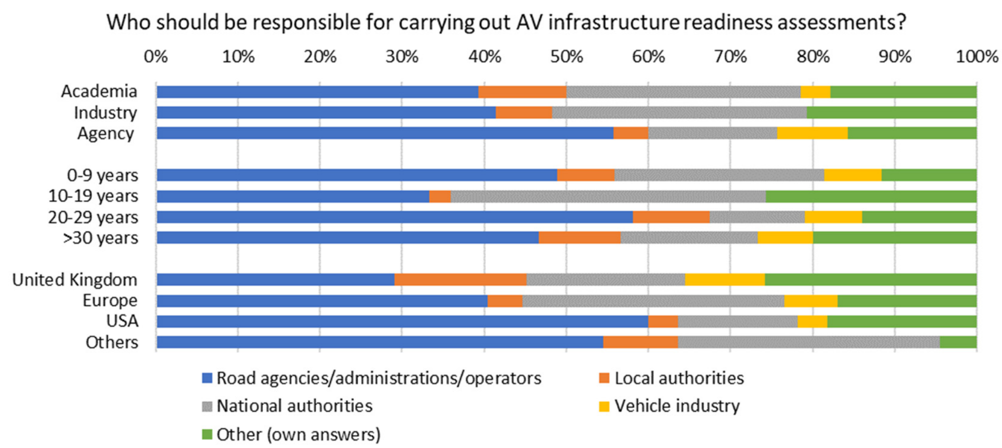

Figure 4.6 Responses to the question about who should be responsible for the assessment of roads for AV, by type of organisation, work experience, and place of residence (%).

Also, some noted that independent and accredited auditors should be responsible for road infrastructure readiness assessments, but that this requires a special assessment body. For example, a respondent from Europe suggests that there should be a system like a type of approval, and it should be in the hands of specific authorities under the responsibility of the transport or infrastructure ministry. Some of the other suggestions by participants are as follows: "*Non-governmental organisations founded by traffic victims and relatives recruiting technical experts*", "*A third party unbiased otherwise countries will try to 'compete' to show they are more ready than others*", and *"It should be done by national authorities and delegated agencies. Self-certification by road operators and compliance checks by public authorities could also be an option"*.

However, few respondents point out that rather than road infrastructure-based control, vehicles type approval standards should be needed for early AV deployments. In other words, these respondents are more in favour of vehicle readiness assessments for existing infrastructure. Some of these responses are: "*AV operators need to understand the vehicle ODD and should assess whether the intended deployment area is covered by the ODD*" and "*To approve usage on roads, the vehicle industry establishes an approved ODD at point of type approval meeting national authority standards*".

4.3.3 What are the basic road infrastructure elements for the safe operation of automated driving?

4.3.3.1 Rationale

The previous section presents the opinions of stakeholders on the need for road assessment for forthcoming automated driving and who should be responsible for these inspections. However, it is unclear how the evaluation should be conducted and how future technological requirements would be satisfied. These issues were also mentioned by stakeholders regarding difficulties that will arise when determining the suitable subsets of road networks for AV operation. However, current academic literature and field reports on this subject are limited (Tengilimoglu et al., 2023). Therefore, to understand the parameters that are likely to be critical in the assessment framework, we asked what the most important road infrastructure features for the safe operation of AVs are. Also in the next section, we asked the experts to rate possible road evaluation factors that could affect the safe operation of automated driving. Therefore, the findings in this section allow understanding of whether the parameters determined from the literature are compatible with the expert opinions.

4.3.3.2 Findings and interpretation of responses

In response to the questions of what are the three most significant (1) physical and (2) digital and operational road infrastructure attributes for the safe operation of AVs, a range of responses from experts and stakeholders was elicited. Word clouds were generated using NVivo 12 software to identify the most frequently used words in the responses (see **Figure 4.7**). This allowed us to identify emergent themes against the question. Then, we coded the responses of the experts to examine attributes and check how often respondents refer to a particular issue (Feng and Behar-Horenstein, 2019).

Table 4.2 shows the results by type of organizations represented by experts and frequency of response, created using the matrix encoding feature in NVivo. It is clearly seen from the table that the quality and conditions of road markings, and traffic signs are mostly stated by the stakeholders. Regarding road marking, many respondents underlined the optimum requirements and conditions (e.g. consistency, dimensions, colour, retro-reflectivity etc.) for the safe operation of AVs. Some respondents point out that lanes, pedestrian crossing zones, junctions and roundabouts should be very clearly marked. Similarly, participants expressed their views on how traffic signs should be for AVs. They noted the need to harmonise and standardise sign types (e.g. symbols, shapes, heights, positions, and directions) to improve the legibility of traffic signs. Also, it is widely stated that high-quality and frequent maintenance of road marking/signs can help overcome the challenges of vision technology. Moreover, the quality and consistency of road surface, and separated roads/lanes for AVs in the early phase of implementation are frequently mentioned by respondents. These are followed by the clear and simple configuration of intersections and roundabouts, low-speed limit adaptation and facilities for vulnerable road users□safety. An unobstructed sight line that simplifies the perception task for AVs at intersections and consistent intersection indicators are some of the examples cited by respondents. Furthermore, the importance of assessment and maintenance of road infrastructure is mentioned by some participants.

Figure 4.7 Word clouds for responses to the question on the most significant physical (left) and digital (right) road infrastructure attributes.

With regards to digital and operational road attributes, the importance of both short-range and long-range communication infrastructure and its quality and reliability is frequently stated by stakeholders. Some also point out the requirements of international standards and protocols for the communication of vehicles and infrastructures. High-definition (HD) maps with dynamic ground truth information and effective information systems for any roadworks or other temporary modifications follows connectivity in importance. Moreover, experts noted the requirements of clear landmarks and better positioning technologies.

On the other hand, a few participants claim that current roads need to handle AVs. For example, a respondent from the USA who represents the agency group stated that “*AVs need to be capable of working on existing roadways as it is without any dependency on I2V information provided by public agencies*”.

Table 4.2 Thematic representation of responses on key physical and digital infrastructure attributes for AVs to safe operation.

Physical and Environmental Factors	**Survey Respondent** **Agency (72)**	**Academia (64)**	**Industry (32)**	**Total (168)**
• Adverse Weather Conditions	3	2	0	5
• Assessment and Maintenance of Road Infrastructure	5	2	5	12
• Dedicated Lanes - Segregation of Roads for AVs	6	11	4	21
• Drainage Systems	0	1	1	2
• Events & Incidents (Accidents, Vehicle Breakdowns)	3	1	2	6
• Facilities for Vulnerable Road Users (VRUs) Safety	4	4	2	10
• Inductive Charging for Electric Vehicles	1	2	0	3
• Junctions - Intersections & Roundabout	7	6	4	17
• Lane Width	2	2	1	5
• Lighting Condition & Infrastructure	1	2	0	3
• Median & Crash Barriers	2	0	0	2
• Parking Facilities (Pick-up and Drop-off Points, Service Points etc.)	1	5	0	6
• Pavement (Road Surface Condition)	9	3	3	15
• Road Alignments (Horizontal & Vertical Curves)	0	2	0	2
• Road Edge Definition	1	0	2	3
• Road Geometric Design (Visibility & Consistency)	10	1	3	14
• Road Markings Quality and Conditions	40	22	16	78
• Roadside Condition (Surrounding Road Environment)	6	0	4	10
• Roadworks (Construction Zone)	2	0	4	6
• Safe Harbour Areas	2	1	0	3
• Shoulders (Widenings) for Minimum Risk Manoeuvre	3	1	1	5
• Special Structures (Bridge, Tunnel, Underpass etc.)	0	2	0	2
• Suitable Speed Limit Adaptation for AVs	3	5	4	12
• Traffic Condition & Flow	2	1	1	4
• Traffic Control Signals (Traffic Light)	5	5	2	12
• Traffic Signs (Road Signage)	25	9	8	42
Total number of respondents (unique)	61	43	25	129
Digital and Operational Factors				
• Connectivity - Comms. Infrastructure (Latency, Reliability, Speed etc.)	30	13	8	51
• Connectivity - Long-range Communication (Cellular, C-V2X, etc.)	7	4	4	15
• Connectivity - Short-range Communication (ITS-G5, V2X, etc.)	14	17	8	39
• Cyber-security & Data Management & Sharing & Standardization	11	6	3	20
• High-Definition Map & Digital Twin	22	16	10	48
• Information Systems (Weather, Work zone, Incident etc.)	15	8	4	27
• Positioning (Localisation)	7	5	5	17
• Remote Fleet Management System	4	4	3	11
• Sensors and Cameras	5	11	2	18
• Traffic Lights Control and Status Communication	4	7	3	14
• Traffic Management Centre and Control Systems	9	6	3	18
Total number of respondents (unique)	59	45	27	131

Overall, stakeholder responses to this question are consistent with the findings of Wang et al. (2022), who conducted an online survey and follow-up interviews with AV industry members alone in California, USA. Similar to their findings, our study indicates that road markings and traffic signs are one of the most critical road infrastructure elements for AVs and are agreed upon among stakeholders. However, with the transition to digitalisation, it is important to start questioning the role and necessity of these elements. Therefore, we asked the participants for their opinions on whether road markings and traffic signs will continue to maintain their importance in the digital twin era, which refers to the digitalisation of the road environment. Around three-fourths of the respondents (72.5%) either strongly agreed (41.9%) or agreed (30.6%) with the statement that road markings and traffic signs will continue to maintain their importance in the digital twin era. On the other hand, about one in seven respondents (13.8%) believe that the requirements of road markings and traffic signs will no longer be important with the digitalisation of road environment. **Figure 4.8** displays the proportion of the responses based on the grouping variables. The results in the figure show that around 80% of industry respondents agreed with this statement. This demonstrates that physical road infrastructure plays an important role in the safe operation of ADS technologies, and the industry acknowledges this. The results were consistent across stakeholders, with no significant differences detected between grouping variables.[23]

Also, we asked a question about the role of HD maps for AV deployments and which road features that support AV operation can be eliminated or reduced in importance by the availability of HD maps. Respondents often stated that HD maps are one of the most critical elements for the safe operation of AV and important for AV deployment as they provide important localisation attributes that can supplement perception sensors such as cameras, LiDAR, radar and ultrasonic. Some of the other comments by participants are as follows: "*HD maps are going to be critical, especially for identifying risks and path planning where existing sensors cannot see around corners; HD maps are extremely important for navigation and the immediate level as well as speed management and warning and regulatory control; HD maps have a role in answering the "Where am I?" question for AVs, but they must be up-to-date and current, connectivity is key for updates and real time interaction".*

[23] According to the Kruskal Wallis H test, p value is greater than 0.05 for all grouping variables. ($\chi^2(2) = 2.563$, $p = 0.278$, with a mean rank score of 77.37 for Academia, 91.58 for Industry and 78.04 for Agency; $\chi^2(3) = 1.913$, $p = 0.591$, with a mean rank score of 75.63 for 0-9 years, 75.48 for 10-19 years, 81.56 for 20-29 years and 87.95 for >30 years; $\chi^2(3) = 4.654$, $p = 0.199$, with a mean rank score of 81.90 for United Kingdom, 75.88 for Europe, 88.05 for USA and 65.95 for Others).

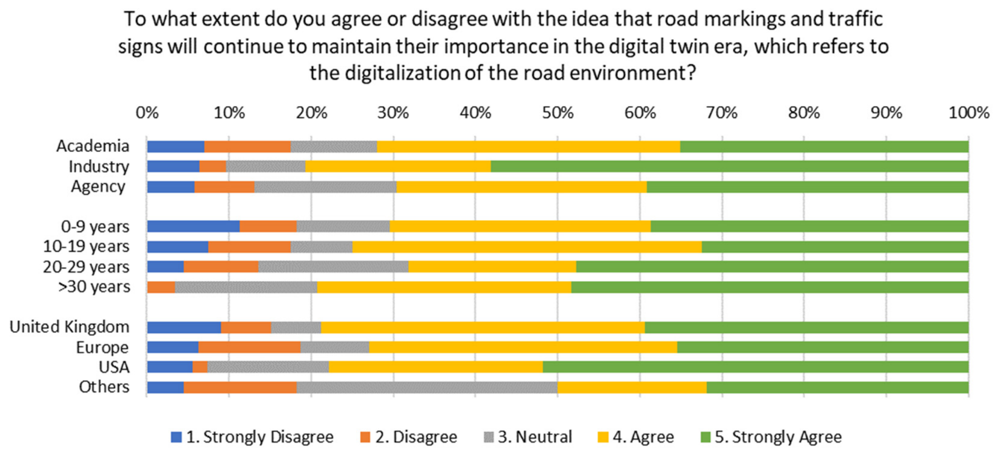

Figure 4.8 Responses to the question regarding the road signs and markings importance in the digitalisation era, by type of organisation, work experience, and place of residence.

Some experts noted that with up-to-date digital maps, some physical infrastructure requirements such as lane markings and signage can be gradually replaced by dynamic digital surrogates, thus reducing the physical maintenance of these features for AV operation would be possible. However, this requires all information to be digitally accessible in a reliable way and legally acceptable. Some commented that it is more around access to certified data/information that is more critical than the definition. This is because driving conditions change rapidly and so they need to be constantly updated and shared. They argue HD maps are not always up-to-date and currently lack sufficient updates and they hold no data on usage of roads or behaviours that would inform safer operation. Therefore, many believe that no physical road features can be eliminated for quite some time.

Given that there will always change in the city and be disruption to roads (e.g. due to blocking parked traffic, roadworks etc), respondents claim that AVs must be resilient enough to not completely depend on HD maps. Another common view is that physical road features will continue to maintain their importance as we will deal with mixed traffic for a very long time. Also, some underlined that both HD maps and existing road features (e.g. signs, markings) need to be "high quality" for redundancy. Therefore, the HD map itself will likely not be the solution without the support of physical road features.

Moreover, some of the points criticised by a few participants from the agency group are as follows: *"Do we have a commonly agreed standard on HD maps? Is there any communication from OEMs on the infrastructure needs to support their ODDs? Do we have a common picture on the digital twins?", "This is a question for the Industry,* *who is responsible for developing a vehicle that operates safely and efficiently. HD maps are clearly needed near term, but to what extent for what purpose is almost completely proprietary information held by private OEMs.",* and *"To date, most ADS developers have done their own mapping, so they do not "give away" what pieces of the map are needed for their vehicle to operate. They also clearly state they would not use a map created by the state agency because it would likely miss or not use the same formats/methods of data collection needed for their AV. Tricky spot to be in unless normalization occurs on data collection and needs.".*

4.3.4 What factors will need to be considered for the safe operation of L4 automated driving?

4.3.4.1 Rationale

In 2018, KPMG introduced a framework to assess the AV readiness of countries at a national level, since then the scope of components and the number of countries has increased each year. Singapore and the Netherlands are the countries with the highest scores according to the latest version of the index, with their high-quality road infrastructure (KPMG International, 2020). However, the *"quality of roads"* indicator used in the index is subject to some criticism as to whether it is the optimum indicator (Visser, 2019). The common hypothesis is that AVs operate safely on high-quality roads, and countries with poor road infrastructure are predicted to be slow to adopt AVs. The indicator is taken from the road quality index in the World Economic Forum's global competitiveness report, and this particular index is based on the views of local business managers of road networks (World Economic Forum, 2019). Visser (2019) highlights that there are obvious constraints on how managers observe and shape their views on the quality of roads. Therefore, concrete evidence should be collected and preferred using an appropriate methodology rather than subjective opinions (FTIA, 2021). For city-level AV readiness, for example, Khan et al., (2019) have assessed the readiness level of cities in the USA by following a similar strategy with KPMG and focusing on aggregated level criteria. On the other hand, limited research has been conducted so far to investigate which roads are relatively suitable for AVs within the city network (Soteropoulos et al., 2020). This requires a disaggregated level analysis and raises questions about what factors will need to be considered in the assessment framework. This section presents possible factors and potential challenges on the infrastructure side of vehicle automation.

4.3.4.2 Findings and interpretation of responses

As noted earlier, respondents were asked to evaluate possible factors that will likely be important for road readiness assessment. For this, a scoring system of not at all important to extremely important (5-point Likert scale) was used to provide quantitative feedback on a total of thirty potential road safety assessment factors or infrastructure elements, which can affect the safe operation of L4 automated driving for the foreseeable future.[24] **Table 4.3** presents the means, standard deviations (SD) of questionnaire items, and order of importance according to the mean of the items. The findings in the table indicate that all possible factors identified in the relevant literature are important according to the stakeholders, having greater than 3 (i.e. important). The mean values of 18 out of 30 items were calculated as greater than 4 (i.e. very important). Among these, positioning and roadworks are the most highly ranked criteria for automated driving operation according to experts. Facilities for vulnerable road users, intersection type and its quality, and HD maps are following these factors. On the other hand, road drainage system quality, availability of fibre optic communication along with the road network and presence of broadcast communication received relatively fewer votes from the respondents compared to the other parameters.

Interestingly, the findings reveal that stakeholders from academia, industry and agency groups have similar views on most of the criteria. When we look at the first 10 parameters of 3 groups, it is seen that 7 parameters are the same. Although the ordering of the factors differed slightly between the grouping variables, the Kruskal-Wallis H test results show that there is no statistically significant difference in attitudes towards potential factors between both the type of organisation and place of residence groups ($p>0.05$ for all factors). Participants were also asked whether there were any other aspects of the road infrastructure challenges for automated driving tasks or automated driving systems functions that were not included in this survey. Some of the responses include: "*smart devices at road construction sites (e.g. worker vests, connected traffic cones, availability of construction information from government server); a national or global data system for facilitating AV operations beyond localised, spot deployments; guidance and standardization of policies regarding deployment for ensuring the interoperability of all AVs and the supporting digital infrastructure*".

[24] It should be noted that different use-cases, different automation levels, and different mobility models might require different infrastructure requirements, including different functionalities and services. Therefore, it is not possible to foresee all configurations of road infrastructure that AVs will have in the future. For this reason, this question focused on generic driving task capabilities of highly automated vehicles (SAE Level 4) equipped with automated driving systems rather than focusing on specific use-case scenarios.

Table 4.3 Ranking of potential factors that affect the safe operation of L4 automated driving (N=160).

Rank	Factors	Rating*						Mean	SD
		1	2	3	4	5	DN		
1	Positioning/ localisation (e.g. Galileo, Glonass and GPS signal accuracy, presence of reference station for localisation assistance, etc.)	0	2	15	31	100	12	4.547	0.733
2	Roadworks (e.g. presence of temporary road work zones / construction zone)	0	4	12	43	97	4	4.494	0.749
3	Facilities for vulnerable road users (e.g. pedestrian crossing type, availability of segregated bicycle lane, pavement configuration and width etc.)	1	1	22	36	97	3	4.446	0.804
4	Intersection type and its quality (e.g. junction type, presence of intersection channelisation, forced lane merges, property access density etc.)	1	5	16	35	97	6	4.442	0.857
5	High-Definition maps (e.g. availability of HD maps and its content)	1	4	13	50	83	9	4.391	0.809
6	Roadway users (e.g. different vehicle types (cars, trucks, buses etc.), pedestrians, cyclists, powered two-wheelers, etc.)	2	6	16	38	93	5	4.381	0.915
7	Road details and context (e.g. road types, number of lanes, road access etc.)	1	7	16	46	87	3	4.344	0.884
8	Special event (e.g. presence of incidents, accident, emergency vehicles, vehicle breakdowns etc.)	1	3	20	59	74	3	4.287	0.809
9	Road geometry challenges (e.g. low curve radius, hilly roads, narrow lane width etc.)	1	3	24	52	77	3	4.280	0.839
10	Road markings quality and its readability (e.g. lane marking condition, presence of ghost markings on the road surface etc.)	1	12	17	40	86	4	4.269	0.977
11	Special road section/ road structure challenge (e.g. presence of tunnel or underpass, bridge or grade-separated structures, toll plazas etc.)	1	9	23	48	74	5	4.194	0.943
12	Road signs and signals visibility (e.g. readability and detectability of traffic signs by humans and sensors, traffic lights, variable message signs, etc.)	4	14	13	41	83	5	4.194	1.089
13	Information systems (e.g. real-time information on congestion, weather condition, incidents, roadworks, digital traffic rules and regulations etc.)	1	6	28	47	72	6	4.188	0.911
14	Weather condition (e.g. poor visibility due to bad weather like rain, snow, fog etc.)	1	7	27	53	67	5	4.148	0.910

(continued on next page)

Table 4.3 (continued)

Rank	Factors	Rating*						Mean	SD
		1	2	3	4	5	DN		
15	Traffic management centre and control (e.g. provide real-time temporary lane closures, dynamic traffic signs, variable speed limits etc.)	0	9	29	50	67	5	4.129	0.920
16	Maximum speed limit (e.g. affecting response time of automated vehicle)	2	7	32	42	72	5	4.129	0.978
17	2G, 3G, 4G - mobile network coverage along with the road network	1	6	26	51	55	21	4.101	0.903
18	5G network coverage along with the road network	2	8	22	49	57	22	4.094	0.965
19	Road edges condition and median type (e.g. discontinuous or damaged road edges, median types/widths, presence of on-road parking facilities etc.)	0	10	36	55	52	7	3.974	0.917
20	Road surface condition (e.g. road surface type, presence of potholes, ruts, and uneven road surface etc.)	2	14	37	60	42	5	3.813	0.982
21	Lighting condition / illumination (e.g. glare due to sunshine or other cars, poor visibility due to darkness, availability of street lighting etc.)	2	13	45	49	46	5	3.800	1.003
22	Presence of roadside units (e.g. 5.9 GHz dedicated short-range communication)	5	7	33	46	35	34	3.786	1.044
23	Road furniture and roadside occlusions (e.g. dense vegetation surrounding road, bins, billboards, streetlamps, signage, traffic lights, etc.)	3	14	36	63	38	6	3.773	0.985
24	Traffic condition (e.g. volume of traffic, flow rate, congestion etc.)	4	15	45	47	45	4	3.731	1.062
25	Remote fleet management system (e.g. vehicle/ fleet supervision with operator in control centre)	4	9	49	52	35	11	3.705	0.980
26	Infrastructure maintenance frequency and presence of asset management and maintenance strategy	7	14	45	42	45	7	3.680	1.128
27	Road accident severity (e.g. number and location of fatalities and serious injuries)	7	15	41	49	41	7	3.667	1.112
28	Road drainage system quality (e.g. surface water)	4	22	49	50	25	10	3.467	1.024
29	Availability of fibre optic along with the road network	11	17	38	26	32	36	3.411	1.261
30	Presence of broadcast communication (e.g. DAB, FM)	14	26	35	29	20	36	3.121	1.245

*(5-point Likert scale where 1 = ‘Not At All Important’, 2 = ‘Low Importance’, 3 = ‘Importance’, 4 = ‘Very Important’ and 5 = ‘Extremely Important’ and DN = Don’t Know)

Notwithstanding, some experts criticised the concept of the survey regarding the infrastructure requirements for automated driving. They claim that AV technology is still immature, and it is not yet clear what the infrastructure requirements are for a safe L4 AV. For example, one respondent stated that "*We are still in the development and testing phase, so it is not possible to predict now which technologies will prove successful and therefore which infrastructure needs".* Another respondent points out the importance of societal benefits of emerging technologies and noted that "*We do not need to be facilitating AV deployment until it proves it is beneficial to overall community goals. If it is not, then why should governments be doing anything to facilitate deployment?"*. Lastly, an academy respondent criticised the road evaluation approach, commenting, *"The questionnaire assumes most of the provision of information should be supplied by the road or road operators. AVs should handle transient hazards and make the best use of all available information but not be dependent on it. Even if an AV does not get a 5G warning signal for road works the public will expect it to use its own detection and recognition systems and respond appropriately".*

4.4 Conclusions and recommendations

This study focused on the road infrastructure side of automated driving and aimed to clarify potential infrastructure challenges requiring considerations in the early stages of L4 AV deployment through an online survey of 168 experts and stakeholders from 29 countries. The research focused on four topics: (1) deployment paths of L4 AVs, (2) the concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operation of L4 automated driving. In the light of these topics, the convergence and divergence of opinions among different types of stakeholders were presented.

There are several factors that have a crucial role in understanding the deployment paths of L4 AVs: types and purpose of AVs, operating zones, compliance and enforcement strategies, technological advancements, and infrastructure investment are the most important among these. There was guarded optimism that L4 AVs with carefully defined ODDs will likely be available for public use within the next decade, but only on small sections of road networks. This is mainly because neither current technology nor the road infrastructure is ready for the network wide operation of AVs. This raises the important question of which roads or areas would be conducive to AV use. There is a difference in opinions regarding the types of roads to be considered safe for the initial phase of L4 automated driving. In general, motorways are expected to be early cases for the implementation of AVs because of their controllable and well-maintained driving environment. However, there were also some supports for the earliest implementation for low-speed urban areas with supporting infrastructure. In a way, these results suggest that there will likely be different types of L4 AV deployments that operate in different areas of the network (Shladover, 2022). This uncertainty in deployment paths will present challenges for road agencies and city authorities in identifying the infrastructure requirements of different technologies and their integration into future urban networks. The wider impacts of AVs could also be quite different depending on the deployment paths.

There was consensus among all stakeholders about the importance of road infrastructure and the surrounding environment for automated driving. In parallel with this, there was clear support for the assessment of roads for automated driving operation, especially during the early stages of deployment. There is a broad consensus among stakeholders that infrastructure owners and operators should be responsible for this assessment, although there were some suggestions in favour of independent organisations and accredited auditors, too. There are also some difficulties in evaluating roads and implementing operation restrictions. In particular, recognition and classification of subsets and ODDs could be difficult. Segmented and different levels of automated driving in mixed usage areas could bring new uncertainties and develop new risk scenarios. Therefore, cooperation and fair sharing of responsibilities among all relevant stakeholders are important to reduce possible risks (García et al., 2021). On the other hand, there were a few strong opposition to road assessment, on two separate grounds: that vehicle automation has not been proven to be beneficial yet, or that the manufacturers should be responsible for safety assurances of these vehicles on roads where they choose to operate. Besides, certification of roads will entail more responsibility and extra costs for the existing road authorities.

Given the "mismatches" noted above, policymakers and transport authorities should start to consider their strategic positions for this new category of road users. They need to consider early actions to mitigate possible negative outcomes from vehicle automation while deciding to support the infrastructure-related requirements of AVs models. However, this may present new challenges for authorities in determining what specific types of action are necessary and appropriate to ensure that automated driving supports sustainable transport planning in cities (Wadud et al., 2016; Fraedrich et al., 2019). This might be particularly important because motorways are seen as the safest roads by many experts for initial deployments. If the AV industry focuses solely on "highway automation" due to limited investment in urban roads, the expected potential benefits of AVs in urban areas (e.g. increasing the mobility of the disabled, reducing the demand for parking, providing affordable and accessible mobility for the community, etc.) might not be realised soon (Fagnant and Kockelman, 2015; Litman, 2020). This may also affect future vehicle ownership patterns, as shared AV models are expected to be more effective in urban areas due to the potential patronage of users

(Wadud and Mattioli, 2021). Thus, initiatives should begin by investigating potential applications and their effects on cost structures, transportation, and the environment.

Regarding the basic infrastructure attributes, this study provides expert insights on physical and digital road infrastructure features that may be critical to the safe operation of automated driving. It is clear that most of the measures regarding the physical road infrastructure for conventional vehicles (e.g. clear and visible road markings and traffic signs) will also continue to be important for automated driving. This highlights the importance of maintenance strategies for road infrastructure for both existing road users and emerging technologies. However, new challenges are expected to emerge, particularly on the digital side of road infrastructure, which must be overcome before AVs starts operating on the roads. Reliable and cyber-secure communication and information systems, localisation support infrastructure and special equipment for roadworks areas are only some examples. Therefore, collaborations between stakeholders and standardisations of the basic requirements are necessary not only to build trust but also to verify that AVs and operation environments are safe. Although the lack of cooperation among stakeholders – especially between the technology industry and the road authorities – is crucial, progress has been slow so far.

In this context, the study presented experts' views on potential factors (e.g. proper delineation of road marking, quality of road surface, lighting, cellular network coverage etc.) that can be critical for the safe operation of automated driving. Responses revealed that stakeholders have similar opinions on most of the identified factors. However, addressing infrastructure-related requirements for all these factors may not be possible and feasible in the short term. Given the current state of the road and city authorities, it is unclear how they will find sufficient funds for AV-related investments, including resources to provide any new infrastructure, if needed (Saeed, 2019). In addition, some dynamic driving scenario-based factors such as interaction with vulnerable road users, accident response or emergency vehicle operations are difficult to overcome with infrastructure improvements. Therefore, AVs must demonstrate their ability to operate safely in some conditions without infrastructure support. For this reason, a combination of smarter vehicles, infrastructure modification and improved operations and maintenance practices will be required for the roads to be ready for automated driving. A structured and incremental approach is needed for achieving readiness for automated driving (Somers, 2019).

On the other hand, most of the road network will probably not be able to support AV operations unless the necessary investment are made (Soteropoulos et al., 2020; Manivasakan et al., 2021). In other words, AVs will likely not be available on all road networks due to the need for a certain level of technical maturity and infrastructure support. This will likely lead to equity issues in access to "AV compatible roads".

Therefore, equity in accessibility to AV services should need to be carefully evaluated by the authorities. This seems to be particularly important because the survey shows that the equity concerns have not been well addressed so far. If we consider road assessment in general, the challenge is not only to determine what roads should AVs be allowed to operate, but also on what roads will they be able to operate. The findings of this study can be used to develop a classification scheme that categorises and harmonises the capabilities of a road infrastructure to support and guide AVs.

Some issues are still unresolved and require further investigation. For example, the importance of almost all items asked in the survey appears to depend on the specific application of AV technologies. As such, future research should address each possible model of automated driving use cases. For instance, automated freight vehicles are getting increasing attention in the market and may have different infrastructure-based requirements for safe operation. It is also worth noting that the current level of development of AV technologies and road infrastructure varies between countries (KPMG International, 2020), so priorities regarding requirements and investments may vary. The different political structures of each country and the limits of what is politically possible, may affect the priorities and actions, too. Given the majority of the responses were from the Western industrialized economies, such regional differences in priorities and opinions may have been under-represented here and requires attention in future.

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CHAPTER 5

Are current roads ready for highly automated driving? A conceptual model for road readiness for AVs applied to the UK city of Leeds

Abstract: The emergence of Automated Vehicles (AVs) promises a transformative impact on future travel patterns and consequently on the design of urban spaces. Despite the revolutionary prospects, the integration of AVs into existing and near-future road infrastructures presents a complex and unexplored challenge. This paper addresses this critical gap by introducing a novel and comprehensive assessment framework designed to evaluate the readiness of road networks for highly automated vehicles (Level 4 AV) operation. Recognising the uncertainties in automated driving technologies, the study defines two distinct AV capability levels and adopts three potential network scenarios to explore varied technological advancement perspectives and their impact on the suitability of the current road network for their use. This multi-scenario approach offers a holistic viewpoint on the prospective circumstances and potential strategies for AV deployment. The proposed framework was empirically applied in a specific area in Leeds, United Kingdom, demonstrating its practical applicability. The findings of this research offer vital insights that contribute to the understanding of AV integration into road networks and support decision-makers and transport planners in developing informed and future-oriented policies, regulations, and guidelines.

Keywords: Automated vehicles, Road readiness, Index, Evaluation framework, Operational design domain

5.1 Introduction

Over the past decade, Automated Vehicles (AVs) have transitioned from a conceptual possibility to an actual presence on public roads because of significant investments and advances in machine learning, sensor technology and computing (International Transport Forum, 2023b). AVs offer various potential benefits, including enhancing road safety, increasing people's accessibility, and reducing energy consumption (Wadud et al., 2016; Milakis et al., 2017). However, realising these benefits hinges on ensuring the safety of the Automated Driving Systems (ADS), typically referenced when discussing Level 3 automation and above. AVs are often described by SAE automation levels, which describe the capabilities of the vehicle in terms of its ability to perform some or all of the driving tasks without human intervention (SAE International, 2021). Levels 1 and 2 of driving automation, which include driver assistance features such as lane centring and/or adaptive cruise control, have been commercially available for several years. More recently, many automakers have introduced Level 3 vehicles, which offer partial automation under certain conditions (Bishop, 2024). At this level, the ADSs take over all driving tasks when engaged, reducing the need for continuous human supervision. However, the higher levels of automation, where human intervention is required only in certain situations (Level 4, hereafter L4) or is not required at all (L5), are still in the early stages, with widespread adoption expected to take decades (Litman, 2023).

Highly automated vehicles are undergoing extensive trials in numerous developed nations globally. Major automobile manufacturers, alongside tech giants and promising startups, have embarked on a race to achieve the pinnacle of vehicle automation. While the design concepts differ, all these vehicles rely on the use of a set of sensors to perceive the environment, advanced software to process inputs and decide the vehicle's path, and a set of actuators to act on decisions (Wevolver, 2020). Yet, their automation capabilities differ considerably based on their Operational Design Domain (ODD) due to variations in the type of service they provide or the specific sensors they are equipped with. Broadly, the ODD is characterised as the specific operational conditions under which a particular driving automation system is designed to function. This encompasses factors like environmental constraints, geographical boundaries, time-of-day limitations, and specific traffic or road attributes (SAE International, 2021).

In practical terms, the ODD is instrumental in delineating where an AV's automated functionalities can be effectively employed. Therefore, there is a growing interest in the scientific community to develop ODD taxonomies that define the conditions under which ADSs might operate (Thorn et al., 2018; BSI, 2020; AVSC, 2020; Mendiboure et al., 2023). In this context, there is an emphasis on exploring which factors have an impact on the functioning of AVs. This exploration can be done through empirical investigations of AV trials (Ramanagopal et al., 2018; Klauer et al., 2023) or by analysing AV-involved accident or disengagement data provided by AV manufacturers (Boggs et al., 2020; Ye et al., 2021). Furthermore, significant strides have been made in recent years towards developing risk assessment and safety verification methods for automated driving systems. Among these advancements, scenario-based strategies stand out; they evaluate the safety of AVs by testing individual traffic situations through virtual simulations against a variety of variables (Riedmaier et al., 2020). Apart from this, few studies have introduced models that evaluate the complexity of driving environments or scenarios of traffic based on sensory data of AVs (Wang et al., 2018; Li et al., 2019; Cheng et al., 2022).

On the other side, there is an expectation that AVs require a compatible road infrastructure that provides them with an environment fit for their use (Tsigdinos et al., 2021). However, current specifications lack information on the necessary infrastructure to support each level of automation or service model. The main efforts to date predominantly adopt a vehicle-centric perspective, with safety and reliability issues primarily viewed from the vehicle's standpoint. The role of infrastructure in the deployment of automated driving has often been relegated to the background (Tengilimoglu et al., 2023a). In practice, the road network is a mosaic of varied road types with various conditions, and AVs must transition between them seamlessly during their operation (Chen et al., 2023). It is therefore important for authorities and road agencies to know how ready their current road infrastructure is for safe automated driving.

In addition, for AVs to truly emerge as viable mobility options, they must operate not just in regions where their advanced capabilities have been rigorously tested, but also beyond. Therefore, developing and implementing an assessment framework to measure the readiness of the infrastructure for AVs can assist authorities in identifying areas that need to be addressed, as well as planning for the necessary infrastructure upgrades. This is pivotal as L4 AVs can only achieve full operational capability under specific and limited conditions, which requires a clear understanding of the infrastructure required. Realising this objective, however, is not straightforward, requiring significant effort and financial support (Saeed, 2019; Tengilimoglu et al., 2023b).

Various road categories, their specific design requirements, traffic loads and complexities should be evaluated separately and from different angles to prepare the roads for AVs (Ulrich et al., 2020). However, studies to date have tended to focus on the potential infrastructure requirements for automated driving based on experts' views (Tengilimoglu et al., 2023a) and presented these as a desirable infrastructure characteristic rather than analyse in detail the relationship between road infrastructure and the risk to performance of AVs (Carreras et al., 2018). This is mainly due to the lack of sufficient data to establish an empirical model for this relationship and differences in the technologies adopted in AVs. Therefore, there is currently very limited research on the assessment side of road infrastructure for AVs (Konstantinopoulou and Ljubotina, 2020) and therefore the suitability of road networks for the operation of AVs. Particularly, few studies have been conducted to systematically evaluate the suitability of road networks in urban areas for L4 AV operation and the potential impact of road infrastructure on the travel demand and network performance side. Most of the prior studies have predominantly focused on motorways in relation to automated driving.

Therefore, this study seeks to address the existing gaps in the field. The primary objective is to establish an assessment framework to determine the readiness of urban road infrastructure for the safe deployment of L4 AVs. Moving beyond prior research approaches that overlooked variations in AVs, considering uncertainties in automated driving technologies, this study highlights two distinct AV capability levels. Additionally, it adopts three potential network scenarios, depending on the technical capability of the AV. This approach moves beyond the current literature on presenting infrastructure requirements, instead leveraging expert opinions to critically evaluate the importance of various infrastructure elements for AV operations, and thereby determining the suitability of specific road sections for such technologies. To the best of the authors' knowledge, this study is the first exploratory research that evaluates the compatibility of road infrastructure and the surrounding environment for automated driving based on the opinions of key stakeholders and experts in the field. In the absence of actual AV trials, which can be resource-intensive, such an assessment framework might offer a starting point for authorities to assess road segment suitability within the network. In addition, through the visualisation of assessment outputs, potential operational zones for initial AV deployments can be identified to prioritise road user safety. As such the aim of this study is not only to deepen the understanding of infrastructure readiness but also to provide guidance for policymakers and road agencies as they navigate the impending transformation in transport: the broader adoption of L4 AVs.

The organisation of the rest of this paper is as follows: **Section 5.2** summarises prior studies regarding road assessment and classification concepts. **Section 5.3** introduces the concept of an assessment framework for evaluating the readiness level of roads for automated driving. It also offers a brief review of the current literature, addressing the basic principle of AVs and the challenges and factors that impact their performance. In **Section 5.4**, the practical application of this framework is explored, with a focus placed on the selected case study area. This section provides an in-depth description of the utilised data and methodological approaches for indicators. Then, it presents insights from this implementation as well as recommendations for future AV infrastructure development. The final **Section 5.5** presents the conclusions drawn from this research, coupled with recommendations for prospective studies in this arena.

5.2 Literature review

In the existing literature, one can find infrastructure-related frameworks designed for pedestrian and bicycle traffic. These frameworks guide the identification of optimal locations for investment, with the aim of maximising societal benefits. These studies often construct walkability (e.g. Su et al., 2019; Zhao et al., 2019) or bike-ability indices (e.g. Winters et al., 2013; Krenn et al., 2015; Arellana et al., 2020). Within these frameworks, various components are calculated for specified reference spaces, such as grid cells or street segments. These are then merged into a singular value, commonly referred to as an "index", which represents the area's suitability for cycling or walking. In a similar context, this approach can be applied to the road network in a given area to assess its suitability for the operation of AVs considering different use cases or levels of automation (Soteropoulos et al., 2020; Tsigdinos et al., 2021).

While several indices have been introduced in the literature to assess the readiness of countries (KPMG International, 2020) or cities (Khan et al., 2019; Jiang et al., 2022) for AV operations, they primarily offer aggregated insights. There is a lack of research investigating which roads are relatively suitable for AVs within an urban network. To achieve this, a more detailed, disaggregated analysis is essential. At such a level, road assessment programs have been already developed worldwide (e.g. the iRAP Star Rating of roads for safety). These protocols often assign ratings to roads based on the presence or absence of key safety-related design features and are validated by recorded accident databases. Such protocols can be adapted to rate the ability of roads to support AVs (Konstantinopoulou and Ljubotina, 2020). However, there is currently an insufficient amount of data on AVs to build an empirical model for this relationship.

As such, early research in this domain has largely relied on the opinions of experts, seeking to chart the unknown terrain of AVs. For example, Nitsche et al. (2014) pioneered the concept of an evaluation framework of road infrastructure for AVs. The study outlined infrastructure-related requirements for highly automated driving, focusing on 14 factors that impact the efficacy of three specific ADS groups: lane assistance, collision avoidance, and speed control systems. Among these factors, the complexity of the urban road environment, quality of lane markings, their visibility and harmonization, temporary road work zones, and discontinuous or damaged road edges or kerbs have been identified as the main challenges by experts. Similarly, Madadi et al. (2018) have attempted to predict potentially challenging road and intersection scenarios for automated driving, as well as the pertinent factors involved. This endeavour was grounded in workshops with experts. They presented experts with images of specific locales, prompting direct questions. Based on the experts' feedback, the authors discerned correlations between certain road attributes and their appropriateness for L3-4 AVs.

Another relevant research strategy has been to use the definition of the vehicles' ODDs as a starting point for defining the suitable road sections for automated driving. This is because various infrastructure and environmental conditions significantly impact an AV's interpretation of its environment, exposing it to operational limitations. Within this framework, a couple of studies have proposed classification schemes that categorise the capabilities of road infrastructure to support and inform AVs about the functionalities offered by different road facilities (Carreras et al., 2018; Poe, 2020; García et al., 2021). These classifications, called Level of Service for Automated Driving, range from "A" (indicating a road segment is compatible with most vehicle ODDs) to "E" (signifying the road segment has minimal compatibility with most automation systems). However, a notable limitation in these classification systems is the tendency to assign existing road infrastructures a uniform low score, neglecting the diverse characteristics and distinctions between them.

On a more detailed scale, a few initiatives have pioneered inspection criteria for assessing the readiness of motorways and arterial roads for automated driving. Among them, for example, the Saving Lives Assessing and Improving TEN-T Road Network Safety (SLAIN) project evaluated the physical road infrastructure of certain road sections across four European countries: Croatia, Greece, Italy and Spain (Konstantinopoulou et al., 2020). Similarly, Austroads, which is a road transport agency, carried out an extensive field audit of Australian and New Zealand highways to assess their readiness for active safety systems and automated driving (Somers, 2019). These studies, grounded in experimentation, aimed to identify the performance characteristics of traffic signs and road markings that might influence machine-vision systems' recognition capabilities. Additionally, in 2021, the Finnish Transport Infrastructure Agency initiated a project focusing on infrastructure support and classification for automated driving on Finnish motorways (FTIA, 2021). The project assessed the suitability of a motorway section for operating L3 and L4 AVs. In a separate study by Carter et al. (2019), certain operational issues with AVs were identified as risk factors and accordingly, potentially hazardous locations along the Route 65 Corridor, which is representative of regional highway corridors, located outside the City of Pittsburgh, USA.

Regarding the readiness index for urban roads, Soteropoulos et al. (2020) have developed a framework to assess the suitability of roads in the network of Vienna for L4 AVs from a technological standpoint. This framework, mainly relying on publicly available data, combines the challenges faced by ADSs in their current technical state and considers diverse street space contexts. The study found that urban motorways and expressways have relatively high values of the automated drivability index. On the other hand, the lowest values of the index were observed in the central districts of the city, where often complex intersections, narrow streets as well as pedestrian crossings or non-structural separated bicycle infrastructure on the roadway are present. For a similar purpose, Cucor et al. (2022) have recently introduced an assessment framework to score segments of physical and digital infrastructure based on their features to expedite the deployment of AVs. This framework is elucidated through its application on a public transport route in Zilina, Slovakia. Utilising both connectivity and positioning data alongside image data, the study identified infrastructure readiness and challenges.

In summarising the literature, current research is still evolving in terms of a generally applicable framework for assessing the suitability of the road network for L4 AV operations. Most prior studies have taken either a broad approach, typically centring on national or city-wide indices, or a more specific one, with a predominant focus on motorways. There is a notable scarcity of research specifically targeting urban roads within cities due to the uncertainties in the automation domain. Additionally, studies commonly provide insights based on the present technological capabilities of AVs, rather than delving into the complex relationship between road infrastructure and the risks associated with AV operation.

5.3 Framework for the assessment of road readiness for L4 AV operation

This section details the methodology and approach employed to develop an assessment framework that can evaluate the readiness level of roads for automated driving, specifically at L4. The task of identifying which road segments are more suitable in a road network for automated driving is complex due to the numerous criteria that affect the operation of AVs. Moreover, as mentioned earlier, there is limited data available on AV-involved traffic accidents or disengagement reasons of automated driving systems, which makes it difficult to explicitly define criteria for assessing road suitability. Furthermore, the available data predominantly originates from countries leading in vehicle automation, such as the USA, and may not represent regional differences. For these reasons, reviewing relevant literature and consulting experts about the capabilities and limitations of automated driving can be viewed as supplementary or alternative ways to establish evaluation criteria for the early stages of this emerging mobility service. To this end, the authors build upon their recent studies (Tengilimoglu et al., 2023a; Tengilimoglu et al., 2023c), which identify limitations that certain road infrastructure features may impose on automated driving. Additionally, updated literature is reviewed to gather the latest knowledge on the identified components and corresponding subcomponents of the index. **Figure 5.1** depicts the steps undertaken to develop the assessment framework, along with the corresponding subsections.

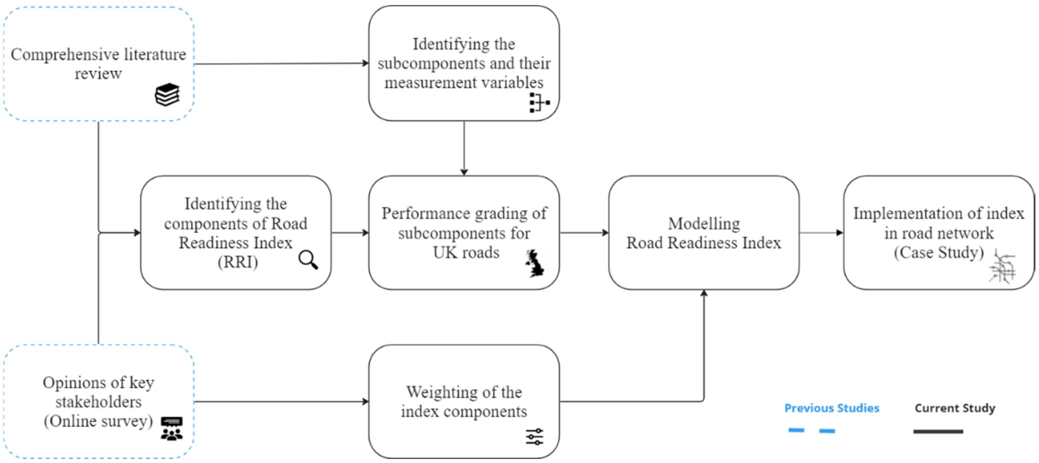


Figure 5.1 Process for developing road readiness index for L4 AV operation.

5.3.1 Identifying the components of the assessment framework

Understanding what a typical automated driving system consists of and how it works is crucial to identifying the components of the framework. As a brief overview, the operation principle of automated driving systems (Level 3 and above) can be broadly categorised into three main subsystems: perception, planning, and control (Tas et al., 2016; Pendleton et al., 2017; Eskandarian et al., 2021). **Figure 5.2** shows the general overview of typical automated vehicle architecture. The perception layer refers to the ability of an AV to collect meaningful information from the sensing data and extract relevant knowledge from the environment. This data can be obtained either directly from on-board sensors such as cameras, lidars, and radars or through sensor fusion techniques or remote data sources such as roadside communication units. The perception layer calculates the global and local location of the ego-vehicle and builds a map of the environment (Van Brummelen et al., 2018). In other words, this layer refers to the understanding of the environment, such as where obstacles are located, detecting road signs/markings, and categorising data by their semantic meaning (Pendleton et al., 2017).

In the planning layer, functions such as action prediction, path planning, and obstacle avoidance are combined to generate an effective plan in a real-time manner. The planning layer determines the best global route from its current position of the world to the requested destination based on the remote map data of road and traffic information. Then, based on real-time vehicle states and the current environment provided by the perception layer, the planning layer computes a locally optimal trajectory through decision-making and trajectory planning (Eskandarian et al., 2021).

Also, with vehicle connectivity, the perception layer can share its perception data with other road users, and the planning layer is able to perform cooperative driving with other road users (Guanetti et al., 2018). Finally, to follow the optimal route decision (e.g. lane change, right turn, or another manoeuvre), the control layer governs the longitudinal and lateral motions of the vehicle by calculating the appropriate command to control the actuators in the vehicle (I. Meneguette et al., 2018).

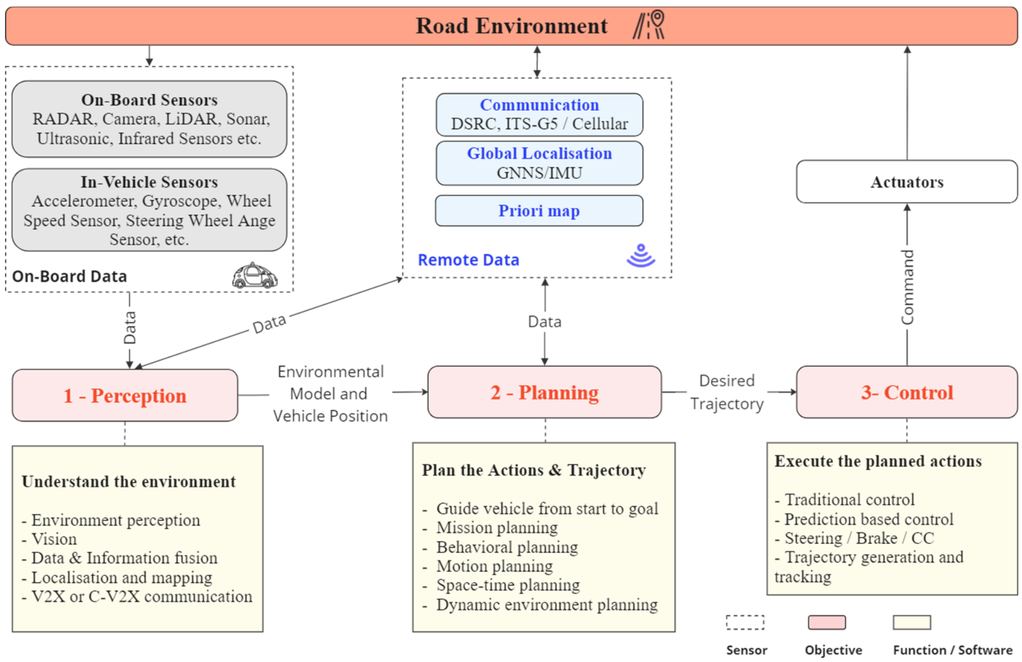


Figure 5.2 The architecture of a typical automated vehicle, adapted form (Eskandarian et al., 2021; Khan et al., 2023).

A thorough review of existing studies reveals numerous factors related to the requirements and limitations of the primary functions, as well as the auxiliary hardware and software integral to automated driving. These factors form a broad set of criteria to assess the operational design domains of emerging technologies (Thorn et al., 2018). From this comprehensive list, 15 pivotal factors have been identified for the proposed Road Readiness Index (RRI). These are: road geometry challenges, road surface condition, road marking conditions, road boundaries, traffic signs visibility, special road section, road lighting, speed limit, number and diversity of road users, precautions for roadworks and incidents, localisation challenges, communication supports, and intersections and roundabouts.

A brief description of these index components and their associated literature references is presented in **Table 5.1**. Further details about these framework components are presented in Supplementary materials (see **SM-1.1**), including the rationale behind their selection and their impact on the capabilities of AVs. However, it is essential to note that there are several dynamic factors such as weather and traffic conditions, accidents, and time of day that significantly influence the safe operation of AVs. As these dynamic factors may change in seconds, it is challenging to incorporate them into the evaluation of road segments in the network. Therefore, this study concentrates primarily on relatively static factors and road environment attributes. Nonetheless, some dynamic factors can be indirectly captured in various subcomponents in the framework.

Table 5.1 Overview of components of the road readiness index for automated driving.

#	Framework Components	Description	References
C1	Road Geometry Challenges	Road geometric design challenges resulting from alignment and cross-section conditions that can affect the driving tasks or capabilities of AVs	(Johnson, 2017; Thorn et al., 2018; Martínez-Díaz et al., 2019; Amelink et al., 2020; Konstantinopoulou and Ljubotina, 2020; Marr et al., 2020; Soteropoulos et al., 2020; Wang et al., 2020; Eskandarian et al., 2021; FTIA, 2021; García et al., 2021)
C2	Road Surface Condition	Appearance and quality of road surfaces ensure safe driving for road users and are less challenging for the perception systems of AVs.	(Johnson, 2017; Thorn et al., 2018; Amelink et al., 2020; BSI, 2020; Konstantinopoulou and Ljubotina, 2020; Soteropoulos et al., 2020; FTIA, 2021;)
C3	Road Marking Condition	Conditions and configuration of road markings that AVs need to detect and read rules of the road segment.	(Huggins et al., 2017; Lawson, 2018; Somers and Jones, 2019; Konstantinopoulou et al., 2020; Marr et al., 2020; FTIA, 2021; Cucor et al., 2022)
C4	Road Boundaries	Continuous and detectable road boundaries that AVs may not struggle with positioning themselves on the road section.	(Transport Systems Catapult, 2017; Suleymanov et al., 2021; Waykole et al., 2021; Wang et al., 2022)
C5	Traffic Signs Visibility	Conditions of traffic signs that AVs may not struggle to read and understand the rules of traffic.	(Roper et al., 2018; Konstantinopoulou et al., 2020; Poe, 2020; PIARC, 2021; Cucor et al., 2022; Mihalj et al., 2022)
C6	Special Road Section	Road sections or structures that require additional attention and may present challenges for AVs.	(Huggins et al., 2017; Lyon et al., 2017; Rios-Torres and Malikopoulos, 2017; Farah et al., 2018; Lu, 2018; Paulsen, 2018; FTIA, 2021; Manivasakan et al., 2021; PIARC, 2021)
C7	Road Lightning	The lighting conditions of the road segment so that AVs can detect and read the road infrastructure and surrounding elements.	(Huggins et al., 2017; Johnson, 2017; Thorn et al., 2018; Liu et al., 2019; Amelink et al., 2020; BSI, 2020; Chen et al., 2020; Konstantinopoulou and Ljubotina, 2020; Soteropoulos et al., 2020; FTIA, 2021; Gopalakrishna et al., 2021)
C8	Speed Limit	The maximum legal operating speed limits of road sections that AVs can stop within their detection range or conventional vehicles can travel along priority junctions safely.	(Pendleton et al., 2017; Soteropoulos et al., 2020; Easa et al., 2021; Magyari et al., 2021; Cucor et al., 2022)

(continued on next page)

Table 5.1 (continued)

C9	Number and Diversity of Road Users	The number and diversity of road users on the road segment that AVs must detect and respond to.	(Thorn et al., 2018; Soteropoulos et al., 2020; Wang et al., 2020; Tabone et al., 2021)
C10	Roadside Complexity	The level of roadside complexity may affect the performance of AVs, due to street furniture, trees, or commercial facilities.	(Huggins et al., 2017; Shladover, 2018b; Koopman and Fratrik, 2019; Ulrich et al., 2020; Soteropoulos et al., 2020; PIARC, 2021; Ebrahimi Soorchaei et al., 2022)
C11	Facilities for Vulnerable Road Users	Infrastructure-related facilities to reduce interaction between AVs and VRUs (e.g. pedestrians and cyclists).	(Nitsche et al., 2014; Johnson and Rowland, 2018; Lu et al., 2019; Madigan et al., 2019; Rasouli and Tsotsos, 2020; Manivasakan et al., 2021; Tabone et al., 2021)
C12	Precautions for Roadworks and Incidents	Measures to reduce the risks that AVs may face in the roadwork area or incident scene.	(Transport Systems Catapult, 2017; Lytrivis et al., 2018; Thorn et al., 2018; Amelink et al., 2020; Gopalakrishna et al., 2021; PIARC, 2021; Wang et al., 2022).
C13	Localisation Challenges	Road sections on the network that may have difficulty receiving a strong GNSS signal due to the surrounding built environment or nature.	(Godoy et al., 2015; Huggins et al., 2017; Kuutti et al., 2018; Meng et al., 2018; Martínez-Díaz et al., 2019; Reid et al., 2019; Eskandarian et al., 2021; Cucor et al., 2022)
C14	Communication Facilities	Digital infrastructure facilities that support critical information transfer or communication between road users and the surrounding road environment so that AVs can operate safely.	(Huggins et al., 2017; Meng et al., 2018; Lytrivis et al., 2019; Martínez-Díaz et al., 2019; Somers, 2019; Poe, 2020; Eskandarian et al., 2021; FTIA, 2021; PIARC, 2021; Cucor et al., 2022; Mihalj et al., 2022)
C15	Intersections and Roundabouts	Types of intersections and roundabouts that reduce conflict between road users and ensure the safe operation of AVs.	(Huggins et al., 2017; Johnson, 2017; Thorn et al., 2018; Liu et al., 2019; Amelink et al., 2020; BSI, 2020; Chen et al., 2020; Konstantinopoulou and Ljubotina, 2020; Soteropoulos et al., 2020; FTIA, 2021; Gopalakrishna et al., 2021)

5.3.2 Weighting of the components according to the opinions of experts

In the previous subsection, components of the index that can affect the performance of automated driving systems (ADS) in relation to road infrastructure and the surrounding road environment were presented. However, it is essential for policymakers and road authorities to understand the significance and relevance of each component in the framework to evaluate their road infrastructure or prioritise their investment. To achieve this, advanced weighting methods, such as Analytic Hierarchy Process (AHP), have been applied in the literature to generate reliable weights for the parameters from decision-makers or expert judgments (Odu, 2019). However, in the absence of evidence-based sources to determine such measures, a weighted score method can be implemented in exploratory research by averaging the weights for each parameter. In addition, indexes consisting of many parameters without hierarchical structures require great effort in terms of computation (i.e. pairwise comparisons by experts).

Therefore, this study drew upon findings from the authors' previous research (Tengilimoglu et al., 2023c) to determine the importance ratings of components. A 5-point Likert scale was utilised in a survey with experts, aiming to evaluate the factors that might influence the safe operation of L4 AVs in the foreseeable future. This survey gathered responses from a total of 168 experts spanning 29 countries, who specialised in the vehicle automation domain. These experts were divided into three groups: Agency (comprising local/regional authorities (9), national authorities (12), road agency/administration/operators (27), consultancy/engineering (24)); Industry (consisting of vehicle industry (15), technology developers (9), service providers and suppliers (4), research and development companies (3), insurance companies (1)); and Academia (encompassing universities (39), research institutes and organisations (25)). Among them, 160 experts assessed factors that were pinpointed from the current literature. Only those factors that were directly related to the components of the index were considered. The weight of each component (Wc_i) was then calculated based on their mean values, as shown in **Table 5.2**.

It is worth noting that different mobility models may require different considerations and infrastructure requirements based on their functionalities (Aigner et al., 2019). For this reason, the ranking of the factors was based on generic driving tasks of highly automated vehicles, rather than focusing on specific use-case scenarios. Nonetheless, each subcomponent representing components of the index was evaluated based on the two different driving capability levels of L4 automated vehicles, which are explained in the next section. In brief, the weights of the framework components are assumed to be valid for all L4 automated vehicles, but the performance grading of the subcomponents may vary according to the capability levels of the vehicles as their response to measurement variables can differ.

Table 5.2 Weightings of the components of the Road Readiness Index (RRI) based on experts' views, adapted from (Tengilimoglu et al., 2023c).

Item (Ci)	Framework Components	Mean*	S.D.	Weight (W_{C_i})
C1	Road Geometry Challenge	4.280	0.838	0.0733
C2	Road Surface Condition	3.813	0.979	0.0653
C3	Road Markings Condition	4.269	0.979	0.0731
C4	Road Boundaries	3.974	0.917	0.0681
C5	Traffic Signs Visibility	4.194	1.088	0.0718
C6	Special Road Sections	4.194	0.940	0.0718
C7	Road Lighting	3.800	1.003	0.0651
C8	Speed Limit	4.129	0.978	0.0707
C9	Number and Diversity of Road Users	4.381	0.914	0.0750
C10	Roadside Complexity	3.773	0.987	0.0646
C11	Facilities for Vulnerable Road Users	4.446	0.804	0.0761
C12	Precautions for Roadworks and Incidents	4.494	0.746	0.0770
C13	Localisation Challenging	4.547	0.733	0.0779
C14	Communication Facilities**	4.101	0.903	0.0702
				1.0000

* Where: 1=Not At All Important, 2=Low Importance, 3=Importance, 4=Very Important and 5=Extremely Important
** For this indicator, the highest average of communication related parameters is taken into account in the study.

5.3.3 Identifying the subcomponents of the components and their performance grading in the context of UK road configuration

This step entails the identification of subcomponents that can represent components within the assessment framework. It also involves assigning performance grades to their measurement variables based on the scoring system. Although each component identified from the literature and the views of experts has an impact on the safe operation of AVs, there is currently no official standard or benchmark to be used by authorities to assess the level of readiness or compatibility of roads for AVs. Similarly, it is challenging to propose objective and proven thresholds for each component since the level of impact of individual subcomponents on the performance of AVs is not entirely clear yet. For this reason, grading systems were established for components to be evaluated quantitatively or qualitatively for road environment compatibility for automated driving. These scoring systems mainly were proposed by considering the current UK specifications and manuals regarding road design, operation, and maintenance.

In this process, first, subcomponents that can represent the framework components have been selected based on current literature insights. The feasibility of gathering data with current technology also played an important role in these selections. Subsequently, the weight of these subcomponents within the components ($Wc_{i,j}$) was determined, with most being assigned an equal weight. In the next step, the measurement variables of the subcomponents were defined in binary or categorical form depending on data availability. Following this, each measurement variable in the subcomponents was assigned a score ($Sc_{i,j}$) ranging between 0 and 1 to signify the grade of a particular road segment, with 0 being the lowest and 1 being the highest.[25] According to the selected grading criteria, a higher score denotes road characteristics that are more suitable for the safe operation of AVs.

However, the current AV industry focuses on developing automated driving technology for different service models with different capabilities (Shladover, 2022). For example, an automated bus and an urban robo-taxi will likely have different automated driving hardware, software, and sensors and thus have different operational domains. Even in the same use case model of AVs, some vehicles may be capable of self-driving on roads where other AVs may not operate, depending on their technology levels and computing budgets. For this reason, the study considered two different automated driving capability levels of L4 AVs for the same use-case model when scoring the measurement variables of subcomponents. These are:

- ***Low Capability of L4 Automated Vehicle (LC):*** refers to a vehicle equipped with basic software and hardware that has limited perception range, needs more time for computation and response and is more dependent on the surrounding road environment to perform driving tasks. In other words, low-capability L4 vehicles have basic sensors and decision-making algorithms that can handle numerous simple tasks, but they may struggle to navigate through more complex environments due to constrained computing budgets. These vehicles may require human intervention in certain situations, such as adverse weather conditions or unexpected road closures.

- ***High Capability of L4 Automated Vehicle (HC):*** refers to a vehicle equipped with advanced software and hardware that has a long perception range with multiple sensors, has advanced decision-making algorithms and processing power, needs less time for computation and response, and is relatively less dependent on the surrounding road environment in order to perform driving tasks. They require less human intervention compared to low-capability AVs due to the heavy use of AI neural networks, high computing budget, and power draw.

[25] The measurement variables in the subcomponents of the components are scored according to the level of difficulty for automated driving: 1=Least challenging, 0.75=Slightly challenging, 0.50=Moderately challenging, 0.25=Highly challenging, and 0=Extremely challenging.

After that, the weight of the subcomponents ($Wc_{i,j}$) and the score of the measurement variables in each subcomponent ($Sc_{i,j}$) were finalised in the light of the literature and the collective insights of the authors. **Table B1** presents a summary of performance grading for each subcomponent and measurement variable within the component, based on UK road configurations (see **Appendix B**). Detailed information on each component in the assessment framework, along with their corresponding subcomponents and measurement variables, is provided in the Supplementary materials (see **SM-1.1**). It is worth mentioning that most of the measurement variables are not only UK-specific, so they can be applied in other countries. However, the subcomponents chosen to evaluate each component and the corresponding assessment system may change and need to be regularly reviewed in response to more precise and specific criteria that are identified.

5.3.4 Modelling of the Road Readiness Index for the road network

The preceding subsections provided an overview of the assessment framework, including the weights assigned to its components, the chosen subcomponents, and the scoring scheme for each subcomponent. After these steps, the Road Readiness Index (RRI) can be modelled separately for road links and intersections/roundabouts. For road links, the RRI calculation is as follows:

$$RRI_{lm} = \sum_{i=1}^{14} \sum_{j=1}^{n} \left[Wc_i \times (Wc_{i,j} \times Sc_{i,j,m}) \right] \tag{5.1}$$

where *l* is road link in the network, m is the type of L4 automated driving based on the capability level, *i* is component number in the index, *j* is the subcomponent number in the corresponding component, *n* is the total number of subcomponents in the corresponding component, Wc_i and $Wc_{i,j}$ are the corresponding weight of components and subcomponents, and $Sc_{i,j,m}$ is a score of measurement variables in a certain subcomponent. The weights attributed to the components and subcomponents are subject to the following constraints:

$$\sum_{i=1}^{14} Wc_i = 1, \quad \sum_{j=1}^{n} Wc_{i,j} = 1 \tag{5.2}$$

For intersections/roundabouts, which are commonly illustrated as nodes in between road links, the RRI calculation is as follows:

$$RRI_{nm} = \sum_{j=1}^{n=4} (Wc_{15,j} \times Sc_{15,j,m}) \tag{5.3}$$

where n is node in the network and m is the type of L4 automated driving based on the capability level, j is the subcomponent number in the component ($i=15$), n is the total number of subcomponents in the corresponding component, $Wc_{i,j}$ is the corresponding weight of subcomponent, and $Sc_{i,j,m}$ is a score of measurement variables in a certain subcomponent.

Note that the value range of the road readiness index is set to be RRI ∈ [0, 1]. That is RRI values range from 0 to 1, where a low score indicates that road infrastructure quality and the surrounding environment are unlikely to be suitable for automated vehicles to safely operate. This suggests that road links or intersections require substantial investment to facilitate automated driving. A high score can be considered as indicating that the infrastructure quality and condition of a road section are very likely to be suitable for automated driving.

On the other hand, if the result of any component score in the analysis of a road link is zero ($i.e. \sum_{j=1}^{n} Wc_j \times Sc_{j,m} = 0$), it is assumed that the RRI_{lm} for that link is also zero. This assumption is made because the zero result suggests that the road situation is extremely challenging for AVs. The literature indicates that many components in the framework are essential for the proper operation of AVs. Consequently, if the calculated result is zero, it implies that the road link poses such difficulties and risks that the other framework components alone are not sufficient to ensure safe and reliable operations for AV. Therefore, a zero RRI is assigned to signify the severity of the road conditions and the need for additional measures or improvements before AVs can navigate that particular road link effectively.

5.4 Application of the Road Readiness Index to a road network

5.4.1 Study area and road network

This section presents a case study that provides an evaluation of a real-world road network through the conceptual framework introduced in **Section 5.3**. The presented analyses of roads regarding the integration of AVs utilise a region in the city of Leeds, United Kingdom. Multiple factors prompted the choice of Leeds for this study. The city embodies a mosaic of urban forms, echoing the historical evolution of urban development patterns found in many UK cities, as outlined in the government document on urban form and infrastructure (Williams, 2014). Its blend of radial and grid patterns, combined with its peripheral developments, mirrors the infrastructure challenges and opportunities present in many urban areas in the UK. Furthermore, Leeds, with its sizable population and multifaceted urban morphology, showcases both the potential and challenges for AV operations. Given the representative nature of Leeds's road network and urban structure, findings from this case study could hold broader implications for several cities across the UK and Europe.

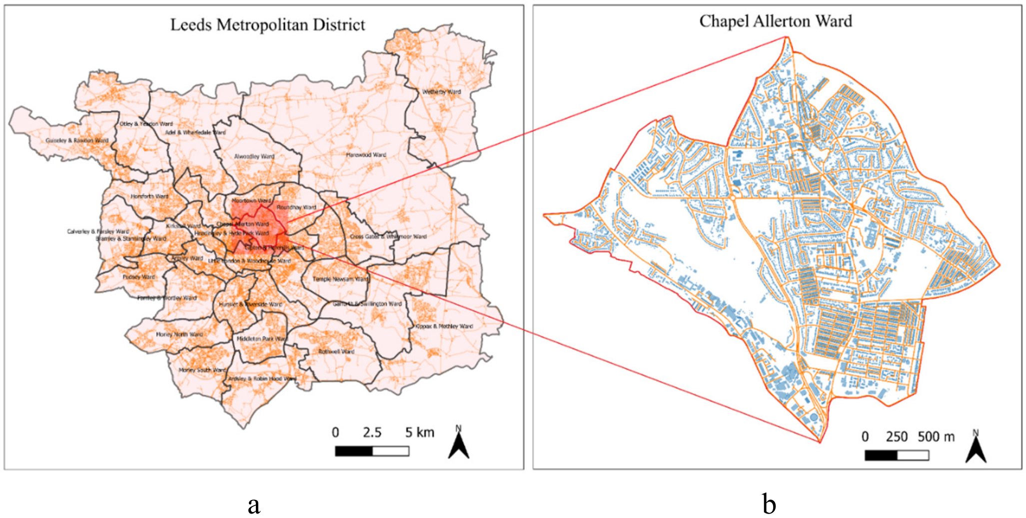


Figure 5.3 Location description of the case study area: Leeds Metropolitan District (a) and Chapel Allerton Ward (b).

The road network data for Leeds Metropolitan District were obtained from the Ordnance Survey MasterMap Highway for the year 2021. This dataset includes all road categories based on eight different levels of hierarchy (N=53,609 road links).[26] However, conducting a comprehensive evaluation of the entire road network in Leeds poses certain difficulties. The sheer size of the road network presents challenges in terms of data collection, analysis, and evaluation. Moreover, assessing each link individually is resource-intensive. Due to these limitations, the study focuses on the Chapel Allerton region, an inner suburb in the northeast of Leeds. This is because focusing on a specific region like Chapel Allerton allows for a more targeted and manageable assessment while still capturing the essential characteristics and challenges of the broader road network in Leeds (see **Figure 5.3**).

[26] According to Ordnance Survey, the road hierarchy in the UK can be categorised based on road function. These are: 1) *Motorway*, which is a multi-carriageway public road connecting important cities. 2) *A Road*, which is a major road intended to provide large-scale transport links within or between areas. 3) *B Road*, which is a road intended to connect different areas, and to feed traffic between A roads and smaller roads on the network. 4) *Minor Road*, which is a public road that provides interconnectivity to higher classified roads or leads to a point of interest. 5) *Local Road*, which is a public road that provides access to land and/or houses, usually named with addresses. Generally, not intended for through traffic. 6) *Local Access Road*, which is a road intended for the start or end of a journey, not intended for through traffic but will be openly accessible. 7) *Restricted Local Access Road*, which is a road intended for the start or end of a journey, not intended for through traffic and will have a restriction on who can use it. 8) *Secondary Access Road*, which is a road that provides alternate/secondary access to property or land not intended for
through traffic.

The selected area is one of the dense wards in the Leeds Metropolitan District. According to the UK Office for National Statistics, based on the 2021 census, the population of Ward is 24,963 and 5.144 km² area with having 4,853/km² population density. The Chapel Allerton area was chosen as the case study area for several reasons. Firstly, its proximity to the city centre, being just 2 miles away, and population density make it an ideal location to assess the feasibility and suitability of AVs in an urban setting. It is considered that users can either own or lease AVs or are served by a shared model of AVs that are circulating in the system. So, this closeness to the city centre suggests that the area could potentially benefit from the implementation of different AV use cases. Secondly, what makes Chapel Allerton an interesting case study area is the presence of different types of urban forms within the area (see **Figure 5.3b**). The area encompasses various types of urban structures, ranging from residential zones comprising terrace houses and a mix of detached houses, to local commercial hubs, parks, industrial sectors, multiple educational institutions, a hospital, shopping centres, and more. By evaluating the road infrastructure in an area with diverse urban characteristics, it becomes possible to understand how the heterogeneity of the environment affects the suitability of roads for automated driving. Additionally, the study area includes various road types, the distribution of which is detailed in footnote 26. This diversity is crucial for assessing the broader implications of AV integration and providing indications for infrastructure planning decisions. Thus selected area can be a good example for evaluating the road infrastructure and plans for the introduction of L4 AVs.

5.4.2 Data collection and score assignment

The framework is data-driven; however, the availability and accessibility of data related to the components of the RRI are often limited. This constrains research on evaluating the suitability of road sections for automated driving. This is because many of the subcomponents heavily depend on extensive field survey data, encompassing both physical and digital infrastructure data, which entails substantial time, labour, and financial resources (Konstantinopoulou and Ljubotina, 2020). This also makes the rapid update of data difficult for authorities. Therefore, a limited number of studies so far have collected detailed data with special equipment only from certain road sections, such as highways in a road network, to assess the level of readiness of roads (Somers, 2019; FTIA, 2021). In response to these limitations, some research has alternatively proposed a framework that relies on publicly available data to assess the complexity of road conditions and the surrounding environment for automated driving (Soteropoulos et al., 2020).

On the other hand, street view images have been widely employed in quantitative and qualitative research on built environments and urban landscapes (Arellana et al., 2020).

In a similar strategy, for this study, most of the data for road infrastructure conditions were gathered from visual inspection using either aerial photography/satellite imagery or street view services such as Google Street View.[27] The approach also involved on-site observations and the utilisation of secondary data to accurately identify the specific requirements of the study area. Then, the proposed methodology involves implementing the index on a road network using a Geographic Information System (GIS) platform. Therefore, the values computed for the measurement variables should be compiled on such a platform. The road network is structured as a set of links and nodes representing the city's streets. While open-source platforms like Open Street Maps can be utilised for this purpose, in this study, road network data were sourced from the Ordnance Survey MasterMap Highway due to having more detailed information in spatial dimensions. So, each link in the road network can be characterised by the evaluated factors and components. That is, using the measurement variables collected from different sources and weights obtained from the experts' opinions, the estimated RRI can be mapped across the city or case study area. Briefly, various sources were utilised to gather data that could represent each measurement variable, and each road link and intersection was evaluated by the authors, such a task required two months. **Table C1** provides an overview of the data sources used and evaluates the quality and representativeness of the collected data for each component (see **Appendix C**).

Regarding the study area, road network data for Chapel Allerton Ward encompass all road categories except motorways, comprising a total of 1,553 road links. After data cleaning for road segments that are restricted to traffic or do not have street view data, 1,495 road links were obtained for analysis. The average length of road links is calculated at approximately 65 m, resulting in a total road network length of 96.8 km.[28] It should be noted that the physical attributes and amenities may vary within a road link or intersection. However, considering that any issues or conditions present on a road link may affect the performance of automated vehicles, it is essential to maintain the integrity of the link conditions in the data representation. As such, any challenging issues on road attributes or environment along the road link were assigned to represent the whole link. For example, if there is a pothole on one small segment of the road surface or damaged traffic signs on the side of the road, this can pose a risk for AVs to operate through this road link. This hypothesis is grounded in the rationale that authorities and societies are likely to adopt a cautious approach and exhibit increased vigilance towards AVs and the road links designed to accommodate them during the

[27] The visual inspection is generally based on satellite images dated March 24, 2022. However, the assessment of many road sections, primarily major roads, is based on the latest Google Street View images from the second half of 2022.

[28] The length of A Road network is 6.7 km (6.95%), the length of the B Road network is 4.3 km (4.44%), the length of the Minor Road network is 14.2km (14.63%), the length of the Local Road network is 59.2km (61.16%) and the length of the Access Road network is 12.4 km (12.84%).

initial phases of deployment. On the other hand, small segment sizes for road links would produce a large amount of noise in the analysis. For these reasons, road links were not split into small sizes for the scope of this study.

5.4.3 Scenarios of road network evaluation

The case study focuses on three scenarios, taking into account two distinct automated vehicle capabilities. Considering the potential technological development in the information and communication and vehicle industry foreseeable future, these scenarios can be explained as:

- ***Network Scenario 1*** concerns the current conditions of the road network in the study area as the base case scenario. It is assumed that the study area does not have High Definition (HD) map and Roadside Units (RSUs) providing connectivity to exchange information between AVs and infrastructure. In this scenario, AVs have to rely solely on onboard sensors to understand the road environment and respond appropriately to surrounding road users. If a connection is required to obtain information, only the current cellular network quality can be used for connection to the outside world. Also, it is assumed that there is no presence of roadwork or incident in the study area.

- ***Network Scenario 2*** considers the incorporation of cutting-edge surveying technology and techniques that allow for the creation of a highly detailed map of cities. Consequently, it is assumed that HD maps are accessible for all roads within the study area. However, the absence of RSUs in the road network can be attributed to the challenges associated with implementation and management costs. Furthermore, the establishment of protocols and standards for vehicle-to-infrastructure (V2I) communications between the vehicle industry and road authorities has not yet been mutually agreed upon. If there is a need for a connection to obtain information, the current cellular network is the only available option, relying on its existing quality and coverage.

- ***Network Scenario 3*** depicts a highly desirable scenario for the AV industry. It envisions the availability of HD maps for the entire road network and widespread coverage of 5G service with at least average quality, ensuring consistent and reliable connectivity across the entire area. Moreover, like the previous scenarios RSUs and roadworks are not present in the road network.

5.4.4 Results and discussion

5.4.4.1 Key findings and their implications

The evaluation results of road links and nodes for each subcomponent in the index components, derived from the existing conditions of the road network, are illustrated in the Figures provided in Supplementary materials (see **SM-1.2**). Subsequently, the final Road Readiness Index values were computed by integrating these subcomponents, which reflect the measurement values of the road links and nodes, as per Equation 5.1. **Figure 5.4** illustrates the mapping of the outcomes obtained from integrating the assessment components for the Chapel Allerton region in Leeds, considering low-capability (LC) and high-capability (HC) automated vehicles. The index scores in the figure were divided into five groups to represent different difficulty levels for automated driving, ranging from extremely challenging to least challenging. Essentially, this categorisation demonstrates the suitability of road sections in facilitating AVs in terms of both road infrastructure and the surrounding environment.

The figure clearly indicates that the majority of road sections in the case study area are categorised as extremely challenging (represented by the colour red) for the safe operation of both AV capabilities. This is mainly due to factors such as poor-quality road infrastructure and the complexity of the surrounding driving environment, resulting in the index score being penalised. In general, the lowest value of RRI can be observed in residential areas, where often the absence of road markings, clear and detectable road edges or pedestrian sidewalks, narrow streets with on-street vehicle parking, poor road surface conditions, the presence of obstructions such as trees or bushes. Similarly, the low RRI values can be also observed in mixed-use with commercial facility areas, where the road environment is complex, no clear segregation between VRUs and public transit.

On the other hand, certain road sections (approximately 23.5% and 26.2% of total road links for LC and HC, respectively) in the network demonstrate relatively high RRI values, which are classified as either slightly or least challenging for AVs. However, there are significant gaps (i.e. lower RRI value sections) among these road links, primarily arising from variations in the quality and consistency of infrastructure and the road environment. As a result, the road network in the case study area demonstrates a marked heterogeneity in terms of its infrastructure and road conditions. Therefore, without modifications or upgrades in the infrastructure regarding the automated driving requirements, it is unlikely that AVs can operate seamlessly throughout the existing road network.

Figure 5.4 Overview of the assessment of the readiness of roads and intersections in Scenario 1, comparing low capability AV (a) and high capability AV (b).

Regarding the evaluation results of nodes, which include intersections and roundabouts, a distinct pattern emerges. Unlike road links, a substantial proportion of these nodes (approximately 66.1 % and 85.7% of total nodes for LC and HC, respectively) in the network were classified as either slightly or least challenging for AVs. One key factor behind this is that many junctions in the case study area are priority-controlled, three-armed, and feature a regular layout. These attributes generally offer a less challenging driving environment for AVs compared to other complex types of junctions. However, this trend can also be attributed to the smaller number of criteria used in the assessment framework for nodes, which reduces the likelihood of the index being penalised. Additionally, when assessing road links, larger areas are considered compared to nodes, thus making them more susceptible to penalties. Furthermore, the observed variations in the performance between different AV capabilities within the network can be linked to the distinct advantages of high-capability AVs, which enable them to mitigate drawbacks or navigate through complexities within the road network. These advantages are typically associated with advanced automated driving systems, encompassing sophisticated sensors and computational capacity. However, some junctions along the links with high RRI values are categorised as having low scores, indicating a high level of challenge for the operation of AVs. This implies that even if the road links themselves are suitable without any upgrades, AVs are likely to encounter difficulties in crossing junctions and may become stuck within the link. Additional consideration will likely be necessary for extending the operational areas of AVs, taking into account the challenges posed by intersections

In Scenario 2, which assumes an HD map is available for the entire road network, it is observed that the operation areas of both AV capabilities extend significantly compared to the base case scenario (**Figure 5.5**). For instance, for low-capability AVs, around 68.8% of all road links in the network exhibit RRI values greater than the moderately challenging category, an increase of 45% compared to Scenario 1. This change highlights the critical role HD maps play in facilitating automated driving, as these maps are linked to many components within the index. Especially for local roads and certain major roads suffering from poor road markings and traffic signs, challenging geometry and complex roadside environments, HD maps can potentially provide AVs with important additional details about the driving environment. Additionally, this scenario yielded higher index values for junctions, predicated on the assumption that HD maps can mitigate risks associated with poor delineation of markings at these locations. Briefly, this scenario utilises static map layers to provide redundancy for onboard sensors, aiding in precise localisation, enhancing perception beyond the sight range, and facilitating more accurate path planning.

Figure 5.5 Overview of the assessment of the readiness of roads and intersections in Scenario 2, comparing low capability AV (a) and high capability AV (b).

Nonetheless, the provision of HD maps alone does not resolve all the challenges inherent in the road network. A substantial proportion of road links pose considerable obstacles for AVs, primarily due to factors such as limited cellular coverage. This is especially pronounced in densely populated areas where road links consistently exhibit low values due to the poor quality of communication services provided by telecom operators. This phenomenon could be rationalised by the direct correlation between population density and the requisite number of base stations; higher population density necessitates a larger number of base stations. Therefore, variances in cellular service quality across the case study area inevitably impact the suitability of roads for AV operation.

Scenario 3 undertakes an assessment of how advancements in cellular technology can influence the operational areas of AVs within the road network. As illustrated in **Figure 5.6**, the findings demonstrate that, given the availability of 5G cellular network coverage coupled with HD maps, most road sections in the network present less of a challenge for automated driving. Furthermore, it is observed that the gaps previously present between main roads in earlier scenarios were largely bridged in this scenario. This highlights the vital role of digital infrastructure in partially compensating for the challenges caused by the physical road environment that AVs are likely to face.

However, certain road sections, including dead-end streets and numerous local and access roads, continue to pose significant challenges for both types of AVs. This challenge can be attributed to the infrequent oversight of these road sections due to their limited traffic. Such roads typically fall at the lower echelons of the road hierarchy. As a result, the quality of their infrastructure and control over their surrounding environments often lag behind that of other road types. These findings underline the point that road links in the network will not be AV-compatible by the implementation of digital infrastructure alone. To fully support AV operation, significant changes are needed in the physical design and conditions of the infrastructure.

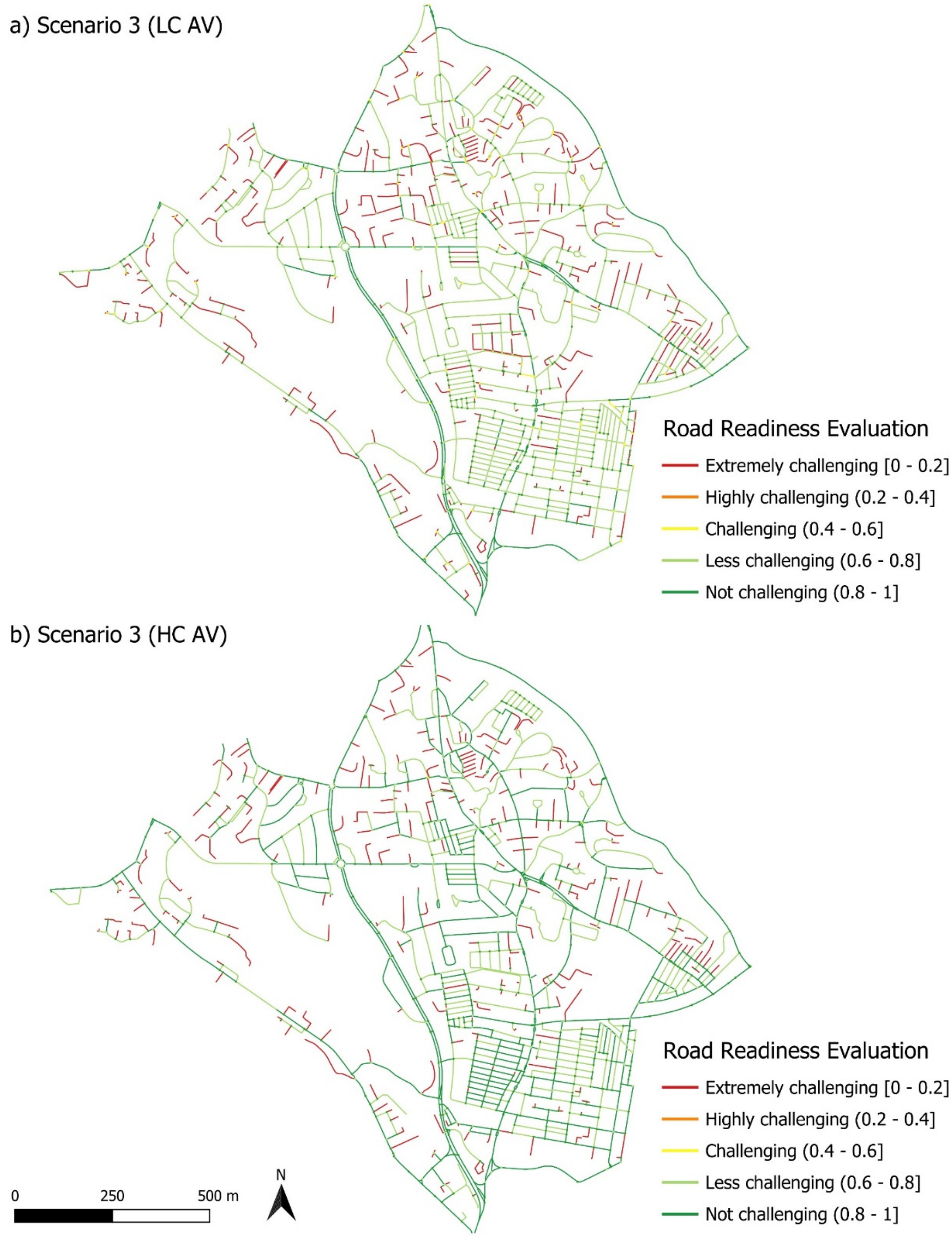


Figure 5.6 Overview of the assessment of the readiness of roads and intersections in Scenario 3, comparing low capability AV (a) and high capability AV (b).

5.4.4.2 Correlations of road hierarchy and deprivation with RRI

Overall, the outcomes from the assessment, in conjunction with the scenarios, highlight the variability in road readiness for automated driving. A significant factor behind this variability is the diversity in the road infrastructure conditions across the network. However, a clear correlation emerges between the road hierarchy and the RRI value. Main roads, including A, B, and Minor Roads (for further details, refer to footnote 26), typically exhibit relatively high RRI values, even with higher speed limits and a greater variety and number of road users. **Table 5.3** presents the distribution of road links in the case study area by road hierarchy and RRI category for Scenarios 1-3. The data shows that most sections classified as Local and Access roads pose significant challenges for automated driving across both AV capability levels. This is primarily because main roads employ comprehensive safety measures for road users and undergo frequent maintenance, making them comparatively well-prepared to accommodate the integration and operation of automated vehicles effectively.

In addition, this study further explored whether road links in economically disadvantaged areas might exhibit lower RRI values. To this end, the Index of Multiple Deprivation (IMD) [29] was employed to assess the deprivation levels of sub-areas within the case study area (Chapel Allerton Ward). Pearson correlation tests were subsequently performed to determine if there was any correlation between IMD scores (where a higher score signifies more deprivation) and RRI values. The results showed no significant correlation in Scenarios 1 and 2. Yet, a distinct correlation emerged in Scenario 3. In this context, the IMD score and RRI demonstrated a positive correlation, with $r(1493) = .108$ and $p \leq .001$ for LC AVs, and with $r(1493) = .083$ and $p = .001$ for HC AVs.

A possible explanation for this finding in Scenario 3 lies in the unique street typologies of Chapel Allerton Ward's less deprived areas. Predominantly, these are low-density zones marked by a significant number of dead-end streets. Such streets usually act as access routes and are not used as primary thoroughfares. Due to this specific urban structure, many streets lead to residential vehicle parks and often lack comprehensive traffic control measures like pedestrian sidewalks or road markings. As a consequence, these areas frequently receive low RRI values, primarily because of their corresponding lower scores of subcomponents. On the other hand, this indicates that with the necessary investments in digital infrastructure within the study areas, more deprived neighbourhoods could stand to benefit significantly from AV service in the

[29] The Indices of Multiple Deprivation (IMD) are measures used in the UK to identify areas facing multiple types of deprivation. The IMD combines data from various domains to create an overall relative measure of deprivation experienced by individuals in a given area. This measure is determined for each Lower Layer Super Output Area (LSOA) in England. Further information can be found in Consumer Data Research Centre (CDRC). Source: https://data.cdrc.ac.uk/dataset/index-multiple-deprivation-imd

case study area, owing to their urban forms being more conducive to AV operation. However, it should be noted that this correlation might not be reflected in other areas of Leeds, due to the variety in street topology.

5.4.4.3 Sensitivity analysis

The accuracy and robustness of an index are paramount when it serves as a decision-making tool or evaluative metric. In the context of the Road Readiness Index (RRI), the outcomes may vary based on the components it includes and their respective weights. Thus, an extensive sensitivity analysis was performed to understand how variations in the RRI outcomes arise due to different weighting strategies, penalty strategies, and the removal of certain components. This investigation provided insights regarding which components greatly impact the RRI and how the distribution of its values across the road network shifts when specific components are omitted.

Firstly, the impact of uniform weights in comparison to expert-determined weights for each component on the overall index was evaluated. **Table D1** displays the distribution of road links according to categorised RRI values, reflecting the challenging levels for AVs (see **Appendix D**). Despite the varying weighting strategies, there is no remarkable difference in the share of different categories of road links across the network. This can largely be attributed to the consensus among experts that almost all components are of equal importance for automated driving. Additionally, when comparing the perspectives of industry participants to those of all stakeholders combined, a very slight shift was noticed from the least challenging to slightly challenging road categories. This observation suggests a nuanced difference in perception regarding the readiness of road links for AV operation between these groups. However, in general, there is no statistically significant difference in attitudes towards parameters between stakeholder groups—for detailed information please refer to (Tengilimoglu et al., 2023c).

Table 5.3 Distribution of road links by road hierarchy and RRI category for Scenarios 1-3.

Scenario (S)	**Road hierarchy***	**Road Readiness Index category (LC)**					**Road Readiness Index category (HC)**					**Total**
		Extremely Challenging	**Highly Challenging**	**Moderately Challenging**	**Slightly Challenging**	**Least Challenging**	**Extremely Challenging**	**Highly Challenging**	**Moderately Challenging**	**Slightly Challenging**	**Least Challenging**	
S1	A Road	17	0	1	65	0	17	0	0	30	36	83
	B Road	23	0	3	51	0	23	0	0	54	0	77
	Minor Road	87	0	13	120	0	86	0	0	113	21	220
	Local Road	829	0	8	114	0	823	0	0	123	5	951
	Access Roads	161	0	1	2	0	155	0	0	9	0	164
	Total # of links	1117	0	26	352	0	1104	0	0	329	61	1495
	Percentage (%)	74.7	0.0	1.7	23.5	0.0	73.8	0.0	0.0	22.0	4.1	100.0
S2	A Road	3	0	0	28	52	3	0	0	1	79	83
	B Road	13	0	0	46	18	13	0	0	3	61	77
	Minor Road	50	0	0	121	49	50	0	0	7	163	220
	Local Road	377	0	1	533	40	351	0	0	182	418	951
	Access Roads	122	0	2	40	1	86	0	0	62	16	164
	Total # of links	565	0	1	768	160	503	0	0	255	737	1495
	Percentage (%)	37.8	0.0	0.1	51.4	10.7	33.6	0.0	0.0	17.1	49.3	100.0
S3	A Road	0	0	0	21	62	0	0	0	0	83	83
	B Road	0	0	0	30	47	0	0	0	1	76	77
	Minor Road	0	0	0	105	115	0	0	0	1	219	220
	Local Road	240	0	0	600	111	212	0	0	72	667	951
	Access Roads	102	0	0	60	2	60	0	0	59	45	164
	Total # of links	342	0	0	816	337	272	0	0	133	1090	1495
	Percentage (%)	22.9	0.0	0.0	54.6	22.5	18.2	0.0	0.0	8.9	72.9	100.0

*For further details about the road hierarchy please refer to footnote 2

When penalties in the RRI are removed, a noticeable redistribution occurs across the challenge levels. Many road links, which were previously designated as extremely challenging under both the expert-weighted and equal-weighted approaches, transition to slightly challenging or moderately challenging categories. This indicates that, within the standard RRI, penalties are pivotal for a conservative assessment of road link suitability for automated driving. This further implies that the majority of road links in the case study area either fail to meet current road safety standards or have technological limitations, creating a complex environment for AVs. Another observation is that the presence of HD maps (see results of scenario 2) mitigates numerous penalties within the network, a result stemming from the structural nuance of the assessment framework. Conversely, road links categorised as least challenging largely retain a consistent presence across the network, regardless of penalty adjustments.

Lastly, the omission of certain components from the RRI was examined to understand their individual impact on the overall index. In all scenarios, the proportion of road links classified as extremely challenging remained unchanged. This suggests that the index incurred penalties because multiple components exhibited poor performance in scoring the measurement variables. However, it is evident that some components, when omitted, influence the distribution more than others. For instance, removing the condition of road markings, road boundaries, and facilities for vulnerable road users resulted in noticeable fluctuations in both the slightly challenging and least challenging categories, especially in Scenario 3. Similarly, in Scenario 2, communication facilities and the number and diversity of road users components were observed as critical factors in determining the suitability of road links for automated driving.

In summary, the sensitivity analysis of the RRI brings attention to the influence of certain components, the role of penalties, and the effects of weight adjustments. While the fundamental structure of the RRI is consistent, it is important to be aware of these sensitivities to ensure its effectiveness across various contexts. When utilising the RRI as a tool, these findings can provide valuable insights for those in decision-making roles.

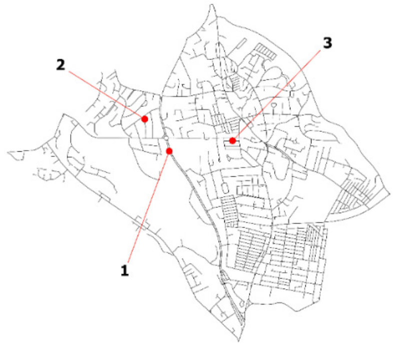
5.4.4.4 Recommendations for improving the road infrastructure for AVs

The implementation of the Road Readiness Index (RRI) in the case study area, complemented by the visualisation of its outputs, offers crucial insights for policymakers and road authorities. These insights highlight prevalent issues within the road network, indicating potential measures that could be proactively taken during the shift towards automated driving. Such measures can be considered to address anticipated equity and accessibility challenges due to the variation in road infrastructure. These issues can be briefly explained as follows:

- There is a common view that higher penetration of AVs may lower parking demand in residential areas and in business districts by reducing car ownership and increasing ridesharing. However, during the initial stages of AV deployment, there is a need to substantially modify parking layouts and rights-of-way to mitigate conflicts between AVs and their surrounding environment, as well as interactions with human-operated vehicles. To ensure the safe operation of AVs, particularly on local and minor roads (e.g. snapshot 2 in **Figure 5.7**), reconsideration of on-street parking regulations might be essential. For narrow roads, measures such as implementing a one-way system or permitting parking only on one side may be worth considering. These approaches also necessitate clear markings of prohibited road sections and parking spaces.

- Another prevalent issue within the road network is the high number of dead-end streets. As it is not yet clear how AVs will navigate such roads, in this index, these road sections were considered as extremely challenging for both AV capabilities. However, not all dead-end streets will likely present high challenges. Some, due to the presence of well-designed turning points at their ends, may allow AVs to manoeuvre easily. Yet, it was observed that inconsistencies in turning points, both in terms of their layout and size, as well as vehicle parking at these locations, pose challenges for AVs to manoeuvre smoothly. Therefore, to facilitate door-to-door AV services, considerable effort needs to be made towards standardising turning points and enforcing restrictions on on-street parking at these points.

- While urban trees are crucial for reducing the impacts of climate change (Tan et al., 2016) and contributing to walkable, societally desirable streets within the urban road network (Su et al., 2019), they can potentially present challenges for automated driving from several perspectives. Beyond the challenges for localisation (Cucor et al., 2022), trees and bushes have been observed as one of the main challenging roadside objects that cause obstructions on vertical traffic signs, street lighting and line-of-sight at intersections. Moreover, the accumulation of leaves on road surfaces can pose difficulties in detecting road edges or line markings, particularly during the autumn season. Although, digital mapping can help address this issue, more frequent maintenance of physical road elements in areas with high greenspace coverage will likely be required, and removal or pruning of trees may be necessary to mitigate potential obstructions.



RRI values: Scenario 1 0.6848 (LC) / 0.8038 (HC)
Scenario 2 0.8124 (LC) / 0.9153 (HC)
Scenario 3 0.8299 (LC) / 0.9328 (HC)

RRI values: Scenario 1 0.0000 (LC) / 0.0000 (HC)
Scenario 2 0.6863 (LC) / 0.7669 (HC)
Scenario 3 0.7214 (LC) / 0.8020 (HC)

RRI values: Scenario 1 0.0000 (LC) / 0.0000 (HC)
Scenario 2 0.0000 (LC) / 0.0000 (HC)
Scenario 3 0.0000 (LC) / 0.7776 (HC)

Figure 5.7 An overview of road sections with different RRI values in the case study area**.**

- Maintaining consistency in physical infrastructure features, aligned with AV requirements, will be critical for automated driving. Significant heterogeneity has been observed in the road network in terms of the quality of road surfaces, and traffic signs, as well as the condition and configuration of markings. Certain sections of roads, for instance, present visual challenges for vision-based systems due to the diversity of surface materials, the patching of potholes, and the presence of numerous manholes. To mitigate the potential risks for AVs, authorities need to consider regular maintenance schedules to enhance road infrastructure. This would also include adhering to a standardised and consistent methodology in the placement and maintenance of road markings and traffic signs. Furthermore, minimizing potential sources of confusion, such as numerous manholes and patches, can be achieved through comprehensive and organized planning during the stages of infrastructure development and repair. Therefore, there will likely be a need for advanced road assessment systems that can provide more accurate and precise data from the road network.

- While urban roads are often well-lit at night, object detection and recognition at night-time is a challenging task for AVs (Milford et al., 2020). As such, sufficient street lighting can significantly contribute to the perception systems of AVs by aiding in the detection of road markings, signs, and surrounding objects. Notably, it has been observed that some sections of the road network have limited lighting operation times due to energy saving strategies. However, with the introduction of AVs, there is a need to reevaluate these operational time restrictions, particularly around bus stops, pedestrian crossings, speed bumps, and intersections. There are other challenges like motion blur and glare that can cause failures under night-time conditions (Milford et al., 2020). Thus, AV developers must demonstrate that their systems can robustly handle challenges posed by inadequate lighting conditions.

- Wheelie bins exemplify objects that are neither static nor dynamic, yet frequently appear alongside roads in certain areas. They pose a unique challenge as they are not traditionally considered roadside furniture, yet their varying positions and outlines make their incorporation into a static world model difficult (AVSC, 2020). It was observed that wheelie bins often change position within many local roads (e.g. snapshot 3 in **Figure 5.7**), occasionally even located on the roadway. To mitigate this issue and reduce roadside severity, one recommendation would be for local authorities to consider reducing the number of individual household bins by implementing larger, communal ones, or designating specific areas for bin placement. This could potentially result in a more predictable roadside environment conducive to the safe operation of automated vehicles.

- The outputs of scenarios indicate that HD maps can effectively expand the operational areas of AVs by providing either prior or real-time information about the road environment. However, some studies have argued that digital maps will likely not be available or not be at the desired level for many cities in the early stage of AV implementation due to the cost of the mapping and communication technologies (International Transport Forum, 2023b; Tengilimoglu et al., 2023). Hence, to ensure a feasible and affordable investment in the early stages of implementation, initial efforts should be focused on major roads and crucial regions within the network that are expected to experience high travel demand. Policymakers and authorities need to develop incremental investment strategies for the digitisation of the road environment. However, most of the current initiatives come from the AV industry or service providers.

- Additionally, the digitalisation of infrastructure has the potential to support AVs by providing critical information (e.g. work zone, road closure, signal phase, speed limit) that can be used for their safe operations and allow potential improvements in real-time road monitoring and maintenance period scheduling (Mihalj et al., 2022). Communication technologies will also play a pivotal role in supporting the digitalisation of roads and the surrounding environment, where connectivity is deemed a key component. However, there are notable variations in the quality of cellular network services across the road network. Notably, lower quality of service was identified in densely populated areas of the road network, this can present a challenge for AV services aiming to maximise societal benefits. Similar to the strategy for HD maps, initial investments in high-quality cellular networks or short-range communication devices should be focused on major roads and crucial regions within the network.

- Intersections pose significant challenges for automated driving due to their dimensions, visibility issues and the complexity of traffic situations. Current AV trials in mixed traffic conditions reveal that intersections are the most challenging road sections for automated driving as most of the reported AV-involved accidents happened around the intersections. However, most of these accidents are rear-end crashes involving human-driven vehicles (Favarò et al., 2017). A recent report indicated that nearly all collision events involved one or more road rule violations or other errors by a human driver or road user (Schwall et al., 2020). At these locations, AVs need to detect, identify, and predict the actions of other road users, ensuring appropriate responses and trajectory planning. Although most signal-controlled intersections in the study area seem to pose relatively fewer challenges for automated driving, the diversity and configuration of lane markings might create difficulties, especially regarding lane detection and motion planning. As such, the role of advanced mapping technology becomes crucial. Road topological data for trajectory planning, or semantically enriched maps, can address these challenges. Otherwise changes to lane markings at such locations may be required.

- Last but not least, the performance of L4 AVs is expected to vary across different road environments (Chen et al., 2023). One of the likely key requirements to make automated driving technology work optimally in the UK will be the availability of large custom datasets gathered from urban streets that have been labelled in machine-learning-friendly ways with respect to markings, signage, streetlights and so forth. Such datasets will enable AV developers can improve their systems, while also assisting various AV service providers in familiarising themselves with the specific road conditions. This is crucial, as most current AV trials rely on their own collected data, and often restrict their operational zones to legally permitted areas.

5.5 Conclusions

Automated Vehicles (AVs) are expected to profoundly influence various dimensions of mobility, ranging from passengers' behaviour to urban spaces' structure (Soteropoulos et al., 2019). However, the adoption and operation of AVs hinge on the readiness of today's existing or near-future road infrastructure and this challenge is yet to be fully addressed. This study sought to bridge this gap by proposing a comprehensive assessment framework to evaluate the readiness of road networks for highly automated vehicles (L4 AVs) operation. The framework was then put into practice in a specific area in Leeds, United Kingdom, as a case study to demonstrate its practicality. Following this application, the study provided key insights that can aid decision-makers and transport planners in shaping future policies, regulations, and guidelines for AV implementation on road networks. While the framework is primarily tailored to the UK context, the index can be applied to different geographical regions with subtle variations.

A key conclusion from this study is the significant heterogeneity in readiness levels throughout the road infrastructure network. The network exhibits substantial diversity, from highly structured environments with robust infrastructure support to less structured ones with limited or no support. As such, the potential benefits of AV services in urban areas - such as enhancing mobility for disabled or elderly individuals, and providing affordable and accessible transportation (Milakis et al., 2017; Litman, 2023) - may not be immediately achievable under current conditions. Similarly, door to door shared options of AVs, for example, robotaxis, which are widely perceived to reduce reliance on personal vehicle ownership, may not be possible in the near term without significant infrastructural modifications or considerable advancements in AV technologies. This is largely due to the majority of road sections presenting a challenging environment for automated driving technologies, in terms of both digital and physical infrastructure. A common assumption among stakeholders is that AVs operate safely on high-quality roads, and cities or areas with poor road infrastructure are predicted to be slow to adopt AVs. Such a situation could precipitate equity issues within communities, as access to AV-based services may be limited to certain AV-compatible zones. This disparity could also influence property values, thereby exacerbating existing social inequalities.

Given the diverse nature of urban roads and their conditions, the advantages and disadvantages of the deployment of L4 AVs will vary from one urban area to another, leading to a selective deployment of AVs in certain areas. As highlighted by stakeholders in a recent report (International Transport Forum, 2023a), the introduction and management of AV-based services should be aligned with policy objectives such as enhancing safety, improving accessibility, increasing equity, mitigating environmental impact, and stimulating economic development. Despite the evident heterogeneity in road environments, the findings highlight that the main roads, those at the upper echelons of the network hierarchy, demonstrate a relatively high readiness value for AV operation. This observation is consistent with the insights obtained from a study conducted in Vienna, Austria (Soteropoulos et al., 2020). Therefore, a strategic approach that prioritises these segments for the initial investment for enhancement of road infrastructure and integration efforts for AVs seems sensible. Particularly, the digitisation of the road environment should commence from main roads to optimise societal benefits and financial viability. This initiative could further aid in the adoption of shared mobility services of AVs, such as shuttles or buses, that operate within specific subnets of the network. Nonetheless, actualising this vision necessitates proactive government backing facilitated through a well-designed regulatory framework for AV-based services (Tengilimoglu et al., 2023c).

Another critical issue is that the transition stage should be carefully managed, as technological advancements in the AV industry and modifications in physical and digital road infrastructure are likely to occur at different speeds. In this regard, authorities should be aware of the potential operational areas in their networks for these new technologies to effectively manage the transition phase. The framework presented in this study can serve as a valuable tool for such an undertaking. Implementing the readiness index can offer authorities preliminary insights into their road network without running actual AV trials. This approach is especially beneficial for cities yet to experience AV deployments, as waiting for real trials might result in substantial delays due to the barriers related to costs, technological limitations, supply chain issues, and local regulatory environments. Furthermore, city authorities have an opportunity to position their road networks attractively for AV developers. By identifying and promoting suitable operational areas, they not only ease the path for AV integration but also become an attractive spot for the emerging AV sector. Moreover, the insights derived from the assessment can be instrumental in refining AV control strategies. Utilising these outcomes to identify and anticipate highly challenging road sections enables AVs to proactively adjust their driving behaviours—for example, by decelerating earlier upon approach.

However, as AV technology continues to evolve, there would be a need to continuously adapt and revise the assessment framework to reflect the state-of-the-art technology and the emerging requirements for road infrastructure. Additionally, subsequent phases of this research should focus on examining the demand side of automated driving, specifically investigating how variations in the readiness level of road infrastructure could influence the accessibility of AV-based services, and in turn, alter traffic patterns within the network. The study conducted by Madadi et al. (2019) may serve as a valuable reference for this exploration. Furthermore, the integration of travel models into the readiness index can yield more comprehensive and nuanced insights. For example, this inclusion could enhance the understanding of the capacity of current road networks to accommodate AV-based services, and identify which areas or demographics may reap the most benefits. This enriched understanding could provide road authorities with valuable inputs for investment agendas, providing a basis for better optimisation of infrastructure.

Finally, as the current study is more of an exploratory and conceptual model than a descriptive index, it is clear that further research is needed in certain areas:

- Firstly, the proposed assessment framework was developed based on relevant literature and insights of experts, rather than empirical findings, due to the limitations associated with the availability of real-world AV data. As such, the importance level of the proposed index components was determined by experts based on a simple ranking technique. Moving forward, in-depth interviews or focus group discussions with stakeholders could potentially refine the index structure, particularly the scoring of measurement variables for specific use cases of L4 AVs. Such an approach may reduce the subjectivity inherent in the opinions of experts, leading to a more robust and universally applicable index.

- Secondly, the study has primarily focussed on relatively static factors and road environment attributes, due to the challenging nature of integrating rapidly changing dynamic factors into the road segment evaluation. With the ongoing advancements in intelligent transportation systems along with information and communication technologies, however, road and city authorities are gaining access to a myriad of dynamic data through sensors within the road network. Therefore, future iterations of this study should aim to develop a dynamic road readiness index incorporating the use of real-time data. For example, incorporating environmental conditions and traffic flow-related factors into the index by evaluating them in real time could offer a more comprehensive and responsive assessment of road suitability for AVs. Furthermore, leveraging real-time AV sensor data allows for dynamic modelling of parameters, such as the number and diversity of road users. This also enables the integration of research (Wang et al., 2018; Cheng et al., 2022) focused on modelling environmental complexity into to framework.

- Thirdly, given that physical attributes and amenities can significantly vary within a single road link or at intersections, future research might aim to evaluate road segments of equal or smaller lengths to increase the granularity of data. Specifically, implementing the index at a lane-level detail could offer a more precise understanding of the road environment. This would provide authorities with more specific information, optimising decision-making, and investment strategies for the development of “AV-compliant” road links.

- Fourthly, most data used in this study was assessed via visual inspection, employing aerial photography, satellite imagery, and street view services. However, these images, being snapshots from the past, present a limited perspective and are updated irregularly. Additionally, the evaluation process is potentially susceptible to human errors and can be time-consuming. Future research could consider the use of digital image processing techniques for the evaluation of subcomponents. While this method may require more resources and effort, the resulting insights could significantly enhance the accuracy and relevance of the readiness index for AVs. This becomes particularly important when real AV data are available that could provide more up-to-date information about the road environment.

- Lastly, a critical future direction for this study involves focusing on the validation and feasibility of the proposed framework using real-world AV test data, especially within UK cities. An analysis of network locations where AVs encounter collision risks or necessitate disengagement of their automated driving systems could serve as a basis for verifying the factors adopted in the (sub)components. Additionally, exploring the correlations between the Road Readiness Index (RRI) scores at these locations will be instrumental. Further, the weights or impact coefficients of these factors could be refined using a Bayesian network approach. This method would help mitigate the subjectivity associated with expert insights, providing a more objective basis for evaluating the framework's components. The recent study by Tu et al. (2023), which focuses on evaluating the safety risks for AV road testing in China using iRAP attributes, could offer a valuable methodological reference for this verification process.

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CHAPTER 6

The effects of infrastructure quality on the usefulness of automated vehicles: A case study for Leeds, UK

Abstract: With rapid advancements in automated driving technologies, there is a growing emphasis on enhancing physical and digital infrastructure to ensure safe and efficient integration of Automated Vehicles (AVs) into road networks. This study conducts the first exploratory analysis of the impact of heterogeneity in road infrastructure readiness on the usefulness of AVs for urban commuting, with a focus on Leeds, UK. Employing a hypothetical scenario where current car commuters have access to AVs for their daily trips, this research explores possibility of replacing commuting trips by AVs, given the existing levels of infrastructure readiness. Through the evaluation of various road network configurations and AV capabilities, the study evaluated the usefulness of AVs for such journeys. The findings reveal that infrastructure readiness levels significantly impact AV performance and usefulness, potentially necessitating infrastructure upgrades to facilitate future AV deployment. The analysis indicates that relatively less challenging paths for AVs tend to be longer than those typically used by human-driven vehicles, with an increase of approximately 5 miles (8 km) in travel distance for some origin-destination pairs. Despite only 20% of road links being classified as extremely challenging within the network, their dispersed distribution resulted in significant connectivity barriers, rendering a considerable number of trips infeasible for AV navigation. The research findings can provide valuable insights to help understand the integration of AVs into road networks and assist decision-makers and transport planners in developing informed and forward-looking policies, regulations and guidelines.

Keywords: Automated vehicles, Infrastructure assessment, Physical and digital infrastructure, Urban road network, Commuting patterns

6.1 Introduction

Automated Vehicles (AVs) are expected to bring transformational changes in transport and society by transferring some or all of driving responsibilities from human drivers to computer-based systems. This paradigm shift is promising an array of potential benefits, including enhanced road safety and efficiency, improved accessibility and productivity for individuals, and a reduction in energy consumption (Fagnant and Kockelman, 2015; Wadud et al., 2016; Milakis et al., 2017; Harb et al., 2021). However, the realisation of these benefits crucially hinges on the safety assurance of the Automated Driving System (ADS), which manages the dynamic driving tasks at Level 3 automation and above (SAE International, 2021). As underlined by Madadi et al. (2021), many studies have examined the impacts of AVs under the scenario where the entire vehicle fleet is fully automated (Level 5), with an unlimited Operational Design Domain (ODD).[30] As such the primary benefits are derived from the ability of Level 5 AVs to navigate the entire road network under all conditions without human intervention. Nonetheless, achieving a high market penetration rate of fully automated vehicles is expected to be a gradual process, potentially spanning several decades (Saeed et al., 2021; Litman, 2023; Bishop, 2024).

The successful integration of AVs into road systems necessitates comprehensive preparation across multiple fields, including transport infrastructure, policy and legislation, technological innovation and consumer acceptance (Rashidi et al., 2020; Tengilimoglu et al., 2023a). Among these, the role of infrastructure in facilitating automated driving[31] has been underestimated in the last decade (Farah et al., 2018; Tafidis et al., 2021). The main effort in the domain has largely been vehicle-centric, with safety and reliability concerns predominantly assessed from the perspective of the vehicle itself. Nonetheless, there is an emerging consensus among stakeholders on the critical role of infrastructure, especially digital infrastructure, in paving the way for the deployment of highly automated (Level 4) vehicles[32], i.e. vehicles that do not require fallback to a human driver (Tengilimoglu et al., 2023b). Similarly, empirical

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[30] Broadly, the ODD is characterised as the specific operational conditions under which a particular driving automation system is designed to function. This encompasses factors like environmental constraints, geographical boundaries, time-of-day limitations, and specific traffic or road attributes (SAE International, 2021).

[31] In this study, the term "automated driving" is used to describe the technology that integrates automation of the driving task, vehicle connectivity, and data management. Additionally, the terms "automated driving" and "automated vehicles" are used interchangeably.

[32] In this study, the automated driving system (ADS) is responsible for controlling L4 AV and performs the entire dynamic driving task (DDT) while the system is engaged. The ADS continuously monitors all relevant ODD attributes; if any attribute falls outside its specified range, the ADS can no longer autonomously operate the vehicle. In such scenarios, the vehicle occupant must take control, or the ADS will execute a minimal risk manoeuvre, such as a safe stop. If the occupant takes control, the journey may continue, but the vehicle will no longer be under ADS operation. We specifically refer to scenarios where the occupant remains a passenger, and the ADS is solely responsible for completing the trip.

studies examining current AV trials (Ramanagopal et al., 2018; Klauer et al., 2023) and analyses of AV-involved accidents or disengagement reports from AV manufacturers (Ye et al., 2021) underscore that AVs require road infrastructure that is conducive to their operational needs.

On the other hand, the operation of AVs to date has largely been confined to testing and piloting initiatives within specific geographical areas, characterised by well-defined road types and relatively less complex driving environments under certain weather conditions (Erdelean et al., 2019). This strategic limitation has been instrumental in fostering repeated experiences crucial for learning and continuous improvement, essential for unlocking automation benefits. However, it has concurrently constrained the geographical spread of automated services offered by developers (International Transport Forum, 2023a). As AVs become more prevalent across a broader section of the road network, identifying the types of infrastructure that could enhance their safety-critical functions becomes important (International Transport Forum, 2023a). Addressing these questions will likely be vital for acquiring essential insights into AVs' safe and efficient integration into the roadway ecosystem, including connected and intelligent systems.

In response, road authorities and safety organisations globally are exploring the potential infrastructure upgrades or adjustments that will likely accelerate the deployment of AV operations effectively (Huggins et al., 2017; Santec and ARA, 2020; Gopalakrishna et al., 2021; PIARC, 2021). Additionally, many studies have provided extensive lists of possible infrastructure modifications to support the safe integration of AVs, drawing on comprehensive literature reviews (Farah et al., 2018; Liu et al., 2019; Tengilimoglu et al., 2023c) and expert opinions (Lu et al., 2019; Wang et al., 2022; Tengilimoglu et al., 2023b). Implementing these infrastructure adjustments, however, presents complex challenges that demand substantial resources and financial investment. Therefore, many studies have attempted to use optimisation or cost-benefit analysis to determine the most cost-effective network-wide plan for the deployment of AVs. Such research has led to the proposition of various policies and infrastructural strategies tailored to AV-compatible road systems (Madadi et al., 2021; Manivasakan et al., 2021), including the establishment of dedicated AV lanes (Razmi Rad et al., 2020), designated AV zones (Conceição et al., 2017), and AV-ready subnetworks that facilitate mixed traffic or hybrid configurations (Madadi et al., 2019; Madadi et al., 2021).

However, to minimise the cost of infrastructure investment, evaluating the readiness level of current road sections is also critical in order to formulate a more economical plan. This consideration is particularly relevant given the financial constraints faced by infrastructure owners and operators in maintaining their roads to a certain quality standard (Tengilimoglu et al., 2023a). To this end, recent research efforts have focused on developing and applying assessment frameworks to evaluate the readiness of both physical and digital road infrastructure for supporting the safe operation of AVs (Soteropoulos et al., 2020; Cucor et al., 2022; Tengilimoglu et al., 2024). These studies have uncovered significant diversity within the road network, ranging from highly structured environments with robust infrastructure support to those less structured, with limited or no support. Yet, to date, no study empirically assessed the impact of infrastructure readiness levels on the usefulness and performance of AVs.

This research aims to fill this gap by focusing on the variations in the readiness of road sections in the network. To the best of the authors' knowledge, this study represents the first exploratory research evaluating the potential impact of heterogeneity in road infrastructure readiness on the use of AVs within a city network.[33] Understanding how variations in road quality and features affect potential AV use can enable the development of targeted strategies to upgrade and optimise the road network for future travel demand in the city. As such this investigation is crucial for identifying key areas requiring infrastructure improvements and for planning future developments to facilitate the widespread adoption of AV technology. Thus, the aim of this study goes beyond simply enriching the understanding of infrastructure readiness; it seeks to provide empirical insights for policymakers and road agencies as they prepare for the broader adoption of highly automated vehicles.

The organisation of the remainder of this paper is as follows: **Section 6.2** provides a brief overview of the assessment framework utilised for evaluating the readiness level of roads for automated driving. In **Section 6.3**, the practical application of this framework is explored, with an emphasis placed on the selected case study area. Additionally, this section presents the findings from the evaluation of the network based on various network configurations and AV capability scenarios. **Section 6.4** investigates the impact of heterogeneity in road infrastructure readiness levels on AV usage for commuting trips within the study area. The findings are discussed by means of comparison with trips made by human-driven vehicles. The final **Section 6.5** summarises the conclusions drawn from this research and offers recommendations for future studies in this field.

[33] The term of usefulness can be described from various perspectives, such as reducing driving stress during vehicle use. However, in this study, commuting trip completion rates serve as the metric for assessing usefulness.

6.2 Framework utilised to evaluate the readiness of roads for AV operation

Currently, there is no established official standard or benchmark for authorities to assess the readiness or compatibility of roads for AVs, primarily due to limited knowledge in the field. Despite this, there is a growing body of research aimed at developing a framework applicable across various contexts for evaluating the suitability of road networks for Level 4 AV operation. Initial studies in this area have taken a broad approach, often focusing on national (KPMG International, 2020) or city-wide indices (Khan et al., 2019; Jiang et al., 2022), which typically compare the rankings of various parameters to ascertain their readiness for AVs. Another prominent research approach involves using the definition of vehicles' Operational Design Domains (ODDs) as a baseline for identifying road sections suitable for automated driving. This approach is grounded in the understanding that various infrastructure and environmental conditions significantly influence an AV's ability to interpret its environment, thus affecting its operational capabilities (Mehlhorn et al., 2023). Within this context, several studies have developed classification schemes to categorise the capabilities of road infrastructure in supporting AVs and informing them about the functionalities provided by different road facilities (Carreras et al., 2018; Poe, 2020; García et al., 2021).

However, there is a noticeable research gap in specifically addressing urban roads within cities, attributed to the existing uncertainties in the field of automation. A limited number of studies so far have collected detailed data with special equipment from certain road sections, such as highways in a road network (Somers, 2019; Carter et al., 2019; Konstantinopoulou et al., 2020; FTIA, 2021) or public transit route (Cucor et al., 2022) to assess the level of readiness of roads. As an alternative to these limitations, some research has proposed frameworks relying on publicly available data to assess the complexity of road conditions and the surrounding environment for automated driving (Soteropoulos et al., 2020). Similarly, Tengilimoglu et al. (2024) have introduced an assessment framework, scoring segments of physical and digital infrastructure based on their characteristics to facilitate the deployment of AVs. This framework acknowledges the uncertainties in automated driving technologies and considers various scenarios of AV capability and supporting digital technologies in road networks. In this way, it helps explore different perspectives of technological advancement and their impact on the suitability of the current road network for AV use. Therefore, the Road Readiness Index (RRI) proposed by Tengilimoglu et al. (2024) was utilised for the current study. This section provides a concise overview of this framework.

The RRI framework integrates various components identified from relevant literature and stakeholder expertise in road vehicle automation (see **Table 6.1**). The weighting of these components (Wci) was derived from a 5-point Likert scale survey with 160 experts from various sectors in the automation domain. The framework also includes subcomponents, selected based on their relevance and the feasibility of data collection, with most assigned equal weight (Wci,j). Measurement variables within these subcomponents are defined in binary or categorical forms, according to data availability. Due to the uncertain impact of individual parameters on AV performance, grading systems for these variables were established, considering UK specifications for road design, operation, and maintenance. Each measurement variable was then assigned a score ($Sc_{i,j}$), ranging from 0 to 1, indicating the challenging level of a particular road segment for AVs.[34] In this step, two different Level 4 automated driving capabilities within the same use-case model were considered for evaluating the measurement variables of the subcomponents.[35] These are:

- ***Low Capability of L4 Automated Vehicle (LC):*** Refers to a basic automated vehicle with limited perception capacities, slower computational processing, and lower intelligence. It relies heavily on its surroundings for driving tasks and might need human intervention in challenging situations such as adverse weather or unexpected road closures.

- ***High Capability of L4 Automated Vehicle (HC):*** This vehicle features advanced software, extensive sensor coverage, quick decision-making capabilities, and relatively higher intelligence - results of accumulating machine learning experiences from real-life driving and simulation of various traffic situations. It is less dependent on the environment and demands minimal human intervention, thanks to its use of AI neural networks and high computing power.

Table 6.1 presents an overview of the RRI structure and supplementary **Table B.1** provides further details on performance grading for measurement variables (see **SM-2.1**). For an in-depth understanding of each component, subcomponent, and

[34] The measurement variables in the subcomponents are scored according to the level of difficulty for automated driving: 1=Least challenging, 0.75=Slightly challenging, 0.50=Moderately challenging, 0.25=Highly challenging, and 0=Extremely challenging.

[35] The AV industry is rapidly advancing with a focus on developing diverse automated driving technologies for different service models, each with unique capabilities (Shladover, 2022). This development is characterised by a spectrum of operational features influenced by the varying hardware, software, and sensors in AVs, which create distinct operational domains. Notably, even within the same service model, discrepancies in technology levels and computing resources lead to diverse driving capabilities (Wevolver, 2020).

measurement variable in the assessment framework, readers are referred to Tengilimoglu (2024).

The Road Readiness Index (RRI) is calculated for a road link in the network as follows:

$$RRI_{lm} = \sum_{i=1}^{14}\sum_{j=1}^{n}\left[Wc_i \times \left(Wc_{i,j} \times Sc_{i,j,m}\right)\right] \tag{6.1}$$

where *l* represents the road link in the network, *m* is the type of L4 automated driving capability level, *i* is component number in the index, *j* is the subcomponent number in the corresponding component, *n* is the total number of subcomponents in the corresponding component, Wc_i and $Wc_{i,j}$ are the corresponding weight of components and subcomponents, and $Sc_{i,j,m}$ is a score of measurement variables in a certain subcomponent. The weights attributed to the components and indicators are subject to the following constraints:

$$\sum_{i=1}^{14} Wc_i = 1, \quad \sum_{j=1}^{n} Wc_{i,j} = 1 \tag{6.2}$$

RRI values range from 0 to 1, where a low score indicates that road infrastructure quality and the surrounding environment are unlikely to be suitable for automated vehicles to safely operate. On the other hand, a high score indicates that the infrastructure quality and condition of a road section are very likely to be suitable for automated driving. However, if the result of any component score in the analysis of a road link is zero ($i.e. \sum_{j=1}^{n} Wc_j \times Sc_{j,m} = 0$), it is assumed that the RRI_{lm} for that link is also zero. This assumption is made because the zero result suggests that the road situation is extremely challenging for AVs. This implies that the road link poses such difficulties and risks that the other framework components alone are not sufficient to ensure safe and reliable operations for AV. Therefore, a zero RRI is assigned to signify the severity of the road conditions and the need for additional measures or improvements before AVs can navigate that road link effectively.

Table 6.1 Overview of the components, subcomponents, and corresponding scores of the Road Readiness Index, adopted from Tengilimoglu et al. (2024).

Ci	Wci	Framework components	Ci,j	Wci,j	Subcomponents	LC (Sci,j)	HC (Sci,j)
C1	0.0733	Road Geometric Challenges	C1,1	0.25	Horizontal curvature	(0, 0.5, 1)	(0.25, 0.75, 1)
			C1,2	0.25	Longitudinal gradient	(0.25, 0.75, 1)	(0.5, 1, 1)
			C1,3	0.25	Road width consistency	(0, 0.5, 1)	(0.25, 0.75, 1)
			C1,4	0.25	Digital mapping of road geometry	(0, 1)	(0, 1)
C2	0.0653	Road Surface	C2,1	0.5	Road surface type	(0, 0.5, 1)	(0.25, 0.75, 1)
			C2,2	0.5	Road surface condition	(0, 0.5, 1)	(0, 0.75, 1)
C3	0.0731	Road Markings	C3,1	0.25	Digital mapping of road markings	(0, 1)	(0, 1)
			C3,2	0.25	Marking configuration	(0, 0.25, 0.50, 0.75, 1)	(0, 0.50, 0.75, 1, 1)
			C3,3	0.5	Marking condition	(0, 0.50, 1)	(0, 0.75, 1)
C4	0.0681	Road Boundaries	C4,1	0.5	Median type	(0, 0.25, 0.50, 0.75, 1)	(0.25, 0.50, 0.75, 1, 1)
			C4,2	0.25	Road edge condition	(0, 0.50, 1)	(0.25, 0.75, 1)
			C4,3	0.25	On-street vehicle parking	(0, 0.50, 1)	(0.25, 0.75, 1)
C5	0.0718	Traffic Signs Visibility	C5,1	0.5	Digital mapping of traffic signs	(0, 1)	(0, 1)
			C5,2	0.5	Traffic signs conditions	(0, 0.25, 0.50, 1)	(0, 0.50, 0.75, 1)
C6	0.0718	Special road section	C6,1	1.0	Special road sections	(0, 0.25, 0.50, 0.75, 1)	(0, 0.50, 0.75, 1, 1)
C7	0.0651	Road Lightning	C7,1	1.0	Lighting condition	(0, 0.25, 0.50, 1)	(0.25, 0.50, 0.75, 1)
C8	0.0707	Speed Limit	C8,1	1.0	Speed limit of road section	(0, 0.25, 0.50, 1)	(0, 0.25, 0.50, 1)
C9	0.0750	Number and Diversity of Road Users	C9,1	0.50	Road access	(0, 0.25, 0.50, 1)	(0.25, 0.50, 0.75, 1)
			C9,2	0.25	Counterflow	(0, 1)	(0.25, 1)
			C9,3	0.25	No. of lanes	(0,25 0.50, 1)	(0.25, 0.75, 1)
C10	0.0646	Roadside Complexity	C10,1	0.25	Presence of trees	(0, 0.50, 1)	(0.25, 0.75, 1)
			C10,2	0.25	Street furniture density	(0, 0.50, 1)	(0.25, 0.75, 1)
			C10,3	0.25	Proximity of buildings	(0, 0.50, 1)	(0.25, 0.75, 1)
			C10,4	0.25	Digital mapping of surrounding road environment	(0, 1)	(0, 1)
C11	0.0761	Facilities for Vulnerable Road Users	C11,1	0.25	Pedestrians crossing type	(0, 0.25, 0.50, 0.75, 1)	(0.25, 0.50, 0.75, 1, 1)
			C11,2	0.25	Pedestrian sidewalk	(0, 0.50, 0.75, 1)	(0.25, 0.75, 1, 1)
			C11,3	0.25	Cycling infrastructure	(0, 0.50, 1)	(0.25, 0.75, 1)
			C11,4	0.25	Public transit access point design	(0, 0.25, 0.50, 0.75, 1)	(0.25, 0.50, 0.75, 1, 1)
C12	0.0770	Precautions for Roadworks and Incidents	C12,1	1.0	Precautions for roadworks and incidents	(0, 0.25, 0.50, 0.75, 1)	(0.25, 0.50, 0.75, 1, 1)
C13	0.0779	Localisation Challenges	C13,1	0.5	Localisation challenges	(0, 0.25, 0.50, 0.75, 1)	(0, 0.50, 0.75, 1, 1)
			C13,2	0.5	Digital mapping of road environment	(0, 1)	(0, 1)
C14	0.0702	Communication Facilities	C14,1	1.0	Cellular network coverage	(0, 0.25, 0.50, 0.75, 1)	(0, 0.50, 0.75, 1, 1)

6.3 Application of the Road Readiness Index to road network

6.3.1 Study area and road network

This research examines the integration of Level 4 Automated Vehicles (L4 AVs) within the road network of Leeds, a city in the United Kingdom. Leeds is the second largest Metropolitan district in England with a population of 812.00 and has witnessed considerable economic growth in the last decades (ONS, 2021). The city is divided into 33 wards or alternatively 107 census Middle Layer Super Output Areas (MSOAs) with an average population of just over 8,000 each (ONS, 2021). The selection of Leeds for the application of RRI is grounded in several factors. Leeds exemplifies a variety of urban forms that mirror the historical development patterns common to many UK cities, as discussed in a government document focusing on urban form and infrastructure (Williams, 2014). The city's diverse road network, featuring both radial and grid patterns, along with its suburban growth, highlights the typical infrastructure challenges and opportunities present in many urban areas within the UK. Therefore, Leeds, with its substantial population, intricate urban structure, and surrounding suburbs, presents a representative view of both the potential benefits and complexities inherent in the deployment of AVs.

Leeds' road network, comprising approximately 4,200 km (2,610 miles) includes a variety of roads at different hierarchical levels.[36] The road is depicted by over 50,000 road links by Ordnance Survey, Great Britain's national mapping agency. For the purposes of this study, the analysis is concentrated solely on major roads, deliberately excluding local and access roads. This focus is informed by the study of Tengilimoglu et al. (2024), which found that local and access roads generally have lower Road Readiness Index (RRI) values, indicating higher challenges for the operation of automated vehicles. Therefore, local and access roads were excluded from the network. After this omitting, the remaining sections of the network amount to about 1,300 km (808 miles), represented by over 13,000 links.

[36] Ordnance Survey classifies the UK's road hierarchy according to their function. These are: 1) *Motorway*, which is a multi-carriageway public road connecting important cities. 2) *A Road*, which is a major road intended to provide large-scale transport links within or between areas. 3) *B Road*, which is a road intended to connect different areas, and to feed traffic between A roads and smaller roads on the network. 4) *Minor Road*, which is a public road that provides interconnectivity to higher classified roads or leads to a point of interest. 5) *Local Road*, which is a public road that provides access to land and/or houses, usually named with addresses. Generally, not intended for through traffic. 6) *Local Access Road*, which is a road intended for the start or end of a journey, not intended for through traffic but will be openly accessible. 7) *Restricted Local Access Road*, which is a road intended for the start or end of a journey, not intended for through traffic and will have a restriction on who can use it. 8) *Secondary Access Road*, which is a road that provides alternate/secondary access to property or land not intended for through traffic.

However, implementing the index across such an extensive road network presents challenges in terms of data collection and evaluation since individually assessing each link requires intensive resources. Therefore, the case study area was narrowed down to cover the north-western part of the city (consisting of 44 MSOAs and representing over 40% of the population). The selected area is a mosaic of different urban forms such as: the central business district, offices and shops, residential areas, suburbs, and rural areas. Moreover, it covers key locations such as universities, hospitals, the city centre, and the main transport hubs such as central train station and airport. The choice of focusing on the northern area of Leeds is mainly based on its demographic characteristics. This region is distinguished by relatively higher income levels and lower scores on the Index of Multiple Deprivation (IMD)[37] compared to other areas in Leeds.[38] Such demographic attributes suggest that residents in this area might be early adopters of AV technology, primarily for commuter trips (Wadud and Mattioli, 2021; Rahman and Thill, 2023). Additionally, this area serves as an appropriate case study for early AV buyers, considering that the cost of AVs is likely to be higher than that of vehicles in the current mass automotive market (Transport Systems Catapult, 2017; International Transport Forum, 2023b). **Figure 6.1** illustrates the selected 44 Middle Layer Super Output Areas (MSOAs) (shown in yellow) in the northwest part of the city boundary and selected major roads for analysis (depicted in red) within the road network of Leeds.

The road network data for Leeds were obtained from the Ordnance Survey MasterMap Highway for the year 2023. After data cleaning for road segments that are restricted to traffic (e.g. bus gates), dead-end roads, or do not have street view data, 5,456 road links were obtained for analysis in the selected study area. The average length of road links is calculated approximately as 74.3 m, resulting in a total road network length of 405.2 km. The Motorway network spans 9.76 km, accounting for 2.41% of the total. The A Road Primary network extends over 118.29 km (29.19%), while the A Road network measures 29.55 km (7.29%). The B Road network covers 16.45 km (4.06%). The Minor Road network is the largest, with a length of 227.85 km, constituting 56.24% of the network. Lastly, the Local Road[39] network encompasses 3.27 km, making up 0.81%.

[37] The Indices of Multiple Deprivation (IMD) are utilised in the UK as a comprehensive tool for identifying areas that are subject to various forms of deprivation. This index consists of data from diverse domains to formulate an overall relative measure of deprivation experienced by individuals within a specific area. More detailed information about the IMD, including its methodology and applications, can be found at the Consumer Data Research Centre (CDRC). Source: https://data.cdrc.ac.uk/dataset/index-multiple-deprivation-imd

[38] https://www.plumplot.co.uk/Leeds-salary-and-unemployment.html

[39] The inclusion of 56 local roads in the case study network ensures consistency with the previously established travel demand model, which utilised here for analysis.

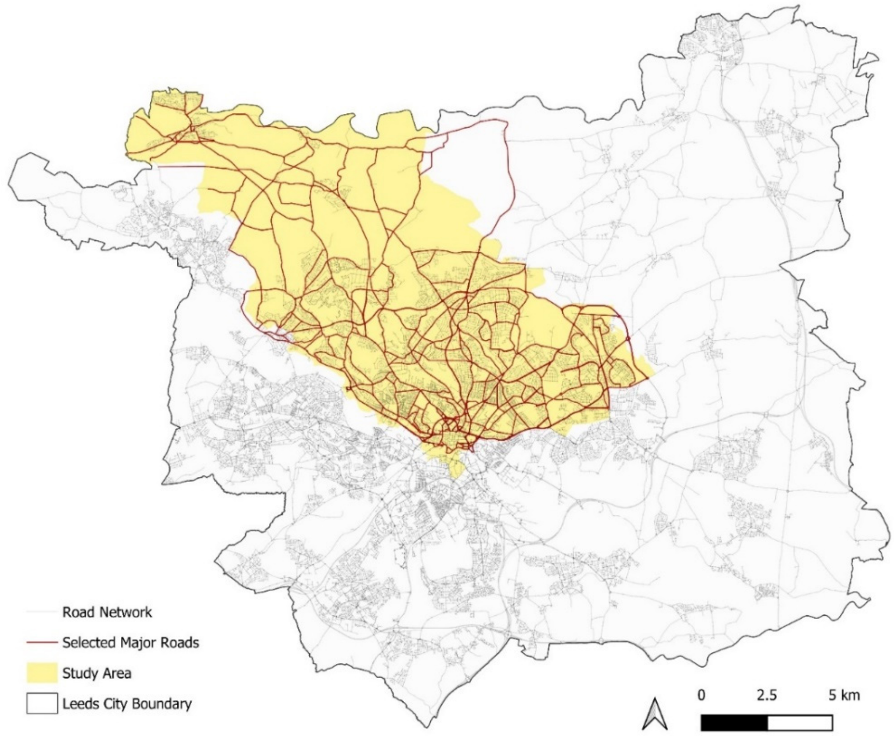

Figure 6.1 Location map indicating study areas of Leeds, UK and select road sections in the network. MasterMap Highway © Crown copyright and database rights "2023" Ordnance Survey (AC0000851941).

6.3.2 Data collection and score assignment for road sections

This section provides a concise overview of the method for assigning scores to real-world road networks, following the conceptual framework introduced in **Section 6.2**. As previously highlighted, evaluating the various (sub)components of the Road Readiness Index (RRI) heavily relies on extensive field survey data, encompassing both physical and digital infrastructure information. The process of data collection, demanding significant time, labour, and financial resources, complicates the frequent updating of this information across the network. As a result, current data that are relevant to the components of the RRI are often limited in availability and accessibility. This scarcity poses challenges to the objective assessment of the suitability of road sections for automated vehicle operations.

Despite these challenges, street view imagery has been widely used in both quantitative and qualitative research to analyse built environments and urban landscapes (Arellana et al., 2020). Adopting a similar approach, this study primarily sourced data on road infrastructure conditions through visual inspections using aerial or satellite imagery and street view services such as Google Street View.[40] The approach also involved on-site observations for some locations that have limited information. Additionally, secondary data from a variety of sources (see supplementary material **SM-2.2**) was utilised to accurately reflect the specific requirements of (sub)components. This collected secondary data was categorised based on the scoring system and subsequently integrated into the corresponding road links using QGIS, an open-access Geographic Information System (GIS) platform. Following this, the visual inspection data was compiled into the measurement variables in the scoring systems. Thus, each link in the road network was characterised by scores, in detailed spatial dimensions.

Briefly, the authors utilised diverse sources to collect data representing each measurement variable within the subcomponents, this comprehensive evaluation of each road link spanned four months. Additionally, this study examines two potential scenarios within the network based on the anticipated advances in the information, communication, and vehicle industries. These are:

- ***Network Scenario 1*** represents the study area's existing road conditions, which currently lack High Definition (HD) maps due to the anticipated costs of digitalising the road network in the near future, as well as Roadside Units (RSUs) for information exchange. In this scenario, AVs must depend solely on onboard sensors to navigate road sections without a prior detailed map, and use the existing cellular networks for external connectivity. The detection of roadworks or construction sites around the roadway were considered as a challenge for AVs.

- ***Network Scenario 2*** introduces advanced surveying techniques to produce detailed city maps, providing HD maps for all roads in the study area through third-party services or authorities. However, due to cost and implementation challenges, RSUs are absent in the road network, even though established Vehicle-to-Infrastructure (V2I) communication standards and initiatives are in place to guide the deployment and interoperability of these systems. This is also due to the absence of an agreement between the AV industry and road authorities on any system for implementation. Consequently, AVs in this scenario rely exclusively on the existing cellular network for information exchange. Also, this scenario assumes the absence of roadworks or incidents in the area.

[40] The visual inspection is generally based on satellite images dated March 24, 2022 and April 26, 2023. However, the assessment of many road sections, primarily major roads, is based on the latest Google Street View images from the second half of 2023.

The scoring of the components in the index was adjusted to align with these scenarios. **Table S2.1** in the supplementary materials 2.2 (see **SM-2.2**) provides a detailed view of the data sources and assesses the quality and representativeness of the data for each component.

6.3.3 Results and interpretation of road assessment

The evaluation results for each measurement variable within the components of the Road Readiness Index (RRI), reflecting the near-time conditions of the road network, are visually detailed in the figures found in the supplementary materials 2.3 (see **SM-2.3**). These results are integrated according to Equation 6.1, contributing to the final calculation of RRI values for road links. **Figure 6.2** displays the mapping of these integrated assessment outcomes for selected roads within the study areas. This mapping takes into account both low capability (LC) and high capability (HC) automated vehicles and the two different scenarios for the road network. In the figure, the index scores are divided into five distinct groups, each representing a different level of difficulty for automated driving. These levels range from extremely challenging to least challenging. This categorisation is essential as it highlights the varying degrees of suitability of different road sections for the facilitation of AVs. Such an approach provides a comprehensive understanding of how well different parts of the road network in Leeds can accommodate AVs, considering the specific capabilities of the vehicles and the complexities of the road environment. This categorisation serves as a critical tool in identifying areas that might need improvement or are already well-suited for the introduction of automated vehicle technology.

In Scenario 1, considered the base case scenario, a substantial portion of road sections in the case study area are classified as extremely challenging for the operation of both LC and HC AVs. Approximately 20% of the selected road links for LC AVs and 18% for HC AVs fall into this category, indicated by the colour red in the visual outputs (see **Figure 6. 2**). This situation is mainly attributed to factors such as poor-quality road infrastructure and the complexity of the surrounding driving environment, which result in the index score being penalised. Notably, the lowest RRI values are typically observed in rural areas in the northern parts of the study area. Common issues in these regions include the absence of road markings, detectable road edges, pedestrian sidewalks and consistent road widths, as well as poor road surface conditions. Additionally, factors such as high vegetation coverage surrounding the roads, a lack of street lighting, and poor cellular coverage further contribute to the challenges faced by AVs in these areas. Similarly, some residential areas also exhibit low RRI values due to lacking road markings, having narrow streets with on-street vehicle parking, poor road surface conditions, and traffic signs obstructed by trees bushes or obstructed by graffiti.

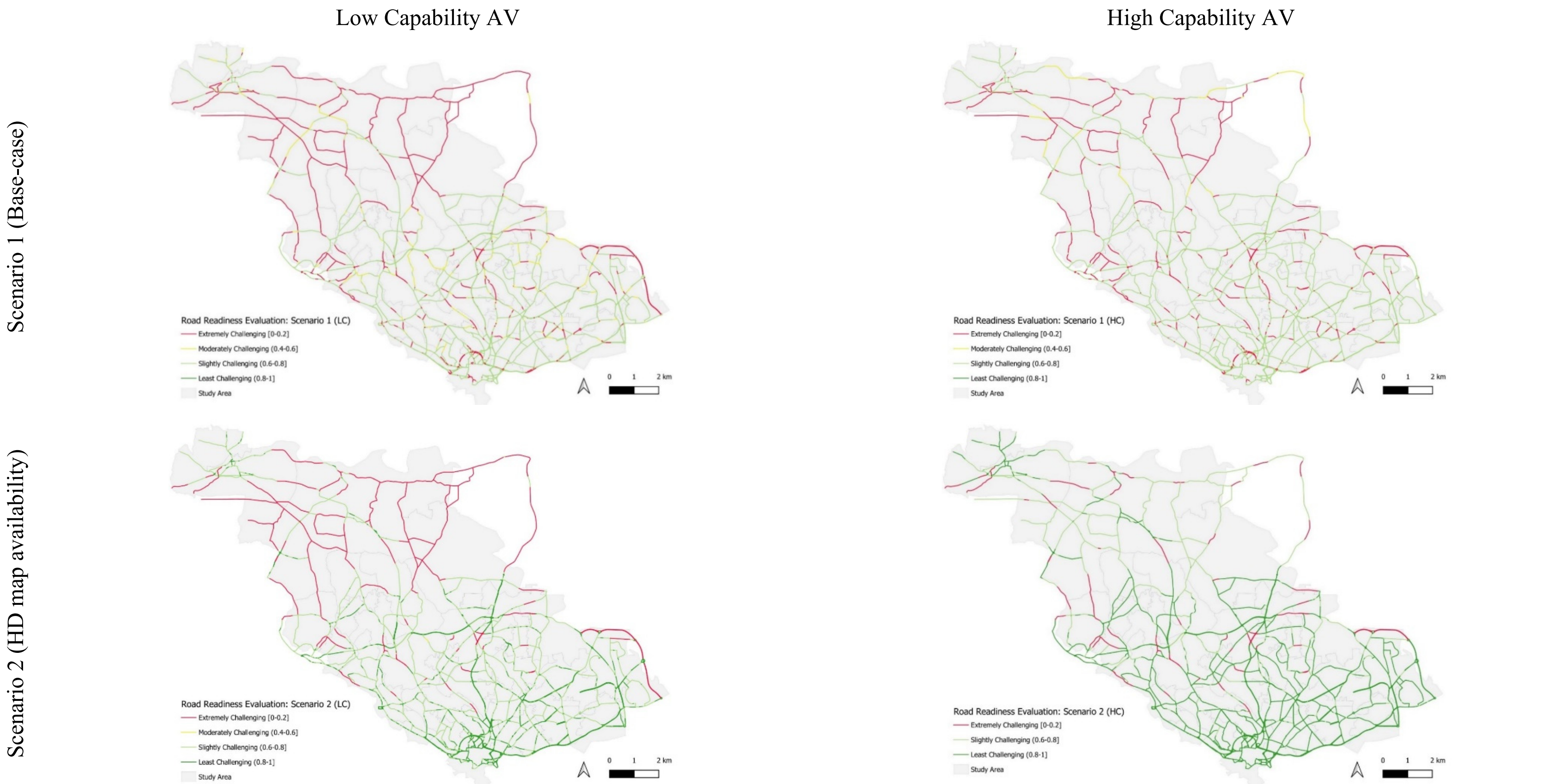

Figure 6.2 Overview of the assessment of the readiness of roads in Scenario 1-2, comparing low capability AV (left) and high capability AV (right). MasterMap Highway © Crown copyright and database rights "2023" Ordnance Survey (AC0000851941).

In urban areas, sections that are particularly challenging for AVs are often found in links with traffic islands designated for pedestrian crossings. These areas are characterised by a high density of street furniture and a noticeable lack of road markings that are important as a primary or secondary input for AV detection and lane localisation. Similar challenges are observed at many single or two-lane roundabouts, particularly due to their curvature forms, resulting in sections that are extremely challenging for AVs. Additionally, road segments passing through tunnels or longer underpasses tend to receive lower RRI scores, primarily due to localisation and illumination challenges inherent in automated driving. Moreover, road sections adjacent to roadworks or construction sites are also marked with lower scores, as they present complex and frequently changing layouts that pose navigation challenges for AVs.

On the other hand, as expected, the majority of road sections in the selected area demonstrate relatively high RRI values, with about 76% for LC AVs and 81% for HC AVs. These sections are classified as slightly challenging for AVs. This is primarily because these selected major roads form the main skeleton of the city's transport system, are maintained frequently, and meet certain safety standards for road users. One notable finding is that road links adjacent to the areas such as the central business district, offices, and shops, despite their complex surrounding environments, have received relatively high RRI values. The main reason for this is that these areas typically have a well-defined separation between Vulnerable Road Users (VRUs) and main traffic flows. Furthermore, they possess high-quality physical infrastructure, including lower speed limits and specifically designed parking bays and public transit access points. These features facilitate the detection of road edges by AVs, making navigation less challenging. Nevertheless, there are noticeable gaps, indicated by lower RRI values, among the road links with higher RRI scores.

In Scenario 2, which assumes the availability of HD maps for the entire road network and the absence of roadworks, there is a significant expansion in the operational areas for both LC and HC AVs compared to the base case scenario. The majority of road links in the network fall into the slightly and least challenging categories of the RRI for LC AVs. Notably, for HC AVs, this distribution has a predominance of links in the least challenging category due to their having advanced automated driving systems, encompassing sophisticated sensors and computational capacity. This shift highlights the vital role of HD maps in facilitating automated driving, as digital mapping of the environment is linked to many components within the index. HD maps are vital for road sections with poor markings, traffic signs, challenging geometries or localisation, as they provide crucial supplementary information for navigating difficult driving conditions.

Scenario 2 utilises static map layers to complement onboard sensors, aiding in precise localisation, enhancing perception beyond the immediate visual range, and facilitating more accurate path planning. This integration of HD maps significantly boosts the operational efficiency of AVs by addressing key information gaps. However, it is important to note that the provision of HD maps alone does not fully mitigate all the challenges in the road network. A considerable proportion of road links still present significant obstacles for AVs, mainly due to issues such as limited cellular coverage. This indicates that while HD maps are a significant step forward, they are part of a broader ecosystem of technologies and infrastructure improvements needed to fully facilitate effective and safe AV operations.

Table 6.2 details the distribution of road links in the case study area by road hierarchy and RRI category for both scenarios. Interestingly, the table shows that motorways have a relatively higher proportion of low RRI values compared to other road types, contrary to expectations. This is predominantly due to sections of motorways in the case study area that traverse long tunnels in the university region of the city centre, posing significant challenges in terms of lighting and localisation for AVs, particularly in the absence of HD maps.

Table 6.2 Distribution of road links by road hierarchy and RRI category for Scenarios 1,2.

Scenarios & AV types	Road hierarchy*	Road Readiness Index category					Total
		Extremely Challenging [0-0.2]	Highly Challenging (0.2-0.4]	Moderately Challenging (0.4-0.6]	Slightly Challenging (0.6-0.8]	Least Challenging (0.8-1]	
S1 – LC	Motorway	73	0	0	77	2	152
	A Road Primary	280	0	24	1088	0	1392
	A Road	108	0	6	283	0	397
	B Road	35	0	10	334	0	379
	Minor Road	596	0	166	2318	0	3080
	Local Road	8	0	9	39	0	56
	Total # of links	1100	0	215	4139	2	5456
	Percentage (%)	20.16	0.00	3.94	75.86	0.04	100.0
S2 – LC	Motorways	0	0	0	20	132	152
	A Road Primary	115	0	0	326	951	1392
	A Road	56	0	0	141	200	397
	B Road	6	0	0	215	158	379
	Minor Road	260	0	0	1622	1198	3080
	Local Road	0	0	1	45	10	56
	Total # of links	437	0	1	2369	2649	5456
	Percentage (%)	8.01	0.00	0.02	43.42	48.55	100.0
S1 – HC	Motorway	73	0	0	74	5	152
	A Road Primary	260	0	6	1124	2	1392
	A Road	84	0	9	302	2	397
	B Road	35	0	0	344	0	379
	Minor Road	529	0	9	2536	6	3080
	Local Road	8	0	0	48	0	56
	Total # of links	989	0	24	4428	15	5456
	Percentage (%)	18.13	0.00	0.44	81.16	0.27	100.0
S2 – HC	Motorway	0	0	0	5	147	152
	A Road Primary	96	0	0	85	1211	1392
	A Road	34	0	0	34	329	397
	B Road	6	0	0	18	355	379
	Minor Road	149	0	0	339	2592	3080
	Local Road	0	0	0	16	40	56
	Total # of links	285	0	0	497	4674	5456
	Percentage (%)	5.22	0.00	0.00	9.11	85.67	100.0

6.4 Analysis of AV usefulness in a heterogeneous road network

The implementation of the RRI on selected major roads in the case study area reveals a remarkable heterogeneity in terms of infrastructure and road conditions. This diversity primarily stems from variations in the quality and consistency of the infrastructure within the road environment. Such heterogeneity highlights the potential need for improvements in specific road segments, where existing conditions are less conducive to the safe operation of AVs. This situation also gives rise to the hypothesis that without specific modifications or upgrades to the infrastructure to meet automated driving requirements, seamless operation of AVs across the existing road network might be unlikely. As such this section investigates the effect of heterogeneity in road readiness levels within a network on the use of AVs.

6.4.1 Commuting trips within the study area

In examining the impact of existing road infrastructure on AV usefulness, the study focused on understanding the network's travel demand characteristics, mainly represented by origin-destination (OD) data. This data, capturing movement through geographic space from an origin to a destination, is crucial for understanding travel patterns. This study utilised open access data from the UK Census 2011, which contains aggregate statistics on number of commuters between administrative zones - Middle layer Super Output Areas (MSOA), by mode of travel (ONS, 2011).[41] The dataset provides 2011 estimates, classifying usual residents aged 16 to 74 in England and Wales by their method of travel to work.

Within the scope of this study, the focus is specifically on car or van driving as the mode of travel to work. This approach is taken to concentrate on how AVs could potentially replace existing trips made by human-driven vehicles. To maintain this focus, other modes of transportation, such as public transit and active transport (walking or cycling), are excluded from the analysis. Additionally, the study omits intra-zonal trips, which are trips that both start and end within the same zone (MSOA). These trips are typically shorter and may not significantly contribute to understanding the potential for AV usefulness. Some inter-zonal trips, particularly those that either start or end outside of the defined study area, are also excluded. This exclusion helps to maintain the relevance of the data by focusing on trips that are wholly contained within the study area.

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[41] Since the study focused solely on major roads within the network, using a Lower Layer Super Output Area (LSOA) level Origin-Destination (OD) matrix for this analysis is not suitable. This is primarily because many LSOA boundaries do not encompass major road links. Consequently, the LSOA-level OD matrix may not accurately reflect the traffic patterns and flows that are specifically relevant to the major roads being studied.

a)

b)

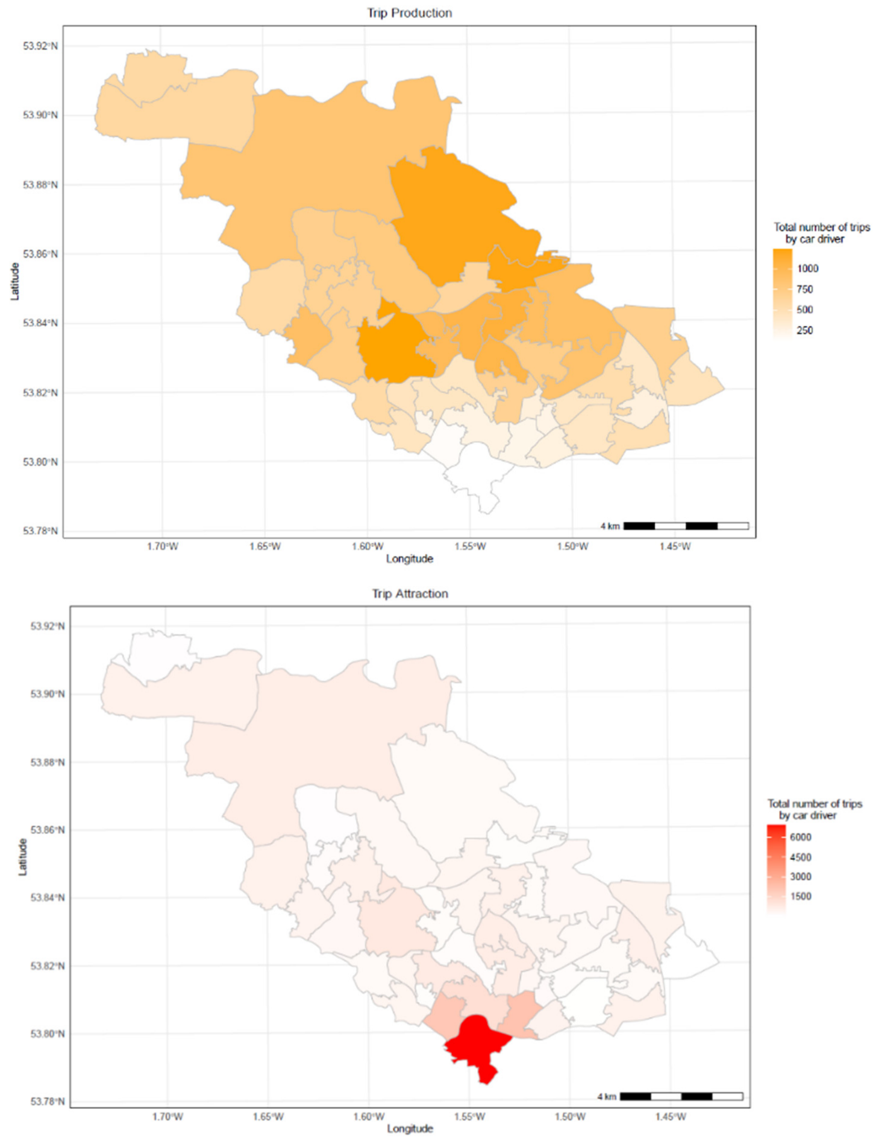


Figure 6.3 Trip production (a) and attraction (b) of MSOAs in selected study area for commuting trips made by car drivers only based on 2011 census data.

The analysis resulted in a total of 27,187 trips across 1,715 OD pairs within 44 MSOAs -134 OD pairs did not include any car or van trips for commuting. The number of these trips varied, ranging from 1 to 401. As expected, the main destinations of these trips are the city centre areas, where the main business district and transport hubs are situated. **Figure 6.3** illustrates the number of trips made by car drivers increases with distance from the city centre. Additionally, the distribution of Origin-Destination (OD) pairs exhibits homogeneity and encompasses nearly the entire network within the study area, making it an appropriate framework for analysing AV usage within the system (see **Figure 6.4**).

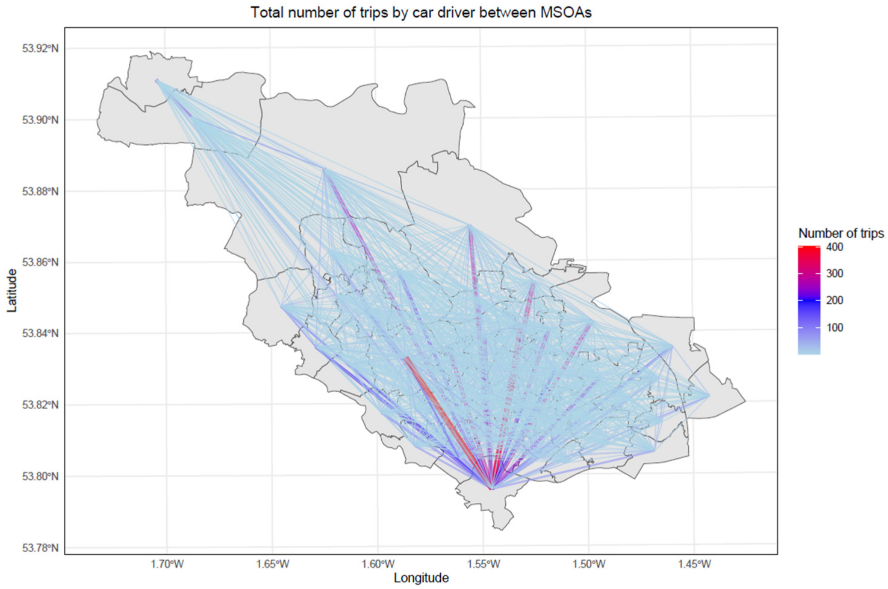


Figure 6.4 Distribution of commuting trips made by car drivers, illustrated by desire lines between centroids of MSOAs.

6.4.2 Converting spatial road network into a graph system for routing

After establishing the travel patterns within the study area, the subsequent stage involved transforming the spatial road network into a graph format for routing analysis. Street networks, a specific type of spatial network, possess unique characteristics and can be abstractly represented in various ways (Marshall et al., 2018). The prevalent method, and the one adopted for this study, involves representing each road as an edge within a graph, while intersections, typically found at road junctions, serve as vertices. This approach might also include vertices at points other than junctions, depending on the network's complexity (Gilardi et al., 2020). For this conversion, the study utilised the "igraph" package in R, a fast and open-source library for graph and network analysis (Csardi and Nepusz, 2006). In conjunction with "igraph", the "sf" (simple features) package (Pebesma, 2018) was employed for handling and manipulating spatial data.

The transformation of a three-dimensional road network, with overpasses, underpasses, and varied intersection types, into a two-dimensional graph system presents certain challenges (Gilardi et al., 2020). To address these, related nodes at these intersections were duplicated and assigned new identifiers, ensuring accurate link and node representation, and reducing potential routing errors. In addition, the graph system of the road network was constructed considering the traffic direction provided in the OS MasterMap Highway. However, due to its complexity, turn restriction rules at some junctions were not incorporated into the routing analysis.

Then, the closest nodes to each MSOA centroid were identified to represent the origin and destination points in routing. The analysis assumed an unlimited capacity for traffic volume on road links, simplifying the approach by excluding the potential for congestion. This assumption also implies that vehicles travel at the speed limit of each road section. Furthermore, time spent at junctions was not included in the analysis, as junctions were not a focus of this study, and the primary emphasis was on distance-based comparisons. The objective is not to find a precise result, but rather to demonstrate the potential impacts of heterogeneity in road infrastructure on AV usefulness.

Shortest path algorithms such as Dijkstra's or the A* search algorithm are designed to find the path with the lowest cumulative cost (or weight) between two nodes in a graph. In most cases, these algorithms are used to find the shortest distance or the least time-consuming path, where lower values are preferable. In the igraph package for R, the default method used for finding the shortest path is Dijkstra's algorithm (Dijkstra, 1959)[42]. Moreover, when calculating shortest paths, the default behaviour of the package is to consider the unweighted shortest path. This means that each edge in the graph is considered to have the same weight (usually a weight of 1), so the shortest path is determined based on the number of edges (i.e. road links). However, some links might be very short (a few meters) while others could be much longer (several miles). Therefore, the length of each edge was normalised by dividing it by the maximum length found in the graph. This puts all lengths on a scale from (0 – 1]. In this way, the algorithm balances between finding the fewest number of edges and the shortest total distance.

6.4.3 Results and interpretation of routing of commuting trips

The following subsections present the findings and interpretation of the shortest path analysis of OD pairs based on varying scenarios in network and vehicle capability.

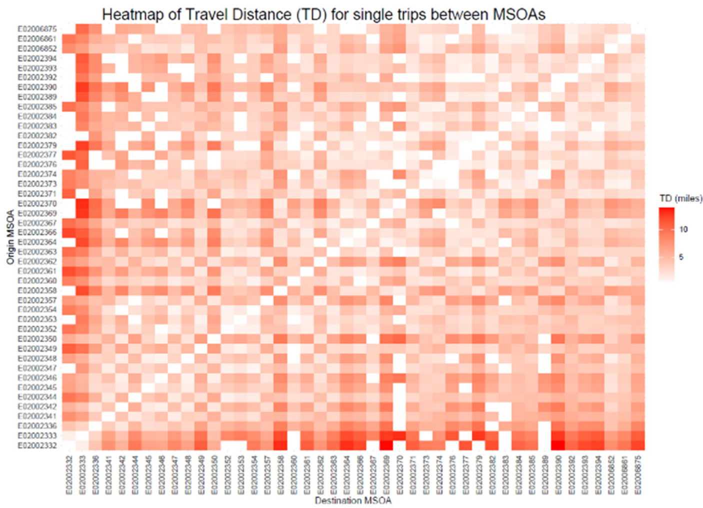
6.4.3.1 Base case scenario: Human-Driven Vehicle (HDV)

In this study, the base case scenario is defined by trips made by car drivers, representing human-driven vehicles (HDVs) in the network. The routing results for each OD pair in the weighted and directed road network are illustrated in **Figure 6.5**. This figure presents a heatmap showing the travel distance in miles for each shortest path of HDV trips, along with their corresponding durations at the speed limit. The average trip length is found to be 4.4 miles, with the shortest trip being 0.6 miles and the longest reaching 14 miles. Besides, the average trip duration in the case study area

[42] The algorithm works by iteratively selecting the node with the smallest distance from a starting point, then exploring its neighbours, updating their distances if a shorter path is found. This process is repeated until the shortest path to the destination node is determined.

is 8.8 minutes, with the fastest trips estimated at 1.3 minutes and the longest at 30.5 minutes.

a)



b)

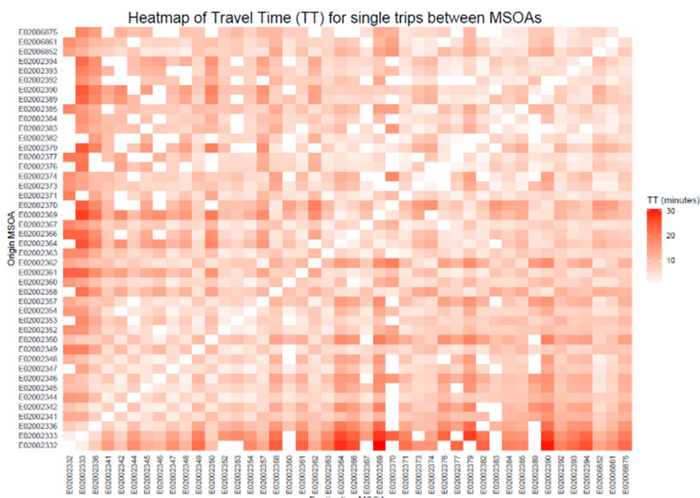


Figure 6.5 Heatmap illustration of travel distance for a single trip (left) and corresponding travel time (right) of 1,715 OD pairs within 44 MSOAs.

Adopting a similar approach to the concept of "edge betweenness", which refers to the number of shortest paths that pass through each edge (link) in a network (Lovelace et al., 2019), all 27,187 car trips for commuting across 1,715 OD pairs were allocated to corresponding road links. **Figure 6.6** visually represents the total number of car trips passing each road section within the network. This illustration is based on the shortest path calculations for each of the OD pairs, providing a clear depiction of the flow patterns on different road segments. It also provides insight into the most frequented routes in the network and helps in understanding the spatial distribution of HDV trips in the study area.

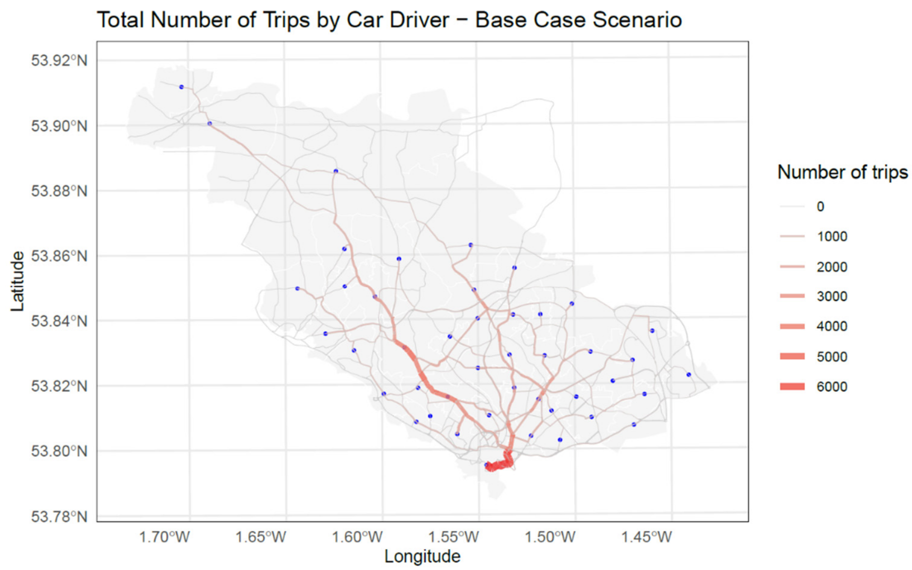


Figure 6.6 Visual representation of the total number of car trips passing through each road section, based on the shortest paths of each OD pair.

6.4.3.2 Network scenario 1: Automated Vehicle (AV)

In the base case scenario, HDVs are assumed to travel all roads without restrictions, except for traffic directions, as access-controlled sections such as bus gates and bus-only roads were excluded from the analysis. However, for AVs, their operation may be limited to roads meeting certain readiness criteria. Roads with low RRI scores are likely unsuitable or unsafe for AVs. Thus, by excluding edges (links) with an RRI score of 0 in the graph system, the model focuses on road segments more appropriate for AVs, creating a network that better aligns with realistic operating conditions for these vehicles. Moreover, the weighted road network is structured by combining normalised road lengths and inverted RRI scores (i.e., 1-RRI, where a low RRI score implies a higher cost) into a combined weight for each road segment. Normalising road lengths ensures that the algorithm accounts for physical distance, while inverted RRI scores introduce a weighting factor that represents each road's suitability for AVs. This weighting scheme balances the importance of road length and readiness, ensuring that the shortest paths calculated for AVs are not only the shortest in distance but also the least challenging and most suitable according to their readiness scores. This approach facilitates a meaningful comparison between current HDV road usage and potential AV usage, offering insights into possible changes in traffic patterns and road utilisation with AV integration. The adopted weighting strategy for road links is formulated as:

$$\text{Weight of edges (road links)} = \alpha(l_i/l_{max}) + (1-\alpha)\,(1-RRI_i) \qquad (6.3)$$

Where: l_i represents the length of road link i in the network, l_{max} is the maximum length of any link in the network, RRI_i is the assessment value of the index corresponding to road link i, α is the coefficient adopted for weighting the importance of the parameters, which is taken as 0.5 in this study.

Figure 6.7 presents a heatmap illustrating the differences in routing results for each OD pair between HDVs and LC AVs within an adapted weighted and directed network. This heatmap compares travel distances in miles for the shortest path of each AV trip with its HDV counterpart, along with the corresponding durations at the speed limit. This visual representation effectively highlights the variations in travel patterns and efficiency between HDVs and AVs, indicating how AV capabilities could potentially alter road usage across the network. Among the 1,715 OD pairs evaluated, the network only allows for the successful completion of 100 OD pairs by LC AVs. A significant majority of trips were deemed infeasible due to the presence of roads that are extremely challenging for AV navigation. Despite approximately 20% of road links receiving penalties, their dispersed distribution resulted in significant barriers to connectivity between MSOAs.

Out of a total of 27,187 trips analysed, only 1,799 corresponding to those 100 OD pairs could potentially be replaced by LC AVs in this scenario. An in-depth analysis of these trips revealed that the average trip length is 2.3 miles, with the shortest trip being 0.6 miles and the longest reaching 5.5 miles. Additionally, the average trip duration is 5 minutes, with the fastest trips estimated at 1.3 minutes and the longest at 12 minutes. High Capability (HC) AVs exhibit only slightly better performance, with the network accommodating successful completion for 120 OD pairs. Similar to LC AVs, the majority of potential trips were hindered by the challenging nature of certain road sections. From the total of 27,187 trips analysed, only 2,018 corresponding to those 120 OD pairs could potentially be replaced by HC AVs in Scenario 1. For HC AVs, the average trip length is slightly longer at 2.5 miles, with the shortest and longest trips being 0.6 miles and 5.8 miles, respectively. The average trip duration of these trips slightly increases to 5.4 minutes, with durations ranging from 1.3 minutes to 12.5 minutes.

When analysing AV trips within the network, it was observed that relatively less challenging paths designated for both AVs tend to be longer than those typically used by HDVs. As can be seen from the **Figure 6.7**, there is an increase of approximately 2.5 miles in the travel distance for certain OD pairs. The analysis revealed that trips made by LC AVs are, on average, 28% longer than those made by human-driven vehicles. Similarly, trips made by HC AVs in the analysed 120 OD pairs are on average 27.2% longer than those of HDVs.

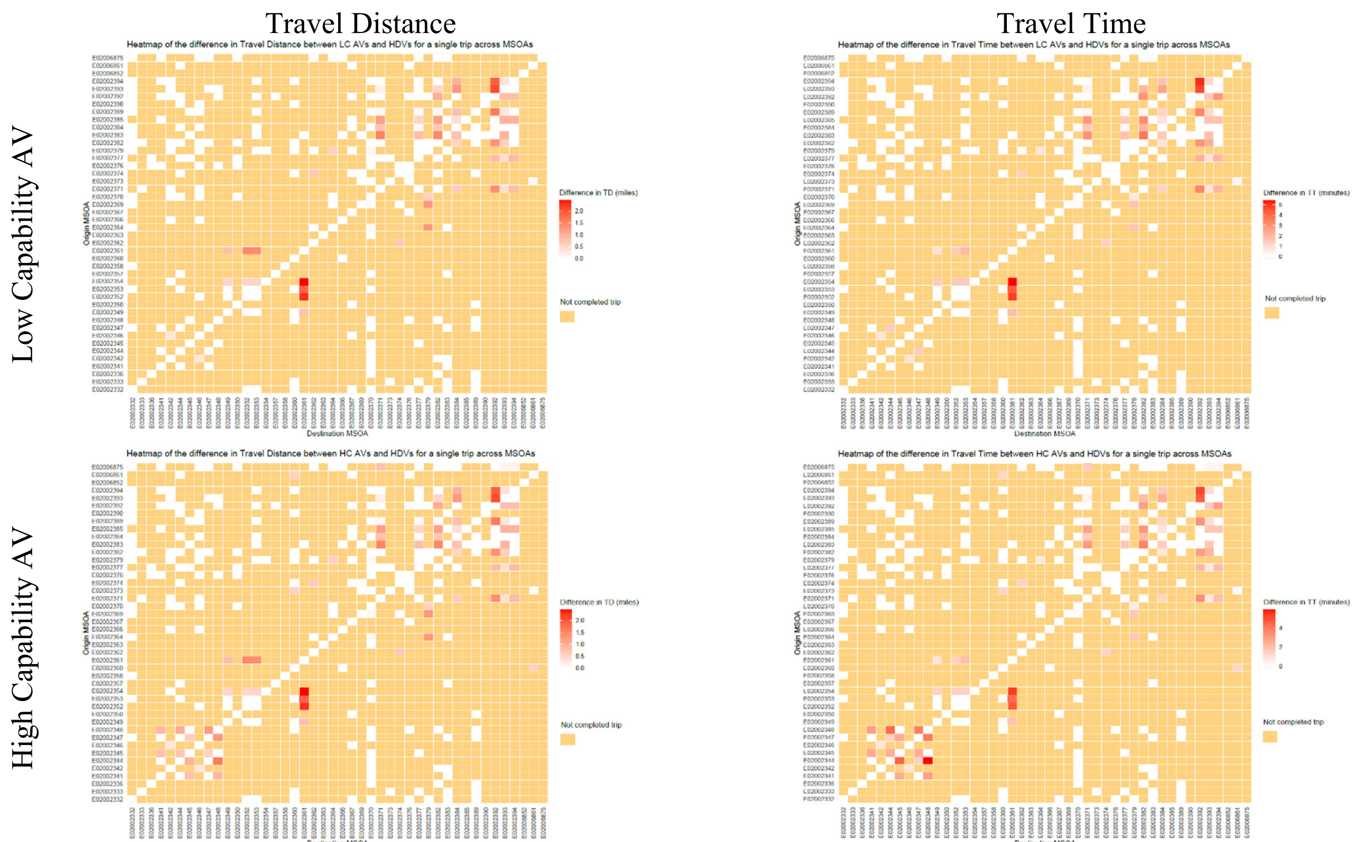


Figure 6.7 Heatmap illustration of the difference in travel distance (left) and time (right) for a single trip between AVs and HDVs across 1,715 OD pairs within 44 MSOAs, based on AV capabilities in Network Scenario 1 (base-case).

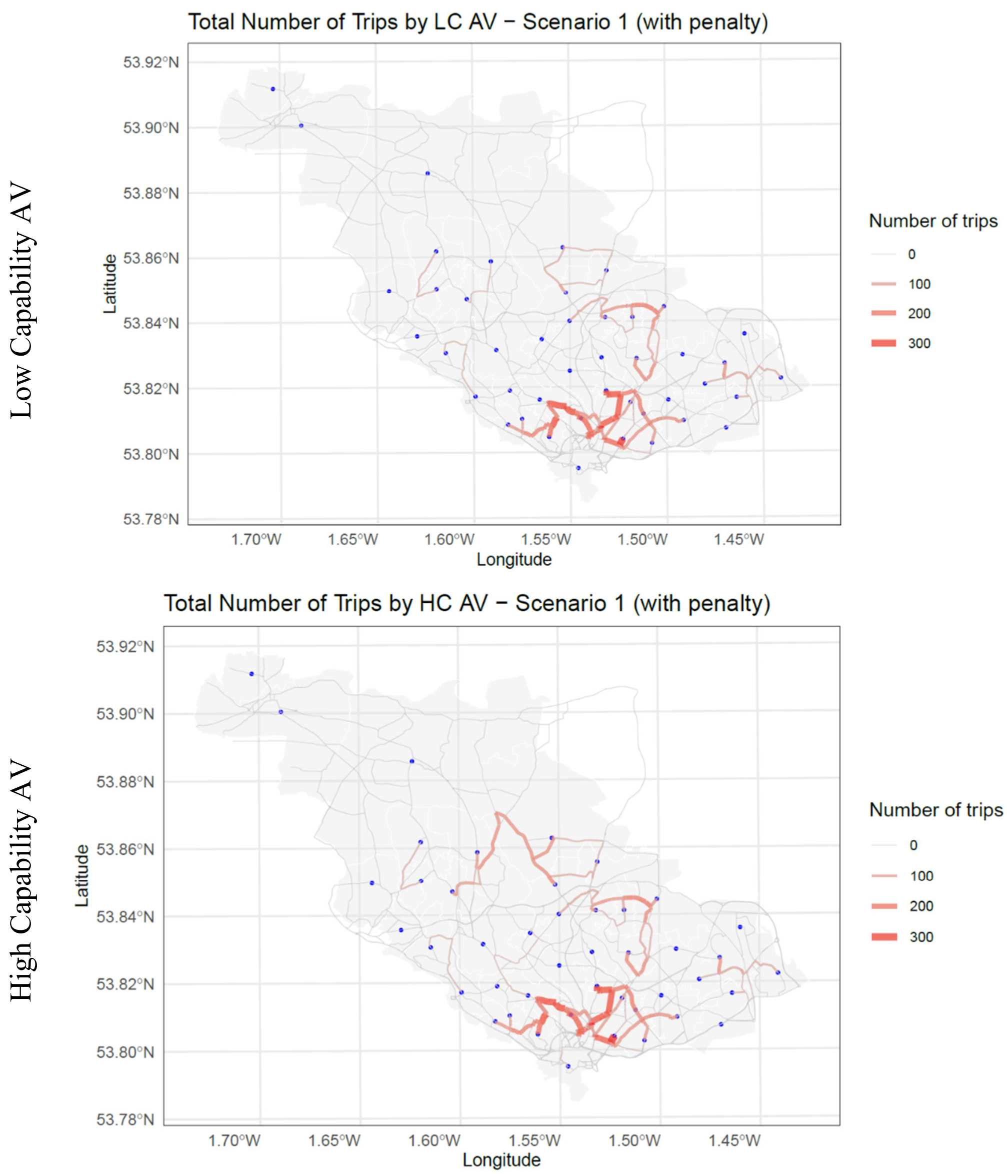


Figure 6.8 Visual representation of the total number of car trips passing through each road section, based on the shortest paths of each OD pair in Network Scenario 1 (base-case).

Lastly, the spatial distribution of feasible AV trips is illustrated in **Figure 6.8**, offering valuable insights into how the integration of AVs might transform the existing transportation landscape within the study area. The figure reveals that most of these trips occur between MSOAs that are geographically closer to each other. This implies a lower likelihood of encountering extremely challenging road sections along shorter routes compared to longer ones. Thus, without physical and digital infrastructure modification or upgrades in the network, LC AVs will likely not serve most of the travel needs within the urban environment.

6.4.3.3 Network scenario 2 (HD map availability): Automated Vehicle (AV)

As previously mentioned, in Scenario 2 most road links in the network are categorised into the slightly and least challenging categories of the Road Readiness Index (RRI) for AVs. As such, compared to the previous scenario, the operation areas of AVs expand significantly, enabling the completion of most trips. **Figure 6.9** displays a heatmap comparing the differences in travel distance in miles for each shortest path of AV trips with HDVs, along with their corresponding durations at the speed limit of a road section. Out of 1,715 OD pairs, the network allows LC AVs to successfully complete 1,423 OD pairs. This significant increase in feasible trips is attributed to the advantages of High Definition (HD) maps for AV navigation and the assumption of the absence of road work in the network. The analysis of 22,670 trips corresponding to the 1,423 OD pairs revealed an average trip length of 4.8 miles, with the shortest trip being 0.6 miles and the longest being 12.9 miles. Additionally, the average trip duration of these trips within the case study area is 9.1 minutes, with the fastest trips estimated at 1.3 minutes and the longest at 26.4 minutes.

In contrast, High Capability (HC) AVs demonstrate slightly better performance, with the network facilitating the successful completion of 1,498 OD pairs. This represents an 87% coverage of the existing road network for vehicle-based commuting trips, marking an almost 80% increase compared to the previous scenario. In the analysis of 23,847 trips associated with the 1,498 OD pairs for HC AVs, the average trip length remains consistent at 4.8 miles (compared to trips completed by LC AVs), with a range from 0.6 miles to 14.1 miles. The average trip duration for these trips slightly increases to 9.3 minutes, with durations ranging from 1.3 minutes to 28.5 minutes. This is primarily due to the ability of HC AVs to make trips over slightly longer distances within the network for additional OD pairs compared to LC AVs. Furthermore, when the trips completed by both AV capabilities were analysed, it was observed that HC AVs generally completed the trips at shorter distances. This is attributed to their ability to navigate challenging network sections more effectively due to their advanced capabilities.

As with scenario 1, it was observed that the least challenging paths for both AV capabilities tend to be longer than those typically used by HDVs. Specifically, **Figure 6.9** indicates that for certain OD pairs, there is an increase of approximately 5 miles in travel distance for both AV capabilities. The analysis revealed that trips made by LC AVs in 1423 OD pairs are, on average, 24.9% longer than those made by HDVs. Similarly, trips made by HC AVs in the analysed 1498 OD pairs are on average 22.6% longer than those of HDVs. This implies that AVs will likely to navigate alternative routes compared to HDVs, which could result in additional distance being travelled within the city. Such deviations from the shorter HDV routes have potential implications for energy consumption and environmental impact, underscoring the need to consider the broader effects of integrating AVs into urban traffic systems. Regarding the trip duration of certain OD pairs, there is an increase of approximately 10 minutes for LC AVs compared to HDVs. A similar trend was observed for HC AVs, with some trips extending more than 13 minutes longer than those made by HDVs. This is mainly because AVs often follow longer routes for many OD pairs due to the challenging infrastructure levels of certain road segments. However, some routes, despite being longer, are approximately 3 minutes faster than those taken by HDVs, as road segments have different probably higher speed limits.

In this scenario, out of a total of 27,187 trips analysed, 22,670 could potentially be accommodated by LC AVs, and 23,847 by HC AVs. Despite the integration of HD maps, a notable number of trips remained infeasible due to challenges on approximately 8% and 5% of road sections for LC and HC AVs, respectively, which were deemed extremely challenging for AV navigation. The spatial distribution of these feasible AV trips, as illustrated in **Figure 6.10**, offers valuable insights into the potential transformation of the transportation landscape within the study area through AV integration. Moreover, it is observed that AVs tend to follow slightly different paths compared to HDVs, resulting in variations in the total number of cars passing through certain links in the network. This deviation underscores the possible necessity of adapting road networks to better support AV navigation and potentially enhance overall traffic flow. However, it should be overlooked that today's current ADS technologies may already be capable of overcoming some challenges posed by road infrastructure, but most AV manufacturers have yet to share or verify such data. This required a holistic perspective in the assessment of the road network for these technologies.

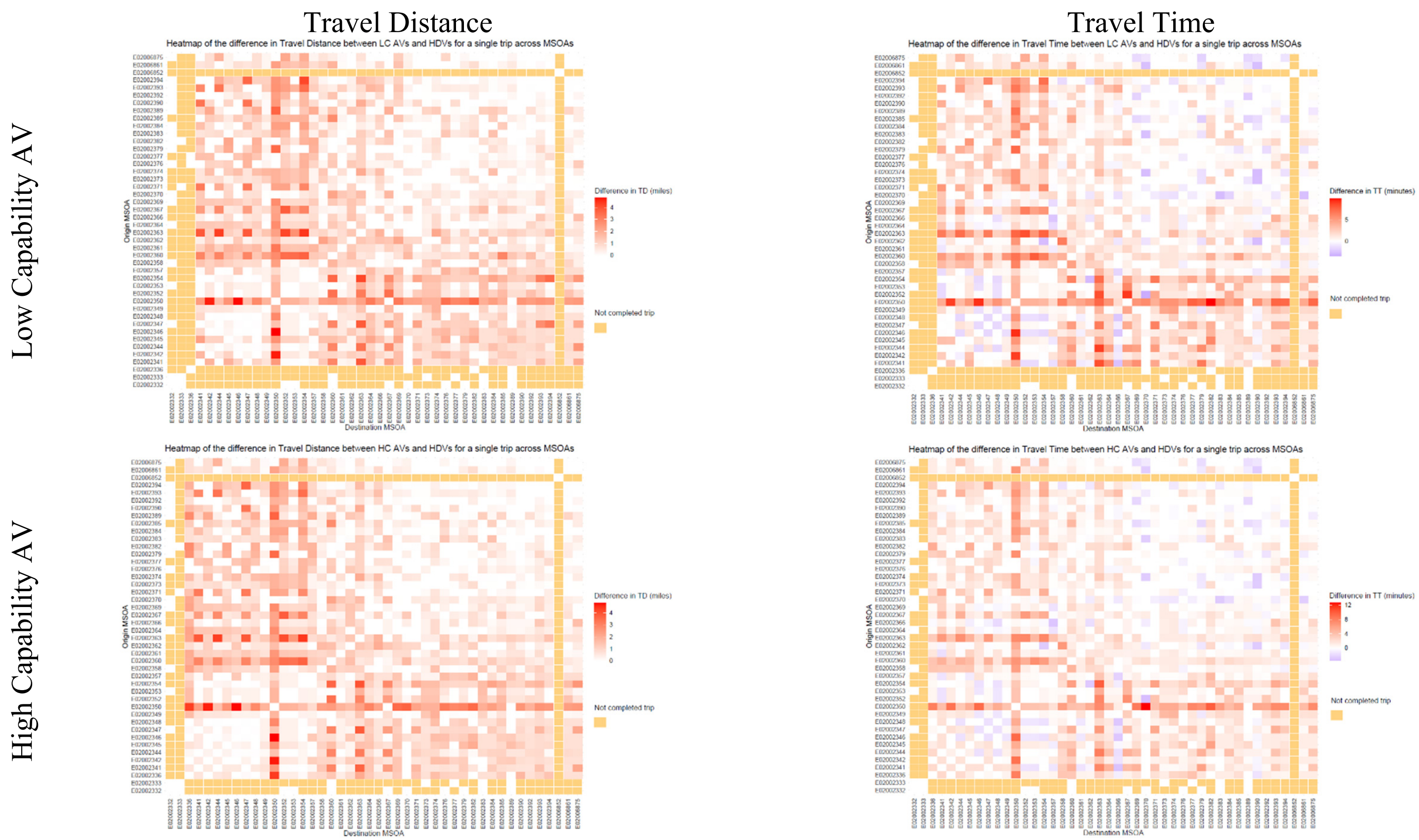


Figure 6.9 Heatmap illustration of the difference in travel distance (left) and time (right) for a single trip between AVs and HDVs across 1,715 OD pairs within 44 MSOAs, based on AV capabilities in Network Scenario 2 (HD map availability).

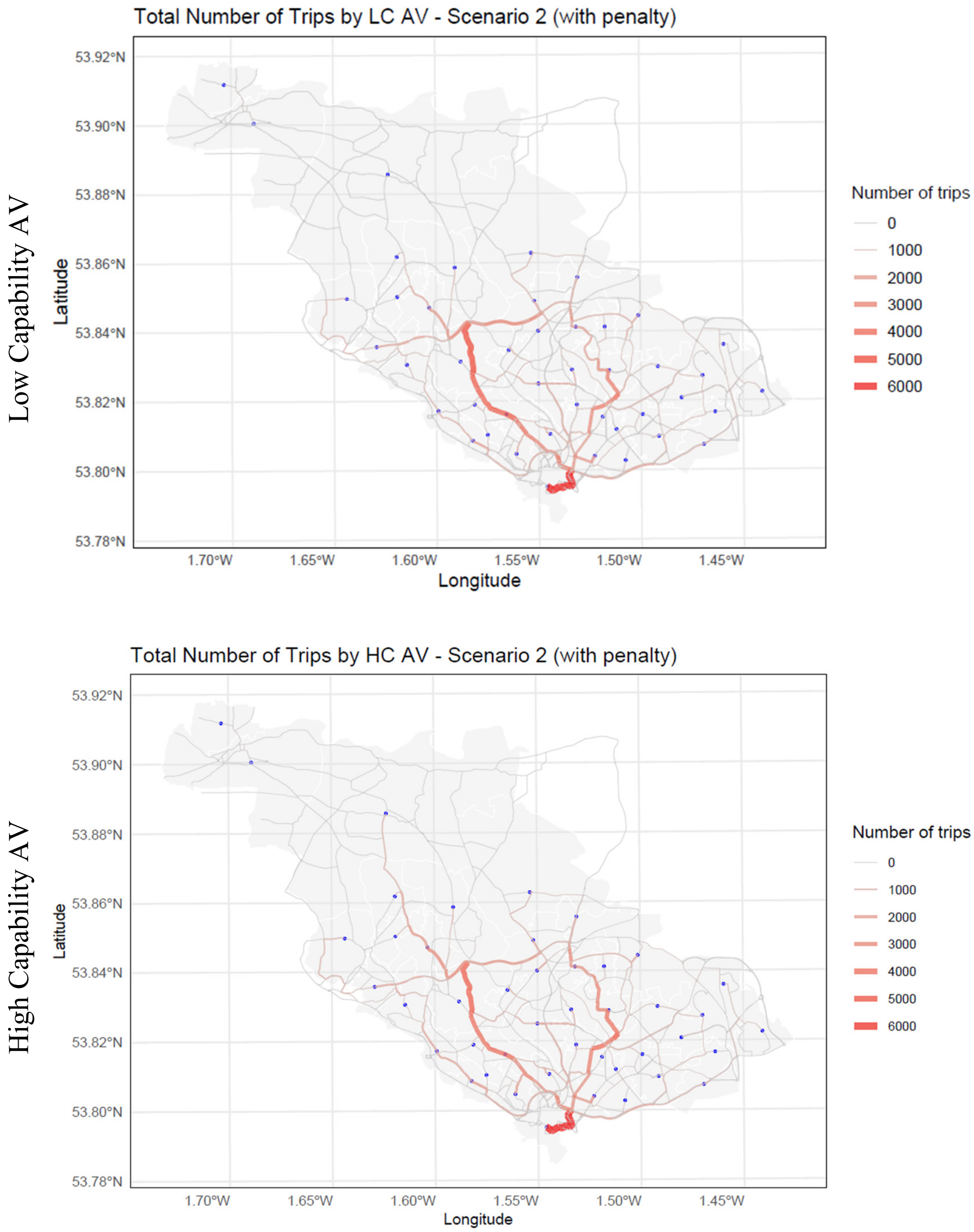


Figure 6.10 Visual representation of the total number of car trips passing through each road section, based on the shortest paths of each OD pair in Network Scenario 2.

6.4.4 Sensitivity analysis

This section examines how the routing results for OD pairs fluctuate based on the adopted α values in Equation 6.3, reflecting the relative importance of the normalised length of links versus Road Readiness Index (RRI) values. **Figure 6.11** depicts the distribution of travel distances for OD pairs within the network for HC AVs in Scenario 2, considering different weighting coefficients. Each boxplot corresponds to a distinct α coefficient value, ranging from 0, highlighting the RRI, to 1, giving full priority to the length of the road link in determining the route. The figure indicates that the mean travel distance does not significantly change with different α values. Notably, while the average travel distances remain relatively stable across different α values, the total system-wide travel distance, which accounts for individual trips for each OD pair, exhibits considerable variation, ranging from 6,813 to 7,527 miles. Additionally, slight route changes are observed for some OD pairs. Nonetheless, the weighting scheme employed effectively balances the importance of road length and readiness levels without being overly sensitive to the selected α values, demonstrating its practical applicability for network analysis.

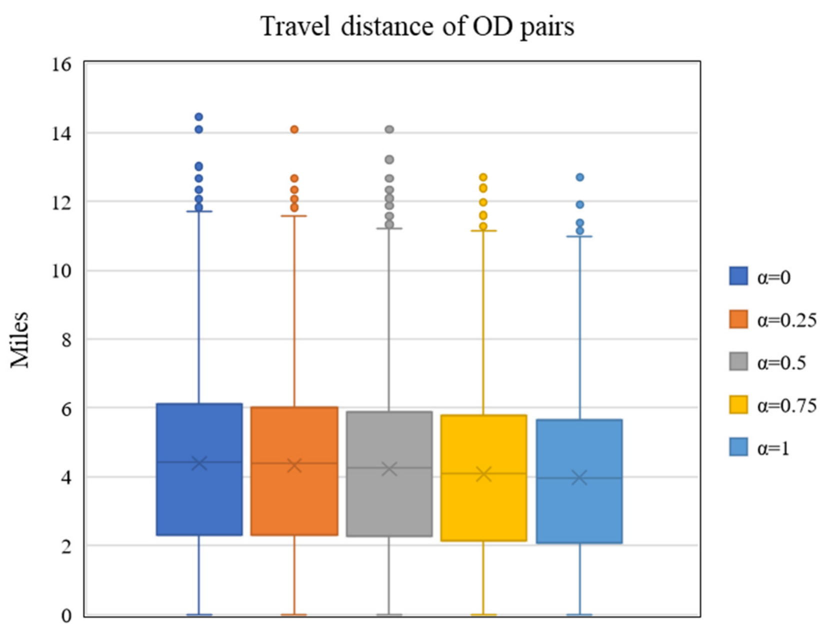


Figure 6.11 Boxplot of Travel Distances for OD Pairs with varied weighting coefficients in Scenario 2 for HC AVs.

6.5 Conclusion and recommendations for further research

The current automated vehicles (AVs) have not yet reached a point where their automated driving systems can operate without fail across the entirety of regular road infrastructures (Bishop, 2024). This limitation underscores the role of importance of both the infrastructure and the surrounding environment in the initial phase of transitioning towards fully autonomous vehicles. However, preliminary research in this area has revealed considerable variation in the level of preparedness of road infrastructure in city networks (Soteropoulos et al., 2020; Tengilimoglu et al., 2024). This variability suggests that certain roads or zones may not be as conducive to continuous AV operations as others. As such, the present study carried out the first exploratory analysis to understand how heterogeneity in road infrastructure readiness may impact the utility of AVs for urban commuting, specifically focusing on the city of Leeds, UK.

A key conclusion is that automated vehicles will likely be required to travel more distance than human-driven vehicles when taking over control of the vehicle is not an option (i.e., utilised as a passenger mode only). Although the analysis was concentrated on road segments that constitute the main arteries of the road network, there remains significant variation in both their physical and digital infrastructure quality, and hence, in their readiness levels. This diversity in infrastructure quality will likely lead AVs to take different routes than human-driven vehicles to reach their destinations, which will potentially result in additional miles travelled within the city. The routing analysis of OD pairs revealed that relatively less challenging paths for both AV capabilities could be up to 5 miles (8 km) longer than those potentially utilised by HDV for some OD pairs. Importantly, the analysis revealed that AV trips are on average about 20-25% longer than human-driven vehicle trips in the analysed OD pairs. This observed increase in total travel distance is consistent with the insights obtained from a study conducted in the Amsterdam metropolitan region (Madadi et al., 2021), suggesting potentially adverse implications for energy consumption and environmental impact. Moreover, with the likelihood of increased empty-vehicle travel and the relocation of parking spaces outside of the city centre, AVs are expected to contribute to a rise in travel distance (Milakis et al., 2018; Soteropoulos et al., 2019). Therefore, the broader implications of integrating AVs into urban traffic systems warrant thorough consideration.

The findings also highlighted that infrastructure, especially digital infrastructure, plays a more crucial role than AV capability in expanding operational areas. For instance, when solely reliant on on-board sensors, without the aid of digital mapping, a substantial majority of commuting trips could not be facilitated by AVs due to the absence of suitable routes between origins and destinations. In this scenario, it was observed that only 7% of OD pairs within the study area could be serviced by high-capability AVs as limited routes fully meet the requirements of AVs. This underscores the likelihood that substantial enhancements to both physical and digital infrastructure will be necessary to enable AVs to fulfil a significant portion of urban travel demands. Notably, the integration of digital mapping into the network—corresponding to a reduction in around 13% of the penalised road sections—increased the number of accessible OD pairs to 87%. This affirms the vital role of digital infrastructure in enhancing AV compatibility and demonstrates a marked improvement in AV network accessibility, facilitating connectivity for nearly an additional 80% of OD pairs. Nonetheless, there is still a considerable amount of OD pairs that could not have connected. The primary obstacle appears to be the provision of communication support for AVs to exchange safety-critical information, which is notably challenging in rural areas and certain urban locations. This is crucial to achieving a more uniform level of readiness across the entire road network and enhancing the safety of AV operations across various environments.

In particular, catering to demand in rural areas poses a problem for AVs. For example, establishing connections between urban centres and rural areas or towns is not viable with the road sections analysed. In scenarios where AV ownership is personal, drivers may need to take control of the vehicle for these segments to make trips possible within the study area. However, this requirement could diminish the full potential benefits of AVs, particularly in terms of time value for users (Wadud, 2017). It could also lead to driver annoyance with the ADS. Similarly, in a shared AV model, such rural locations are likely to fall outside the geofenced service areas during the initial stages. Rural populations, which generally have a higher proportion of individuals aged 65 and over, may include some who are unable to drive (Department for Environment Food & Rural Affairs, 2024). Moreover, rural areas tend to have poorer quality and less frequent public transport services compared to urban areas, leaving residents with limited alternative transport options. A recent study indicated that, on average, rural bus services in England and Wales have declined by 52% since 2008 (Friends of the Earth, 2023). Consequently, these communities might face increased challenges in accessing vital services, particularly healthcare. This situation underscores the critical need to enhance accessibility for rural populations, ensuring that they benefit equitably from advancements in AV technology. However, while AVs promise the convenience of door-to-door service, such service may be impractical in many parts of the urban network as lower-tier roads, such as access or local roads, often present significant challenges for automated driving (Tengilimoglu et al., 2024). Therefore, the implementation of AV-compatible drop-off and pick-up points on the main arteries of the network will likely be crucial in alignment with emerging technology to maximise the benefits of AVs (Bruck and Soteropoulos, 2022).

In addition, the findings underscore that, within the existing infrastructure, high capability AVs, such as advanced equipped robo-taxis, can efficiently meet short to medium distance commuting needs within urban areas. This efficiency primarily stems from the challenge of finding relatively less challenging routes for longer trips due to the heterogeneity in the quality of infrastructure. Furthermore, differences between the shortest and least challenging (i.e. most suitable) routes for AV trips across the network can be utilised by authorities to identify the critical road sections needing further investment to obtain optimal routes and facilitate broader AV adoption. This enables policymakers, city authorities, and third-party service providers, such as those offering communication services or digital mapping, to assess the network with a solid empirical basis. Therefore, the findings from this study may serve as useful indicators for guiding investment strategies and near-term planning, suggesting potential early operational routes to optimise benefits across the transportation system. However, these near-term actions should be implemented with “no regrets” and should benefit both road network operations and human-operated vehicles (Amelink et al., 2020). In this context, the activities and plans of the vehicle automation industry towards improving ADS capabilities are also crucial for reducing heterogeneity in road readiness. Therefore, achieving readiness for automated driving in a safe and efficient manner will likely require coordinated efforts in improving ADS capabilities, as well as in upgrading infrastructure and its maintenance practice (Somers, 2019; Sauvaget et al., 2023).

Finally, there is a clear need for further research in specific areas. Firstly, limitations in the methodology of the source RRI (Tengilimoglu et al., 2024) are also applicable for this study since it followed a similar strategy. To mitigate the uncertainties in automated driving technologies, this study adopted a holistic approach to assessing the readiness levels of road sections by considering two distinct capabilities and two network scenarios. However, as AV technology continues to advance, there will be a need to continuously update and refine the assessment framework to keep pace with cutting-edge technology and the evolving requirements of road infrastructure, especially for the specific use case of Level 4 AVs. Secondly, this study primarily examines scenarios of uncongested traffic, without any constraints on flow based on link capacity. Hence, incorporating RRI into traffic models could provide more detailed and nuanced insights. Furthermore, a significant barrier to AV adoption in urban road networks is the diversity of intersections and roundabouts, each with its unique rules and complexities. Intersections are critical as they directly influence trip routing. Just as some road sections pose challenges for AV operation, certain intersections also present difficulties, necessitating further analysis to include these interactions. Additionally, local access roads are omitted from the scope of this study. Future studies should consider including local roads to conduct a detailed analysis, especially from the perspectives of accessibility and equity related to AVs.

Regarding travel outcomes, the OD data utilised in this study, derived from the 2011 census, may not accurately represent the current network state. While offering valuable insights, this data might not capture changes in travel patterns or infrastructure developments since the census. This temporal discrepancy should be considered when assessing the study's findings and their relevance to contemporary and future transportation planning and policy formulation. Additionally, the analysis could be further enriched by integrating the effect of the built environment on interest in the ownership and use of self-driving vehicles (Nodjomian and Kockelman, 2019). Besides, the exact numbers (e.g., increase in driving distance) presented in this study may not be reliable, as ADS capabilities change with technological enhancements, the increases in travel distance and emissions will also change. Similarly, a different readiness index may also change the numbers. However, the key is that there is a strong possibility of a remarkable increase in driving miles due to operational reasons. Despite these limitations, we believe this is the first study that demonstrates the usefulness of RRI in highlighting the need to incorporate infrastructure preparedness to fully understand the actual benefits of AVs on the roads.

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CHAPTER 7

Discussion and conclusions

This chapter presents the thesis's conclusions, highlighting the key findings and insights derived from the five investigations conducted. It begins with a reminder about the research questions and outlines the main findings and contributions to enhance existing knowledge. The chapter then highlights the practical implications of the thesis for the relevant stakeholder groups. Then, recommendations for future research to address potential gaps and further advance road safety studies on automated driving are presented. Finally, the chapter concludes by emphasising the importance of shared responsibility, integrating automated driving requirements into road safety initiatives, and continuous dialogue among stakeholders to achieve this.

7.1 Overview of the main findings and contributions

This thesis aimed to develop an appropriate assessment framework to evaluate the readiness levels of existing (or near-term) road infrastructure and the surrounding environment for highly automated vehicles, and using this framework to demonstrate how such readiness might affect the usefulness of these vehicles. In **Chapter 1**, several research gaps were identified that need to be addressed to achieve this overarching goal, focusing specifically on the infrastructure aspect of vehicle automation and the factors affecting the operation of automated driving systems on existing roadways. This section maps the work and findings of each chapter against the corresponding research questions they address, ensuring all conclusions are substantiated by linking them to relevant results. The progression from one study to the next and how each informed the subsequent investigations are also detailed. Below is a review of each of the research questions and the findings:

1. What will be the likely implications of automated vehicles for the road infrastructure? (**Chapter 2**).

Automated vehicles (AVs) hold the potential to significantly alter dynamics in human life and urban settings. While past studies have predominantly focused on a set of impacts ranging from travel behaviour, traffic flow and operations, to urban form, land use, and safety (Fagnant and Kockelman, 2015; Wadud et al., 2016; Harb et al., 2021), the implications of AVs for road infrastructure have not been studied adequately (Rashidi et al., 2020). In particular, studies into the implications for the physical infrastructure side of vehicle automation remain limited (primarily found in grey literature), in contrast to the substantial body of work addressing digital infrastructure for automated driving. However, to assess the readiness of existing road infrastructure and the surrounding environment for the safe and efficient operation of AVs in their early implementation stages, and to adapt roads for better compatibility with AVs, it is essential to understand their potential implications for the physical road environment.

Hence, **Chapter 2** addressed this issue by framing two broad questions: (1) What are the potential impacts of AVs on road infrastructure and (2) What do AVs require from road infrastructure for safe driving. This approach is informed by the premise that AVs are likely to affect infrastructure in two significant ways (Amelink et al., 2020): Firstly, AVs, with their distinct characteristics and behaviours, may interact with the infrastructure differently compared to human-driven vehicles, potentially having different impacts on the infrastructure. This may lead to different requirements for their safe operations during the transition period. Secondly, in response to the operational needs of AVs, road authorities and other stakeholders might initiate changes to the road infrastructure to support the operational design domains necessary for AVs. Therefore, the study followed a semi-systematic approach in reviewing the existing literature to address these two points.

The study revealed that infrastructure has a critical role in the different deployment strategies adopted by the AV industry and automakers. It identified and discussed thirteen critical infrastructure-related topics from the literature on vehicle automation that need to be considered during either the initial phase of deployment or the transition to full automation. These topics are: road alignments, road cross-sectional elements, road surface, road markings, traffic signs and control signals, junctions and roundabouts, parking facilities, structures (e.g. bridges, tunnels), facilities for vulnerable road users, roadside equipment, lighting, drainage systems, and the assessment and maintenance of road infrastructure. For each of these topic headings, the study examined the implications of both the vehicles equipped with Advanced Driving Assistance Systems (ADAS) and Automated Driving Systems (ADS) for road infrastructure since the transition period will likely include a mix of traffic between human-driven vehicles and different levels of AVs.

The study in **Chapter 2** highlighted that the road geometric design philosophy and related specifications and guidelines need to be revised as some road design parameters involving a direct relationship with the characteristics of human drivers may lose their importance with the shift from conventional driving to automated driving. For example, stopping sight distance and decision sight distance criteria, which are key elements in designing road alignments, need to be reconsidered due to differences in perception abilities between human drivers and AVs. At full penetration level, it is expected that a significant reduction in stopping sight distance is due to changing design elements related to human characteristics and vehicle performance (e.g. perception and reaction time, deceleration rate, and height of sensors); hence the required length of the crest and sag curves could be shorter for highly automated vehicles. This results in shorter curves that lead to potential economic and environmental improvements through the reduced cut and fill volumes of the new designs. However, some suggest that most of the geometric elements will not change in the era of AVs, especially those related to physics and comfort-based parameters. For example, the required curve radius or ramp terminals will likely be similar for both human-driven vehicles and AVs, as it depends on the driving dynamics and passenger comfort, not the characteristics of human drivers. Therefore, it is not expected any change in road alignments during the initial phase of AVs, but revision can be seen on dedicated roads or lanes for safe operation.

Moreover, AVs will likely present new risks and challenges for existing road structures such as bridges and tunnels and road pavement. Any new design should consider the impact of future scenarios such as the heavy vehicle platoon and precise movement of AVs. More importantly, existing bridge capacities need to be rechecked according to possible scenarios. Also, tunnels and underpasses are likely to need additional investment in positioning and lighting infrastructure for AVs to operate. To address all these points, this chapter underlines the need for international standardisation for the relevant parameters because the findings can vary considerably depending on the design guideline considered and the characteristics of the AVs used.

In general, the results showed that enhanced road maintenance and harmonised physical road infrastructure, in addition to digital infrastructure, can support these technologies' operational safety. However, while some requirements (e.g. clear and visible road markings and traffic signs) are almost universally accepted and supported by experimental research, there is uncertainty regarding the necessary infrastructure changes for AVs (e.g. modification of lane widths). This is due to uncertainty about the pace and state of technological development of AVs, and the unpredictability of user adoption rates after their commercial deployment. In many areas, the study underlined that further research is needed to understand the precise impacts of AVs and their requirements. Additionally, it highlighted the necessity for international standardisation on many aspects of automation. AV technology should be international, not national, to ensure it is more sustainable and effective (International Transport Forum, 2023). The study also underscored the value of research, field testing and deployment pilots as well as organised discussion among stakeholders. Briefly, **Chapter 2** provided an analysis of the current state of research in this area and insights into future directions. Besides, the findings from this chapter form the basis for the stakeholder questionnaire employed in **Chapters 3** and **Chapter 4.**

2. What infrastructure-related challenges are involved in integrating automated driving into urban road networks? (**Chapter 3**)

As noted above, a review of the existing literature reveals uncertainty in various areas concerning the infrastructure aspects of vehicle automation, indicating a need for further exploration. In contrast, research on the software, hardware, and information and communication technologies supporting AVs is growing rapidly. This has prompted researchers who want to gather information about the latest developments in the field to seek opinions from experts. Employing a similar strategy, in **Chapter 3**, an online survey was conducted with experts from various sectors and regions to explore the multifaceted dimensions of the implications and challenges associated with deploying automated driving[43], with a particular focus on road infrastructure. It garnered opinions from a large number of experts, representing one of the largest such opinion samples in this area. The specific aspects addressed in this research include: (1) key challenges of integrating Connected and Automated Vehicles (CAVs) into existing urban transport networks, (2) infrastructure improvements required for shared CAV deployments, (3) maintenance considerations for infrastructure supporting CAVs, (4) timelines for implementing infrastructure support for CAVs, and (5) financing strategies for infrastructure upgrades to accommodate CAVs on the roads.

The work in **Chapter 3** revealed that attitudes and perspectives of experts on the implementation of automated driving vary based on the types of organisations they represent and their geographic regions. Beyond their motivations and roles in the automated driving ecosystem, these differences among experts may be attributed to varying levels of infrastructure, technology, and legislation in each country (as seen in the assessment by KPMG International, 2020), as well as to their unique urban forms. Despite these variations, there was broad recognition among experts that the safe and efficient management of mixed traffic conditions and interactions between AVs and other road users—particularly vulnerable ones—are the main obstacles to adopting automated driving in urban networks.

Additionally, the reliance of AVs on data and technology raises a wide range of new legal issues, such as data protection, cybersecurity, and privacy. Addressing the safety concerns regarding automated driving technologies and deficiencies in developing and implementing relevant policies and legislation will be critical in adapting to AVs. In

[43] As previously mentioned, in this study, the term "automated driving" is used to describe the technology where automation of the driving task, vehicle connectivity, and data are brought together. Also, the term automated driving and connected and automated vehicles (CAVs) are used interchangeably.

this regard, one of the main challenges is to clearly define who will be responsible for what. According to some experts, regulators generally lack the technological expertise required to regulate the companies developing AVs effectively. Therefore, they suggest that road authorities and policymakers first need to be educated about what AVs are in order to effectively produce policies or regulations.

Another commonality was the need for investment in road infrastructures to facilitate the safe deployment of these technologies. This necessity is often cited due to the lack of adequate physical and digital infrastructure to support CAV operations on a large scale, regardless of their mobility models. However, the prevailing opinion among stakeholders was that digital infrastructure offers greater potential for short-term benefits compared to upgrades of physical infrastructure. This is because digital solutions (e.g. HD maps, safe and reliable connectivity) can provide more cost-effective and adaptable means to enhance transportation systems. The findings obtained in the following chapters also support this idea.

Nevertheless, this study identified three distinct perspectives among stakeholders regarding infrastructure improvements to support automated driving. The first group, comprising primarily industry and academia representatives, argues that infrastructure investments should be made "in advance" for widespread consumer adoption of vehicle technologies. They contend that without supportive upgrades, the full benefits of automated driving will not be realised by relying solely on vehicle technology. In contrast, the second group, which includes mostly legislators and infrastructure owners and operators, favours a "wait and see" approach. Their caution stems from the uncertainties around technological advancements and the implementation of automated driving, which pose significant planning challenges for upgrades. Additionally, this group argue that the impact of these technologies on road transport performance remains highly uncertain. The third group is more sceptical, believing that automated driving systems should be capable of safely performing all driving tasks on existing road infrastructure. They argue that it is neither possible nor feasible to prepare all roads for automated driving, so they are in favour of the "leave as is" approach.

The study also revealed diverse opinions among stakeholders regarding the financial models to meet the needs of infrastructure-related investments, maintenance, and operating expenses. In particular, it remains unclear how the authorities will meet the initial infrastructure investments related to CAVs and who should be responsible for them. However, automation will affect vehicle taxation, therefore many experts emphasise that new business models and strategies need to be identified for AV-oriented investments.

In short, the main contribution of **Chapter 3** was to provide an overview of the opinions from various stakeholder groups that may affect the deployment of automated driving, on several issues that are contested or lacking in the literature. Specifically, it presented insights from experts into various key challenges that need to be addressed for the successful implementation of automated driving technologies on public roads, and identified areas of agreement and disagreement among stakeholders. This allows policymakers to identify and prioritise the issues that are essential for addressing weaknesses in their respective territories. Another significant contribution was the examination of critical factors for preparing current road infrastructures to accommodate emerging technologies, a topic that is further explored **in Chapter 4**.

> **3.** What are the critical infrastructure elements necessary for the safe operation of Level 4 AVs? (**Chapter 4**)

To evaluate the readiness of the current road network and develop plans that facilitate the seamless integration of AVs, it is crucial to examine the critical infrastructure elements, both physical and digital, to ensure their safe operation during the early stages of deployment. **Chapter 2** assessed the existing knowledge regarding the infrastructure requirements for the operation of AVs, with an emphasis on understanding the physical road infrastructure needs. This evaluation was not limited to specific levels of automation. Additionally, **Chapter 3** provided a partial overview of critical infrastructure elements for shared automated driving service models at an aggregated level. However, detailed investigations are needed for assessment frameworks. Given that major benefits of AVs are anticipated at the higher automation levels (particularly Level 4 and beyond), where a driver may not be necessary within certain operational areas, **Chapter 4** and subsequent parts of the thesis specifically concentrated on Level 4 automated driving.

The intense competition between automotive and information technology companies for market position leads to carefully protecting industry expertise (Shladover, 2018). Consequently, limited information is publicly available regarding fundamental infrastructure-related vehicle requirements. Meanwhile, the AV community is rapidly evolving; although much of the development in this area is closely guarded, there is substantial knowledge within academia, original equipment manufacturers (OEMs), and public trials. Given these circumstances, expert consultation emerges as a crucial research method to understand the critical requirements for road infrastructure.

In **Chapter 4**, insights and perspectives from experts across the globe were gathered to enhance the understanding of critical factors and challenges associated with urban road infrastructure for the successful implementation of AVs. The research focused on four main topics: (1) deployment paths of L4 AVs, (2) the concept of road certification for automated driving, (3) basic road infrastructure elements for the safe operation of automated driving, and (4) factors affecting safe operation of L4 automated driving.

The study revealed guarded optimism that L4 AVs, defined by carefully specified Operational Design Domains (ODDs), will likely be safe enough for public use within the next decade, though their usage will be restricted to small sections of road networks. This cautious expectation stems from the current limitations of technology and road infrastructure, which are not yet adequate for widespread, network-wide operation of AVs. However, for the early stages of deployment, the study also detected a mismatch between experts' views on the potentially dominant use cases of the technology and the safer sections of a road network. Motorways driving, in their controlled and well-maintained environments, is expected to be among the early applications of AV technology. Additionally, there is support for early implementation in low-speed urban areas equipped with the necessary infrastructure. On the other hand, the majority of experts believe that the public transport L4 AV service model will likely be the first to become widely available, primarily due to its societal benefits and cost-effectiveness. This discrepancy indicates that various types of L4 AV deployments may emerge, each tailored to different areas of the network.

The study also demonstrated clear support for the categorisation or assessment of roads for automated driving operations, especially during the early stages of deployment. There is a broad consensus among stakeholders that infrastructure owners and operators should be responsible for this assessment, although there were also suggestions favouring independent organisations and accredited auditors. In this context, the study elicited a range of responses from experts and stakeholders on the key physical, digital, and operational road infrastructure attributes necessary for the safe operation of AVs. Generally, the experts' views aligned with the parameters identified in the literature, in the scope of **Chapter 2**.

In addition, the study presented experts' views on potential factors (e.g. proper delineation of road marking, quality of road surface, lighting, cellular network coverage etc.) that can be critical for the safe operation of L4 automated driving for the foreseeable future, without focusing on any specific use-cases. A 5-point Likert scale was used to provide quantitative feedback on these potential road safety assessment factors or infrastructure elements. Then, statistical tests were carried out the detect agreement or any disagreements between stakeholder groups. Responses revealed that stakeholders have similar opinions on most of the identified factors, although the ordering of the factors differed slightly between the grouping variables.

The primary contribution of **Chapter 4** to the literature was to provide expert insights on the physical and digital road infrastructure features critical to the safe operation of automated driving. So, the findings of this study can be used to develop an assessment framework that categorises the capabilities of a road infrastructure to support and guide AVs, which will be explored in more detail in **Chapter 5**. Another significant contribution was identifying any regional and sectoral differences in perspectives among experts, and providing clear directives to transport authorities based on the opinions elicited.

> **4.** How prepared is the current urban road infrastructure for the deployment of Level 4 AVs? (**Chapter 5**)

Data on traffic accidents involving AVs or reasons for the disengagement of automated driving systems is limited (Boggs et al., 2020; Ye et al., 2021), which makes it difficult to explicitly define criteria for assessing the suitability of roads. Additionally, the available data predominantly comes from countries that are leaders in vehicle automation, such as the USA, which may not reflect regional variations. This is significant because each country has its own unique characteristics, such as street network design, safety measures, and traffic safety culture and user behaviour. For these reasons, reviewing relevant literature and consulting experts from around the globe about the capabilities and limitations of automated driving were viewed as alternative ways to establish applicable evaluation criteria for the early stages of this emerging mobility service. However, to date, only a few studies have systematically evaluated the suitability of urban road networks for L4 AV operation (Soteropoulos et al., 2020). Most prior research has adopted a broader approach, typically focusing on national (KPMG International, 2020) or city-wide (Khan et al., 2019) indices, or a detailed level that concentrates on motorways (Konstantinopoulou and Ljubotina, 2020; FTIA, 2021).

Chapter 5 addressed this research gap by introducing a novel and practical assessment framework, termed the "Road Readiness Index (RRI)," designed to evaluate road infrastructure readiness for highly automated vehicle operation. The initial phase of this study identified the components of this framework, drawing on experts' opinions from **Chapter 4** and insights from the literature review in **Chapter 2**. This phase involved defining specific subcomponents within the components of the framework and assigning performance grades to measurement variables in subcomponents using a designated scoring system. Given the uncertainties of automated driving technologies, this study adopted a holistic approach, envisioning future scenarios. It distinguished between two levels of AV capabilities and introduced three potential network scenarios to evaluate the impact of technological advancements on the suitability of the current road network for AV deployment. Then, the proposed framework was empirically applied in a specific area within the city of Leeds, United Kingdom, demonstrating its practical applicability.

The assessment results revealed significant heterogeneity in infrastructure readiness across the road network, thereby presenting varied levels of challenges for AV operation. This variability primarily stems from inconsistent infrastructure quality throughout the network. For example, there is notable heterogeneity in the quality of road surfaces, traffic signs, the condition and configuration of road markings, and cellular coverage. However, this heterogeneity observed in the network raises concerns about the immediate feasibility of realising the potential benefits of AV services in urban areas—such as enhancing mobility for disabled or elderly individuals, and providing affordable and accessible transportation (Milakis et al., 2017; Litman, 2023).

In this chapter, a sensitivity analysis was also performed to understand how variations in the RRI outcomes arise due to different weighting strategies, penalty strategies for poor performance of components, and the removal of certain components. The analysis indicated that the significant number of road links in the network incurred penalties because several components exhibited poor performance in scoring the measurement variables. Furthermore, scenario outputs indicate that HD maps can effectively expand the operational areas of AVs by providing either prior or real-time information about the driving environment. This is particularly beneficial for local roads and certain major roads that suffer from poor road markings, traffic signs, challenging geometry, and complex roadside environments. However, as stated in **Chapter 4**, some experts have raised concerns that digital maps may not be available, or not at the desired level, in many cities during the early stage of AV implementation, due to the costs associated with mapping and communication technologies.

The study also found a statistically significant correlation between road hierarchy and road readiness index (RRI) results.[44] This is because roads that are at the upper echelons of the network hierarchy employ relatively higher safety measures for road users and undergo frequent maintenance, making them comparatively well-prepared to accommodate the integration and operation of automated vehicles effectively. Therefore, a strategic approach that prioritises these segments for initial investments in enhancing road infrastructure and integrating efforts for AVs seems sensible. Particularly, main roads (i.e., those in the upper echelons of the network hierarchy, see footnote 36) could be digitised early to optimise societal benefits and efficient allocation of resources since main roads in the network are likely to serve as AV-ready subnetworks during the initial deployment stage. This initiative could also facilitate the adoption of shared AV mobility services, such as shuttles or buses that potentially will operate within these subnetworks.

[44] For instance, in Scenario 1 for LC AVs, Spearman rank correlation analysis revealed that the correlation coefficient between road hierarchy level and RRI values is r=0.545, indicating a moderate positive correlation. This relationship is statistically significant, with a p-value of less than 0.001, suggesting that higher road hierarchies are associated with higher RRI values.

In summary, the main contribution of **Chapter 5** was to introduce a new assessment framework that provides preliminary insights into the road network suitability for L4 AV operation without the immediate need for costly AV trials, making it a valuable tool for city authorities. This is particularly beneficial for cities that have not yet experienced AV deployments, as waiting for real trials could lead to substantial delays due to cost barriers, technological limitations, supply chain issues, and local regulatory environments. Another contribution was that the outcomes of this study and the recommendations based on observations within the network contribute to the understanding of AV integration into road networks and assist decision-makers and transport planners in developing informed, future-oriented policies. In the light of observations, the study provides recommendations on a variety of infrastructure aspects, from parking and bins to lighting, urban trees, dead-end streets, etc. This is intended for policymakers and road authorities to implement strategies that ensure safer and more compatible road infrastructure for users. Despite the study being centred on the UK, its findings have broad implications, offering valuable insights for policymakers globally.

> **5.** How does the (potential) heterogeneity in road infrastructure quality affect the usefulness of Level 4 AVs in an urban setting? (**Chapter 6**)

The study in **Chapter 5**, along with preliminary research (Soteropoulos et al., 2020), highlighted potential differences in the preparedness of road infrastructure across city networks. This variability suggests that certain roads or zones may not be as conducive to AV operations as others. In other words, infrastructure deficiencies could impact the usefulness of AVs—for example, limiting their ability to complete trips if they are restricted to specific roads. This also raises the possibility that when AVs hit the roads, they might be less efficient in terms of traffic outcomes such as travelled distance and duration compared to human-driven vehicles. However, to date, no study has empirically assessed the impact of infrastructure readiness levels on the usefulness of AVs.

As such, the study in **Chapter 6** addressed this gap by conducting the first exploratory analysis to understand how potential heterogeneity in road infrastructure readiness might affect the usefulness of AVs for urban commuting. In this context, the study focused on a part of the city of Leeds, UK, where the demographics of residents are likely to be early adopters of AV technology, primarily for commuter trips (Rahman and Thill, 2023). Additionally, residents are expected to benefit more from the ownership of AVs in terms of cost due to their relatively higher income level (Wadud and Mattioli, 2021). Although the analysis concentrated on road segments that constitute the main arteries of the road network, the study found that there remains significant variation in both their physical and digital infrastructure quality, and hence, in their readiness levels. This finding supports the conjecture made in **Chapter 5**.

On the other hand, the majority of road sections in the selected area demonstrated relatively high RRI values, with around 80% of road sections being categorised as slightly less challenging for the operation of both AV capabilities. Notably, the lowest RRI values are typically observed in rural areas in the study area. Common issues in these regions include the absence of road markings, detectable road edges, pedestrian sidewalks, and consistent road widths, as well as poor road surface conditions. Additionally, factors such as high vegetation coverage surrounding the roads, a lack of street lighting, and poor cellular coverage further contribute to the challenges faced by AVs in these areas.

Although only 20% of road links were classified as extremely challenging within the network, their dispersed distribution caused significant connectivity barriers, making most trips (about 93% of origin-destination (OD) pairs) infeasible for AV navigation. The study found that AVs are likely to travel greater distances than human-driven vehicles due to the varied infrastructure quality, which necessitates taking alternative routes to reach destinations. This could result in additional kilometres travelled within the city. Routing analysis of OD pairs indicated that relatively less challenging paths suitable for both AV capabilities could be up to 8 km (5 miles) longer than those potentially utilised by human-driven vehicles for some OD pairs. Importantly, the analysis revealed that AV trips are on average 20-25% longer than human-driven vehicle trips in the analysed OD pairs. In addition to this heterogeneity-based effect, some studies also revealed that AVs have the potential to increase total travel distance in a network system. For example, network-wide measurements from a study in the Amsterdam metropolitan area found an increase in total travel distance, which is mostly attributed to routing AVs to parts of the network with dedicated infrastructure (Madadi et al., 2021). However, the main reason for this increase here is the increased road capacity of certain road links such as highways due to the platooning effects of AVs, leading to a reduction in time and cost of a trip in a system. Moreover, with the expected increase in empty-vehicle travel and the relocation of parking spaces outside the city centre, AVs may contribute to an overall increase in travel distance (Milakis et al., 2018; Soteropoulos et al., 2019). In general, findings suggest that AVs could potentially have adverse implications for energy consumption and the environment.

Furthermore, the findings underscored that within the existing infrastructure, high-capability AVs, such as robo-taxis equipped with advanced technology, may efficiently meet short-to-medium distance commuting needs in urban areas. This efficiency is primarily due to the difficulty of identifying safer routes for longer trips due to the heterogeneity in the road network's infrastructure quality. That is, longer-distance trips will need a relatively higher number of consecutive suitable links in the network. However, the findings emphasised that infrastructure, particularly digital infrastructure, plays a more crucial role than AV capability in expanding operational areas of AVs. For instance, when relying only on on-board sensors without the support of digital mapping, a substantial majority of commuting trips could not be facilitated by AVs due to the absence of safe routes between origins and destinations. In the scenarios lacking high-definition maps, it was observed that the vast majority (about 93%) of OD pairs within the study area could not be serviced by AVs, even with high-capability AVs. On the other hand, the integration of digital mapping into the network led to only about 7% of road links being classified as extremely challenging, compared to 20% in the absence of mapping scenario. Consequently, this significantly reduced the number of inaccessible origin-destination pairs from 93% to 13% in the evaluated section of road network.

The main contribution of **Chapter 6** to the literature was providing an empirical demonstration of how heterogeneity in road infrastructure readiness can impact AV usefulness. By adopting two AV capability levels and evaluating two potential network scenarios, the study offered a holistic view for policymakers about how future deployment strategies and technological advancements might influence the current infrastructure's suitability and the overall usefulness of AVs.

7.2 Implications for practice

Given the insights derived from the five investigations conducted in this thesis, the findings have practical implications for various types of stakeholders. These are discussed as follows:

Road authorities and policymakers

The advent of Level 4 AVs marks a transformative era in the transport sector and will fundamentally change the traditional dynamics of vehicle operation and road use. This shift will impact the structures and responsibilities of traditional stakeholders, typically well-established organisations responsible for conventional vehicles and road infrastructure. Among these stakeholders are road authorities and policymakers, who own and manage the road infrastructure, overseeing planning, investment, and the safety of traffic operations to ensure conditions are suitable for all users. Thus, the success of AVs will hinge on their strategies for managing the road network infrastructure during the transition to full automation. The studies presented in this thesis provide many critical insights (e.g., expected challenges and potential ways to overcome barriers) derived from both literature reviews and the opinions of experts and stakeholders regarding the infrastructure for AVs. For instance, one common view among stakeholders is that digital infrastructure offers greater potential for short-term benefits compared to upgrades of physical infrastructure – a conclusion supported by the findings of scenario-based assessments. Therefore, road authorities and policymakers can benefit from the outcomes and recommendations of these studies to guide their future policies on accessible, equitable, and sustainable solutions, as well as measures to minimise the potential risks associated with vehicle automation.

Furthermore, the findings in the thesis are of great importance to help frame the public message regarding infrastructure readiness in line with the level of AV capability in vehicles. The implementation of the index into a road network allows authorities to gain preliminary insights into their road network without conducting actual AV trials. Therefore, the outputs of this study offer a practical assessment for authorities to understand their current position and determine where to focus their investments. The visualising of the index score is important not only for identifying potential areas where only AVs might be permitted but also for pinpointing areas that might pose risks to the accessibility of AV services. Additionally, the index allows road authorities to evaluate the current state of roads, highlighting weaknesses and strengths in terms of user safety. In summary, implementing the index within a road network aids authorities in making informed investment, policy, and strategic decisions.

Transport modellers and consultants

Transport consultants develop and utilise transport models to assist policymakers in evaluating decisions and strategies related to transportation. In a broader perspective, they can incorporate the road readiness index (RRI) results in the network into their existing or planned models to evaluate transport policies for AV integration and guide policymakers in making informed decisions. For example, by using the index map in their simulation models, they can analyse the impacts of AVs on traffic outcomes at different penetration rates. More importantly, by using this integrated simulation model, transport modellers can analyse which road links in a network should be upgraded to maximise societal benefits and assist policymakers in making informed investment decisions. For example, they can evaluate potential dedicated road links or lanes within a network for public transport models of AVs, such as Level-4 automated shuttles, to meet the needs of travellers who do not have access to vehicles. The optimal pick-up and drop-off point locations for AVs can also be reevaluated by considering the proposed index in this study. As such these insights can serve as guidelines for planners to develop their strategies regarding road network infrastructure during the transition period to full automation.

AV industry and supporting service providers

Some experts, including current AV developers surveyed for this study, do not anticipate substantial changes to the road network in the near future due to the economic constraints faced by road authorities. This situation makes the business model of AV developers reliant on using existing roads, thereby limiting where and when their vehicles can operate. Thus, AV developers can use the index to discuss and evaluate baseline parameters for the minimum requirements of AVs. The parameters adopted in the index and its measurement variables can serve as preliminary thresholds for highly automated vehicle technology, allowing developers to demonstrate their capabilities to authorities. This approach can allow for determining which roads are ready for specific types of AVs.

The road readiness index explores the initial steps in assessing the suitability of different parts of the road network and identifying potential operational areas for automated driving. Similar to this study, mapping the index score can enable routing software to select the most suitable routes or zones for AVs, benefiting AV operators. This allows them to focus on areas where technology can be adapted at lower costs and to assess the areas that are likely to be most lucrative, taking into account the demographic structure of these areas.

Service providers, such as map and telecommunications providers, also stand to gain from the outcomes presented in this thesis. Despite debates among experts about the feasibility of achieving real-time high-definition maps in the near future, the digitalisation of road networks is expected to contribute to safe and efficient automated driving, especially in urban areas. The findings indicate that digital maps can expand the operational areas of AVs by providing prior or real-time information about the driving environment. This helps mitigate risks associated with deficiencies in physical road infrastructure, such as poor road markings. Thus, map makers could have a chance to strategically manage their investments in service areas by focusing on the outputs of the index for specific cities.

Connectivity is also highlighted as critical for support and, in some cases, such as getting information regarding the locations of roadworks or emergency vehicles, essential for safety measures. Therefore, telecommunications operators will likely need to evaluate their service quality under more stringent rules to provide convenient services for automated driving and address gaps in their service areas. They should display their service quality maps for AV operation on the road network, rather than merely defining cellular coverage maps. However, achieving success in these supporting services will largely depend on strong collaboration with central authorities and international organisations for standardisation. For example, high-definition map structures, communication architecture, and protocols will need to be standardised and certified to support the integration of AVs into the existing road network

Road users

The main contribution of this thesis to road users is to provide valuable information and insights that can be used for strategies to prioritise the safety of all road users. There is considerable variation in the quality, nature and standard of maintenance of roads. This means that some roads will be much less suitable for AVs than others, as demonstrated in the case study evaluations. The implementation of the index proposed in this thesis and the resulting score can indicate how prepared and therefore how safe a particular road section is. Therefore, roads with good infrastructure quality and less challenging sections should be prioritised in the initial stages of implementation to ensure the highest levels of safety.

Furthermore, with the help of this framework, if legislative bodies clearly define the subnetworks where automated driving is permitted, all road users can be better informed about potential mixed traffic areas. This awareness enables non-AV road users to adjust their driving behaviours when sharing the road with these emerging technologies. This is especially crucial for vulnerable road users during the transitional period as their interactions with AVs are critical. Additionally, AV owners or users benefit from the index outputs, as the index can inform them of relatively safer routes or critical sections where they might need to take manual control of their vehicles in advance. This contributes to road safety by mitigating potential risks at these points in the network. Consequently, the outcomes of this assessment framework can serve as beneficial, supportive tools for all road users

7.3 Limitations of the study and suggestions for future research

This study primarily serves as an exploratory and conceptual model for a safe and efficient transition to Level 4 automated driving, rather than an empirically proven index that clearly indicates risky road segments within a network. For this reason, several limitations identified in this thesis should be considered when interpreting the results. These limitations underscore areas that require further research to enhance the validity and generalisability of the findings. Therefore, this section presents the main limitations of the study and recommendations based on these limitations, aiming to address the identified shortcomings and provide directions for future research. They are discussed as follows:

Firstly, the proposed assessment framework in Chapter 5 was developed based on relevant literature and expert insights, rather than empirical data, due to the limitations associated with the availability of real-world data on AV services. As such, the importance level of the proposed index components was determined by experts using a 5-point Likert scale ranking technique **(Chapter 4**). This ranking was based on the aggregated views of several experts, whose experience is derived from current knowledge acquired through AV pilots, simulations or modelling studies, and sometimes anecdotal media coverage. Moving forward, employing in-depth interviews, focus group discussions with stakeholders, or the Delphi method could potentially refine the index structure, particularly the scoring of measurement variables for specific Level 4 AV use cases. Such an approach may reduce the subjectivity inherent in expert opinions, leading to a more robust and universally applicable index. This is especially critical as all potential factors affecting the safe operation of Level 4 automated driving were generally ranked as important, despite slight differences in opinions between stakeholder groups.

In addition, the next step of this study could adopt advanced weighting methods, such as the Analytic Hierarchy Process (AHP), to generate reliable weights for the parameters based on expert judgments. To do this, however, the index structure must first be organised into a hierarchical level, as indexes consisting of many parameters without hierarchical structures require significant computational effort (e.g., pairwise comparisons by experts). In this regard, it is also important to consider the interactions between (sub)components that contribute to the safe operation of AVs and the overall suitability of road sections within a network. Rather than relying solely on a scenario-based approach to account for changes in network conditions, future studies could re-organise the index structure as a fuzzy-rule-based system with dependent (sub)components to better capture potential interactions between factors. However, this approach requires strong support from AV industry members to fully understand the limitations and capabilities of automated driving systems under certain circumstances.

Secondly, the analysis of road sections in **Chapters 5** and **6** primarily focused on relatively static factors and road environment attributes, due to the challenges of integrating rapidly changing dynamic factors into the road segment evaluation. However, with ongoing advancements in intelligent transportation systems and information and communication technologies, road and city authorities now have access to a myriad of dynamic data through sensors within the road network. Therefore, future iterations of this study should aim to develop a dynamic index that incorporates real-time data. For example, incorporating environmental conditions and traffic flow-related factors into the index by evaluating them in real time could provide a more comprehensive and responsive assessment of road suitability for AVs. Furthermore, leveraging real-time AV sensor data allows for dynamic modelling of parameters such as the number and diversity of road users in the index.

Thirdly, given the significant variability in physical attributes and amenities within a single road link or at intersections, future research might aim to evaluate road segments of equal or smaller lengths to increase data granularity. Specifically, implementing the index at a microscopic level, such as lane-level detail, could provide a more precise understanding of the road conditions and environment. This approach would provide authorities with more specific information, optimising decision-making, and investment strategies for the development of AV-compliant road links.

Fourthly, most of the data used in the studies in **Chapters 5** and **6** was assessed by visual inspection, employing aerial photographs, satellite imagery, and street view services. However, as snapshots of the past, these images provide a limited perspective and are updated at an irregular frequency. In addition, the assessment process is potentially prone to human errors and can be time-consuming. Future research could consider the use of digital image processing techniques for the evaluation of subcomponents. While this method may require more resources and effort, the resulting insights could significantly enhance the accuracy and relevance of the readiness index for AVs. This becomes particularly important when real AV data are available that could provide more up-to-date information about the road environment.

Fifthly, as discussed in **Chapter 6**, the study primarily examined scenarios of uncongested traffic, with no constraints based on link capacity. Therefore, incorporating RRI into traffic models could provide more detailed and nuanced insights. Furthermore, a significant barrier to AV adoption in urban road networks is the diversity of intersections and roundabouts, each categorised by its unique rules and complexities. Just as some road sections pose challenges for AV operation, certain intersections also present difficulties. Therefore, further studies should also consider these points in the network, as they directly influence the journey routing of AVs.

Lastly, a critical future direction for this thesis involves validating and assessing the feasibility of the proposed framework using real-world AV test data. Analysing locations in a network where AVs encounter collision risks or require disengagement of their automated systems could serve as a foundation for verifying the factors adopted in the framework's (sub)components. Although current efforts have already been made in this direction, the available data are insufficient to clearly identify these factors. Additionally, exploring the correlations between the RRI scores at these locations will be instrumental. Further refinement of the weights or impact coefficients of these factors could be achieved using a Bayesian network approach. This method would help reduce the subjectivity associated with expert insights, providing a more objective basis for evaluating the framework's components.

7.4 Overall conclusions and recommendations for policymakers

This section presents four main overall conclusions from the studies carried out in the thesis. These are briefly stated as follows:

- The implications of AVs for the physical road environment, particularly at high levels of automation, will be diverse, complex, and highly uncertain as it depends on many factors and will affect many aspects of transport system performance. Stakeholder engagement and shared responsibility are essential for creating a safer road environment for automated vehicles and all road users.

As such, policymakers should foster collaboration and shared responsibility among stakeholders to ensure a safer road environment and harmonise activities on an international scale. In this evolving context, the taxation structures related to road transportation, as well as the management and maintenance of road infrastructure, will undergo considerable changes. Policymakers and road authorities will need to develop new skills and engage with areas and organisations with which they are not previously familiar. Additionally, existing traffic laws and regulations will need to be rearranged for the integration of AVs into the transportation system.

- Various infrastructure-related challenges await stakeholders in implementing AV technologies into the existing road network. In particular, determining road sections where AVs can safely operate and managing mixed traffic situations during the transitional phase are major challenges that stakeholders need to address. A common assumption is that AVs can operate safely on high-quality roads, while cities or areas with poor road infrastructure are predicted to be slow in adopting AVs. This could prevent the deployment of useful AV services in urban and rural areas. Therefore, authorities should assess the readiness of their networks for these emerging vehicles. Redirecting AV traffic to specific parts of the network that are inherently safe for automated driving is important for safe integration into the existing transportation systems. This will also be vital for road administration to achieve economical solutions at the initial stage of deployment.

- Road networks can potentially exhibit heterogeneity in the quality of both physical and digital road infrastructures. Significant infrastructural modifications or advancements in AV technologies will likely be necessary before door-to-door shared options for AVs, such as robo-taxis—which are perceived to reduce reliance on personal vehicle ownership—can become viable. In the near term, this may not be feasible due to the requiring significant infrastructure financing for investment from both private and public entities. If policymakers prefer the "wait to see" option for the deployment of the AVs, the operations of AVs are likely to be restricted only to the compatible road sections or subnetworks within a system. As revealed in this study, this means that AVs are likely to travel greater distances than human-driven vehicles due to the necessity of taking alternative routes to reach destinations. This also brings about implications for increases in VMT, congestion or carbon emissions in a network. Therefore, policymakers and city authorities need to prepare an appropriate plan for this transition period, taking into account the potential negative consequences of these technologies.

- Potential heterogeneity in a road network could precipitate equity issues within communities, as access to AV-based services might be limited to specific AV-compatible zones. For instance, the results of this study showed that meeting demand in sparsely populated rural areas may be problematic for AVs, as these areas often have poor-quality infrastructure that presents relatively high challenges for automated driving. Consequently, during the initial stages, these regions are likely to be excluded from the AVs' geofenced service areas. This situation highlights the urgent need for rural populations to benefit equitably from advancements in AV technology. This disparity could also affect property values, potentially exacerbating existing social inequalities. Therefore, ensuring equity in accessibility to AV services should be a priority for policymakers and city authorities.

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APPENDIX A

Appendix A to Chapter 2

Table A.1 A summary of the key attributes from the literature on implications of AVs for the physical road environment

No	Ref	Outlet type	Location	Level of automation (SAE) considered	Research type[1]	Road attributes considered												
						Road alignments	Road cross-sectional elements	Pavement / Road surface	Road markings	Traffic signs and control signals	Junctions and roundabouts	Parking facilities	Structures: bridges, tunnels etc.	Facilities for vulnerable road users	Road equipment	Lighting	Drainage system	Maintenance
1	(Alonso Raposo et al., 2017)	Report	EU	Unspecified	LR				X	X								X
2	(Amelink et al., 2020)	Report	EU	L4	LR & SV	X	X	X	X	X	X	X	X	X	X	X		X
3	(Aryal, 2020)	Thesis	Sweden	L5	AR	X*	X*	X			X							
4	(Carreras et al., 2018)	Conference paper	Austria, Spain	Unspecified	SV				X	X								
5	(CAVita, 2017)	Report	USA, Canada	Unspecified	SV					X		X						
6	(Chapin et al., 2016)	Report	USA	L5	SV		X			X	X	X		X				
7	(Chen et al., 2016)	Journal	Sweden	Unspecified	AR			X*										
8	(Department for Transport, 2015)	Report	UK	L4-5	LR & SV				X	X								
9	(Ehrlich et al., 2016)	Conference paper	France	Unspecified	LR	X		X	X	X								
10	(EuroRAP and Euro NCAP, 2013)	Report	EU	L2	SV				X	X						X		
11	(Farah et al., 2018)	Book section	Netherlands	Unspecified	LR & SV	X	X	X	X	X	X		X	X				X
12	(FTIA, 2021)	Report	Finland	L3-4	LR & ER		X	X	X	X	X	X	X	X	X	X	X	X
13	(García et al., 2019)	Conference paper	Spain	L2	ER	X	X											
14	(Gill et al., 2015)	Report	Canada	Unspecified	LR & SV		X	X	X	X	X	X	X					X
15	(Gopalakrishna et al., 2021)	Report	USA	L1-5	LR & SV		X	X	X	X	X	X	X	X	X	X		X
16	(Guerrieri et al., 2021)	Journal	Italy	L4-5	AR	X*												
17	(Huggins et al., 2017)	Report	Australia, New Zealand	Unspecified	LR & SV	X	X	X	X	X	X	X	X	X	X	X		X
18	(Intini et al., 2019)	Journal	Italy	L5	AR	X*	X	X									X	
19	(Issac, 2016)	Report	USA	L5	LR		X	X	X	X		X		X				X
20	(Johnson and Rowland, 2018)	Report	Australia	L1-5	LR, SV & ER	X	X	X	X	X	X	X	X	X	X	X	X	X

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Table A.1 (continued)

No	Ref	Outlet type	Location	Level of automation (SAE) considered	Research type[1]	Road attributes considered												
						Road alignments	**Road cross-sectional elements**	**Pavement / Road surface**	**Road markings**	**Traffic signs and control signals**	**Junctions and roundabouts**	**Parking facilities**	**Structures: bridges, tunnels etc.**	**Facilities for vulnerable road users**	**Road equipment**	**Lighting**	**Drainage system**	**Maintenance**
21	(Johnson, 2017)	Report	UK	Unspecified	LR & SV	X	X	X	X	X	X	X	X	X	X	X	X	X
22	(Khoury et al., 2019)	Journal	USA	L5	AR	X*												
23	(Kockelman et al., 2017)	Report	USA	L1-4	LR & SV				X	X	X	X				X		
24	(Konstantinopoulou and Ljubotina, 2020)	Report	EU	L3-5	LR & ER	X	X	X	X	X	X	X	X	X	X	X		X
25	(KPMG and CAR, 2012)	Report	UK	Unspecified	LR & SV		X		X	X		X						
26	(Lawson, 2018)	Report	UK	Unspecified	LR & SV				X	X	X			X		X		X
27	(Liu et al., 2019)	Journal	UK	Unspecified	LR	X	X	X	X	X	X	X	X	X			X	X
28	(Lu et al., 2019)	Conference paper	Netherlands	L4	LR & SV	X		X	X	X	X			X				
29	(Lutin et al., 2013)	Journal	USA	L5	LR		X	X				X						
30	(Lyon et al., 2017)	Report	Australia	Unspecified	LR		X	X	X	X	X	X	X	X	X	X		X
31	(Manivasakan et al., 2021)	Journal	Australia	L4	LR & SV	X	X	X	X	X	X	X	X	X				X
32	(McCarthy et al., 2016)	Report	UK	Unspecified	LR				X	X		X	X		X			X
33	(McDonald, 2021)	Conference paper	USA	L5	AR	X*	X	X	X	X	X							
34	(McDonald and Rodier, 2015)	Book section	USA	Unspecified	SV	X	X				X	X		X				
35	(Mocanu et al., 2015)	Conference paper	Austria	L4	LR & SV	X	X	X	X	X	X	X		X	X	X		X
36	(Nitsche et al., 2014)	Conference paper	Austria	Unspecified	LR & SV	X		X	X	X				X	X			
37	(Noorvand et al., 2017)	Journal	USA	L5	AR			X*										
38	(Othman, 2021)	Journal	Canada	L4-5	LR	X	X	X	X	X		X	X			X		
39	(Paulsen, 2018)	Thesis	Norway	L4-5	LR & AR	X	X	X	X	X	X		X					
40	(PIARC, 2021)	Report	-	L3-5	LR & SV	X	X	X	X	X	X	X	X	X	X			X

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Table A.1 (continued)

No	Ref	Outlet type	Location	Level of automation (SAE) considered	Research type[1]	Road alignments	Road cross-sectional elements	Pavement / Road surface	Road markings	Traffic signs and control signals	Junctions and roundabouts	Parking facilities	Structures: bridges, tunnels etc.	Facilities for vulnerable road users	Road equipment	Lighting	Drainage system	Maintenance
						Road attributes considered												
41	(PSC and CAR, 2017)	Report	USA	Unspecified	LR & SV		X		X	X		X		X		X		X
42	(Rana and Hossain, 2021)	Journal	Canada	Unspecified	LR	X	X	X	X	X								
43	(Saeed, 2019)	Thesis	USA	L4-5	LR & SV	X	X	X	X	X	X	X	X				X	X
44	(Shladover and Bishop, 2015)	White paper	USA	L2-5	LR & SV		X		X	X		X		X		X		X
45	(Somers, 2019)	Report	Australia	Unspecified	LR, SV & ER		X	X	X	X								X
46	(Soteropoulos et al., 2020)	Journal	Austria	L4	LR	X	X	X	X	X	X	X	X	X	X	X		X
47	(Transport Systems Catapult, 2017)	Report	UK	Unspecified	LR & SV		X	X	X	X	X	X	X	X				X
48	(UK Autodrive and Gowling WLG, 2018)	Report	UK	Unspecified	LR & SV		X		X	X	X	X	X					
49	(Ulrich et al., 2020)	Report	EU	L3-5	LR & SV		X	X	X	X	X	X	X	X	X		X	X
50	(Vujic et al., 2020)	Book section	Croatia	L5	LR				X	X								
51	(Washburn and Washburn, 2018)	Report	USA	L5	LR & AR	X					X	X						
52	(Welde and Qiao, 2020)	Journal	USA	L3 & L5	AR	X*												X
53	(X. Ye et al., 2021)	Journal	China, USA	L5	AR	X*			X									
54	(Yeganeh et al., 2022)	Journal	Belgium	L5	AR		X	X*										
55	(Zhang, 2013)	Report	USA	L0-5	LR				X	X								
56	(Zhao et al., 2021)	Journal	Canada	L5	AR			X*										
57	(Zhou et al., 2019)	Report	USA	L5	ER		X	X*										
Total number of research covering identified issues.						28	36	35	41	42	28	30	21	24	14	16	7	26

1: AR= Analytical research, ER= Experimental research, LR= Literature review, SV=Stakeholder views
X: Provides inference from either the problems that emerged in a real situation or the critical thinking through engineering experience.
X*: An in-depth analysis has been made on the subject

APPENDIX B

Appendix B to Chapter 5

Table B.1 Overview of scoring scheme for subcomponents of the road readiness index for automated driving.*

# (C_i)	Framework Components	# ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C1	Road Geometry Challenges	C1,1	Horizontal curvature	0.25	Straight or gently curving (Radius of curvature: R ≥ 400m)	1	1
					Moderate curvature (150 ≤ R<400m)	0.5	0.75
					Sharp curvature or corners (R<150m)	0	0.25
		C1,2	Longitudinal gradient	0.25	Flat or gentle rise (0% to <4%)	1	1
					Moderate rise (4% to <8%)	0.75	1
					Steep rise (≥ 8%)	0.25	0.5
		C1,3	Road width consistency	0.25	Constant or slight change in road or lane width (road width change rate less than 15%)	1	1
					Presence of moderate change (narrowing or widening) in road or lane width (road width change rate is 15 to 30%)	0.5	0.75
					Presence of high change in road or lane width (road width change rate higher than 30%)	0	0.25
		C1,4	Digital mapping of road geometry	0.25	Presence of digital map of road geometry	1	1
					No presence of digital map of road geometry	0	0
C2	Road Surface Condition	C2,1	Road surface type	0.5	Asphalt or concrete and has a homogeneous appearance	1	1
					Pavers, bricks, or presence of different colours or materials on the road surface (e.g. patching, ghost markings, presence of lots of manholes etc.)	0.5	0.75
					Unpaved road surface (e.g. gravel)	0	0.25
		C2,2	Road surface condition	0.5	No presence or low level of deterioration (e.g. potholes, cracks, rutting etc.) or RCI is Green	1	1
					Presence of moderate level of deterioration or RCI is Amber	0.5	0.75
					Presence of severe level of deterioration or RCI is Red	0	0
C3	Road Marking Condition	C3,1	Digital mapping of road markings	0.25	Presence of digital map of road markings	1	1
					No presence of digital map of road markings	0	0
		C3,2	Road marking configuration	0.25	Presence of both the centre lines and two edge markings	1	1
					Presence of centre lines and one-side edge markings	0.75	1
					Presence of only centre lines or two-sides edge markings	0.5	0.75
					Presence of only one-side edge markings	0.25	0.5
					No presence of road markings	0	0

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Table B.1 (continued)

# (C_i)	Framework Components	# ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
		C3,3	Road marking wear condition	0.5	Wear score is 50 (no obvious wear) to 40 (very little wear) according to CS126 standard	1	1
					Wear score is 30 (some visible wear, larger bare sports) to 20 (visible but has randomly spaced small bare spots)	0.5	0.75
					Wear score is 10 (barely visible) to 0 (non-existent, residue only)	0	0
C4	Road Boundaries	C4,1	Median type	0.5	One-way road, or two-way road with concrete/metal safety barrier, kerb stone or grass median	1	1
					Wide or double centre line or central hatching (two-way road)	0.75	1
					Centre line (two-way road)	0.5	0.75
					Cable barrier or flexible posts (two-way road)	0.25	0.5
					No presence of median (two-way road)	0	0.25
		C4,2	Road edge condition	0.25	Continuous road edge (e.g. kerb stone, barriers, grass etc.) on both sides of roadway	1	1
					Discontinuous or damaged road edge (e.g. access points) on one-side of roadway	0.5	0.75
					Discontinuous or damaged road edge (e.g. access points) on both sides of roadway	0	0.25
		C4,3	On-street vehicle parking	0.25	Parking or limited time waiting is not permitted	1	1
					Presence of parking or limited time waiting zone on one side of roadway	0.50	0.75
					Presence of parking or limited time waiting zone on two sides of roadway	0	0.25
C5	Traffic Signs Visibility	C5,1	Digital mapping of traffic signs	0.5	Presence of digital map of traffic signs	1	1
					No presence of digital map of traffic signs	0	0
		C5,2	Traffic signs conditions	0.5	Presence of visible and readable physical traffic signs (e.g. not obstructed, damaged, vandalised etc.) or absence of traffic signs on the roadway	1	1
					Presence of multiple signs in single unit	0.5	0.75
					Presence of electronic signs such as variable message signs	0.25	0.5
					Unreadable, damaged, or obstructed traffic signs (critical defects according to CS125)	0	0
C6	Special Road Section	C6,1	Special road sections	1.0	Not presence of any special road sections stated below	1	1
					Presence of grade-separated interchanges or slip roads/ramps (e.g. merging or diverging sections)	0.75	1
					Presence of weaving areas (merging and diverging sections)	0.5	0.75

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Table B.1 (continued)

# (C_i)	Framework Components	# ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score($Sc_{i,j,m}$)	
						LC	HC
					Presence of toll plazas or gates on the roadway (e.g. chicane or road narrowing)	0.25	0.50
					Presence of dead-end roadway (with/out turning point)	0	0
C7	Road Lightning	C7,1	Lighting condition	1.0	Presence of road lighting systems and no obstacles around (e.g. trees in the surrounding)	1	1
					Presence of road lighting systems with obstruction around or short underpasses (L < 20m) on the roadway	0.5	0.75
					Presence of long underpasses (L > 20m) or tunnels	0.25	0.50
					No presence of median (two-way road)	0	0.25
					No presence of road lighting systems or damaged lighting system	0	0.25
C8	Speed Limit	C8,1	Speed limit of road section	1.0	Speed limit < 37 mph	1	
					37 mph ≤ Speed limit < 42 mph	0.50	
					42 mph ≤ Speed limit < 61 mph	0.25	
					61 mph ≤ Speed limit	0	
					Speed limit < 47 mph		1
					47 mph ≤ Speed limit < 53 mph		0.50
					53 mph ≤ Speed limit < 76 mph		0.25
					76 mph ≤ Speed limit		0
C9	Number and Diversity of Road Users	C9,1	Road access	0.5	Access control roads: VRUs (e.g. pedestrians and cyclists) are not permitted	1	1
					Mixed traffic roads without any public transit facilities (bus, tram etc.)	0.5	0.75
					Mixed traffic roads with public transit facilities	0.25	0.5
					Shared space roads: access to all road users	0	0.25
		C9,2	Counterflow	0.25	No presence of counter flow traffic	1	1
					Presence of counter flow traffic	0	0.25
		C9,3	No. of lanes	0.25	Total number of lanes on the road section (N≤2)	1	1
					Total number of lanes on the road section (2< N ≤4)	0.5	0.75
					Total number of lanes on the road section (N>4)	0.25	0.5

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Table B.1 (continued)

# (C_i)	Framework Components	# ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score($Sc_{i,j,m}$) LC	HC
C9	Number and Diversity of Road Users	C9,1	Road access	0.5	Access control roads: VRUs (e.g. pedestrians and cyclists) are not permitted	1	1
					Mixed traffic roads without any public transit facilities (bus, tram etc.)	0.5	0.75
					Mixed traffic roads with public transit facilities	0.25	0.5
					Shared space roads: access to all road users	0	0.25
		C9,2	Counterflow	0.25	No presence of counter flow traffic	1	1
					Presence of counter flow traffic	0	0.25
		C9,3	No. of lanes	0.25	Total number of lanes on the road section (N≤2)	1	1
					Total number of lanes on the road section (2< N ≤4)	0.5	0.75
C10	Roadside Complexity	C10,1	Presence of trees	0.25	No presence of trees on two sides of roadway (or presence far from the road edges such as d >8-10m)	1	1
					Presence of trees on one side of roadway	0.5	0.75
					Presence of trees on both sides of roadway	0	0.25
C11	Facilities for Vulnerable Road Users	C11,1	Pedestrians crossing type	0.25	Presence of pedestrian bridges or underpasses on the roadway	1	1
					Puffin, Toucan, Pegasus crossing on the roadway	0.75	1
					Pelican crossing on the roadway	0.5	0.75
					Zebra crossing or surface marked crossing on the roadway	0.25	0.50
		C11,2	Pedestrian sidewalk	0.25	Physically segregated pedestrian sidewalk with barriers, buffer, or landscaping zones on the roadway	1	1
					Presence of sidewalk on both sides of the roadway	0.75	1
					Presence of sidewalk on one side of the roadway	0.50	0.75
					No presence of sidewalk for pedestrians on the roadway	0	0.25
		C11,3	Cycling infrastructure	0.25	Physically segregated cycle lane on the roadway	1	1
					Segregation with lane markings or painting on surface on the roadway	0.50	0.75
					No presence of segregation on the roadway	0	0.25

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Table B.1 (continued)

# (C_i)	Framework Components	# ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score($Sc_{i,j,m}$) LC	HC
		C11,4	Public transit access point design	0.25	No presence of bus route, stops, or Presence of dedicated bus lane on the roadway	1	1
					Presence of bus lay-by on the roadway	0.75	1
					Presence of bus shelter on the roadway	0.50	0.75
					Presence of bus stop with road marking and post on the roadway	0.25	0.5
C12	Precautions for Roadworks and Incidents	C12,1	Precautions for roadworks and incidents	1.0	No presence of roadwork or incident on the roadway	1	1
					Presence of roadwork or incident with real-time layout level information, and standardised digital and physical warning signs and markings on the roadway	0.75	1
					Presence of roadwork or incident with standardised digital and physical warning signs and markings on the roadway	0.50	0.75
					Presence of roadwork or incident with only standardised physical warning signs and markings	0.25	0.50
					Presence of roadwork or incident without any precautions for AVs	0	0.25
C13	Localisation Challenges	C13,1	Localisation challenges	0.5	Presence of landmarks or magnetic road markings on the roadway	1	1
					Presence of low-rise development on both sides of the roadway	0.75	1
					Presence of high-rise development or high-vegetation cover on one side of the roadway	0.5	0.75
					Presence of high-rise developments (e.g. urban canyons) or valleys surrounding the roadway or high vegetation cover on both sides of the roadway or short underpasses (L < 20m) on the roadway	0.25	0.5
					Presence of long underpasses (L > 20m) or tunnels on the roadway	0	0
C14	Communication Facilities	C14,1	Roadside Units	1.0	Presence of Roadside Units (RSUs) along with the roadway (e.g. DSRC or ITS-G5)	1	1
		or			No presence of Roadside Units (e.g. DSRC or ITS-G5)	0	0
		C14,1	Cellular network coverage	1.0	Excellent or good 5G NR coverage in operation area for C-V2X	1	1
					Average 5G NR coverage in operation area for C-V2X	0.75	1
					Excellent or good 4G/LTE coverage in operation area for C-V2X	0.5	0.75
					Average 4G/LTE coverage in operation area for C-V2X	0.25	0.5
					Below average, poor, limited cellular coverage or Network blackspots	0	0

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Table B.1 (continued)

# (C_i)	Framework Components	# ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score($Sc_{i,j,m}$) LC	HC
C15	Intersections and Roundabouts	C15,1	Intersection and roundabout type	0.25	Signal controlled intersections with protected turn lane	1	1
					Signal controlled intersections, or Priority-controlled intersections with protected turn lane	0.75	1
					Priority-controlled intersections, or Mini or single-lane roundabouts	0.50	0.75
					Uncontrolled intersections, or Median crossing points	0.25	0.5
		C15,2	Number of arms	0.25	N = 3 (e.g. T or Y intersections)	1	1
					N = 4 (e.g. Cross / staggered)	0.5	0.75
					N > 4 (e.g. multi-armed)	0	0.25
		C15,3	Regularity of layout	0.25	Regular form of intersection	1	1
					Irregular form of intersection	0	0.25
		C15,4	Delineation (marking) conditions	0.25	Clear visible marking or Availability of HD mapping	1	1
					Some visible wear on the markings	0.5	0.75
					Barely visible or non-existent markings	0	0.25

* Detailed information on each component in the assessment framework, along with their corresponding subcomponents and measurement variables, can be found in the Supplementary Materials (**SM-1.1**).

APPENDIX C

Appendix C to Chapter 5

Table C.1 Overview of the data collection method for representing the subcomponents of framework components and general assessment of the quality of collected data.

Ci	Framework components	Ci,j	Subcomponents	Source of data/ method of data collection	General assessment of collected data quality/representation
C1	Road Geometric Challenges	C1,1	Horizontal curvature	It was initially calculated by using ROCA (ROad Curvature Analysis) toolbox in ArcGIS Pro developed by (Bíl et al., 2018). It was then revised by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C1,2	Longitudinal gradient	It was roughly estimated by using the data provided by the Ordnance Survey MasterMap. Elevation differences of road link ends were divided into the length of the road link. However, this method has limitations for long or non-straight road links and no precise gradient level is obtained. Also revised by visual inspection using street view services.	Fair
		C1,3	Road width consistency	It was initially calculated the change rate of width in road links using the data provided by the Ordnance Survey MasterMap. The difference between average road width and minimum road width was divided by average road width. A score of 1 was given if the ratio was less than 0.15, 0.5 if it was between 0.15 and 0.3, and 0 otherwise. Also, it was revised by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C1,4	Digital map of road geometry	An assumption was made according to scenarios (S1: no HD maps, S2-3: available for all network)	Poor
C2	Road Surface	C2,1	Road surface type	It was evaluated by visual inspection using street view services.	Fair
		C2,2	Road surface condition	The condition of the road surface was categorised based on the available RCI data provided by the Department for Transport. The data is available at: https://maps.dft.gov.uk/road-condition-explorer/index.html. Also, it was evaluated by visual inspections using street view services for places where automated inspection data collected by specialised vehicles is not available.	Fair
C3	Road Markings	C3,1	Digital map of road markings	An assumption was made according to scenarios (S1: no HD maps, S2-3: available for all network)	Poor
		C3,2	Marking configuration	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C3,3	Marking condition	It was roughly evaluated by visual inspection using street view services according to examples in Appendix C of the DMRB CS 126 standard.	Fair
C4	Road Boundaries	C4,1	Median type	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services.	Good
		C4,2	Road edge condition	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, the continuity of road edge conditions was controlled from: https://www.leedstraffweb.co.uk/main.html and Ordnance Survey MasterMap Topography Layer.	Fair
		C4,3	On-street vehicle parking	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, parking locations on the network were controlled from: https://www.leedstraffweb.co.uk/main.html	Fair
C5	Traffic Signs	C5,1	Digital map of traffic signs	An assumption was made according to scenarios (S1: no HD maps, S2-3: available for all network)	Poor

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Table C.1 (continued)

Ci	Framework components	Ci,j	Indicators	Source of data/ method of data collection	General assessment of collected data quality/representation
		C5,2	Traffic signs conditions	It was roughly evaluated by visual inspection using street view services according to examples in Appendix E of the DMRB CS 125 standard.	Fair
C6	Special road section	C6,1	Special road sections	It was evaluated by using the data provided by the Ordnance Survey MasterMap. In addition, it was checked by visual inspection using aerial photography/satellite imagery or street view services.	Good
C7	Road Lightning	C7,1	Lighting condition	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Detailed information on the location and unit type of streetlights is available at: https://datamillnorth.org/dataset/street-lights-unmetered. However, the limitation of this method cannot consider whether the lighting systems work properly at night.	Poor
C8	Speed Limit	C8,1	Speed limit of road section	It was evaluated based on the interactive map providing traffic orders of roads that are under the control of Leeds City Council. (https://www.leedstraffweb.co.uk/main.html). Also, it was roughly controlled by visual inspection of speed limit signs on the roadway using street view services. Alternatively, Open Street Map can be used for this indicator.	Fair
C9	Number and Diversity of Road Users	C9,1	Road access	It was initially evaluated by considering road hierarchy. Also, public transit (bus) route was controlled from: Open Streep Map and https://www.geopunk.co.uk/timetables/town/leeds. Then it was controlled by visual inspection using aerial photography/satellite imagery or street view services	Fair
		C9,2	Counterflow	It was evaluated by using the data provided by the Ordnance Survey MasterMap. Also, it was controlled by traffic orders data of the city from https://www.leedstraffweb.co.uk/main.html	Fair
		C9,3	No. of lanes	It was initially estimated by dividing the average road width by the approximate lane widths by type of road hierarchy. It was then revised by visual inspection using aerial photography/satellite imagery or street view services.	Fair
C10	Roadside Complexity	C10,1	Presence of trees	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. For detail analysis for this indicator can be done by using Tree Detection toolbox (deep learning model to detect trees in high resolution imagery) in ArcGIS Pro by aerial photography/satellite imagery.	Fair
		C10,2	Street furniture density	It was roughly evaluated by visual inspection using street view services.	Poor
		C10,3	Proximity of buildings	It was roughly estimated using data provided by Ordnance Survey MasterMap in QGIS. Also, commercial facilities control with visual inspection by using street view services.	Poor
		C10,4	Digital mapping of surrounding road environment	An assumption was made according to scenarios (S1: no HD maps, S2-3: available for all network)	Poor
C11	Facilities for Vulnerable Road Users	C11,1	Pedestrians crossing type	It was initially evaluated by using data provided by Data Mill North and Ordnance Survey MasterMap. It was then revised by visual inspection using aerial photography/satellite imagery or street view services.	Good

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Table C.1 (continued)

Ci	Framework components	Ci,j	Indicators	Source of data/ method of data collection	General assessment of collected data quality/representation
		C11,2	Pedestrian sidewalk	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, it was controlled from: https://www.leedstraffweb.co.uk/main.html	Good
		C11,3	Cycling infrastructure	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, it was controlled from: Google Maps Cycling and Open Street Map.	Good
		C11,4	Public transit access point design	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, public transit (bus) route was controlled from: Open Streep Map and https://www.geopunk.co.uk/timetables/town/leeds	Good
C12	Precautions for Roadworks and Incidents	C12,1	Precautions for roadworks and incidents	As this indicator requires a dynamic evaluation, it was assumed that there was no roadwork or incident on the network. Detailed information on live roadworks and incident are available at https://one.network/uk/leeds.	Poor
C13	Localisation Challenges	C13,1	Localisation challenges	It was evaluated by visual inspection using street view services. Also estimated roughly by using the data provided by the Ordnance Survey MasterMap, such as building heights and average road width.	Poor
		C13,2	Digital mapping of road environment	An assumption was made according to scenarios (S1: no HD maps, S2-3: available for all network)	Poor
C14	Communication Facilities	C14,1	Roadside Unit or	There is no publicly available data for this indicator. Therefore, it was assumed that there were no roadside units on the network.	Poor
		C14,1	Cellular network coverage	It was simply evaluated by using service provider coverage maps or third-party webpages (e.g. https://mastdata.com/index.aspx). Only one service provider (EE Mobile) with widely available network coverage data in the study area was selected for the assignment. Then for the validation of coverage map, experimental data source was analysed. For places where automated inspection data collected by specialised vehicles is available, parameters related to the signal quality of the LTE service provided by Ofcom were categorized according to thresholds suggested by (Cucor et al., 2022). The data is available at: (https://www.ofcom.org.uk/phones-telecoms-and-internet/coverage/mobile-signal-strength-measurement-data).	Fair
C15	Intersections and Roundabouts	C15,1	Intersection and roundabout type	It was evaluated by using the data provided by the Ordnance Survey MasterMap. In addition, it was evaluated by visual inspection using aerial photography/satellite imagery or street view services.	Good
		C15,2	Number of arms	It was evaluated by visual inspection using aerial photography/satellite imagery.	Good
		C15,3	Regularity of layout	It was evaluated by visual inspection using aerial photography/satellite imagery.	Good
		C15,4	Delineation (marking) conditions	It was roughly evaluated by visual inspection using street view services according to examples in Appendix C of the DMRB CS 126 standard.	Fair

APPENDIX D

Appendix D to Chapter 5

Table D.1 Distribution of road links based on categorised RRI values in different index structures.

Scenario	Assessment of road links (N=1,495)	Actual applied: Expert-weighted components (Wc_j)	Industry participants only weighted components (Wc_j)	Equal-weighted components (Wc_j)	Excluding penalties in RRI	Omitting a component from the Road Readiness Index: C1: Road Geometry Challenge	C2: Road Surface Condition	C3: Road Markings Condition	C4: Road Boundaries	C5: Traffic Signs Visibility	C6: Special Road Sections	C7: Road Lighting	C8: Speed Limit	C9: Number and Diversity of Road Users	C10: Roadside Complexity	C11: Facilities for Vulnerable Road Users	C12: Precautions for Roadworks and Incidents	C13: Localisation Challenging	C14: Communication Facilities
Scenario 1 (LC)	Extremely Challenging	74.7%	74.7%	74.7%	0.0%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%	74.7%
	Highly Challenging	0.0%	0.0%	0.0%	1.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Moderately Challenging	1.7%	1.7%	1.5%	48.0%	1.5%	2.3%	0.6%	1.1%	1.1%	4.7%	3.8%	4.3%	1.0%	1.3%	0.8%	5.1%	0.5%	1.1%
	Slightly Challenging	23.5%	23.6%	23.7%	50.6%	23.7%	23.0%	24.7%	24.1%	24.0%	20.6%	21.5%	20.9%	24.2%	23.9%	24.4%	20.2%	24.7%	24.2%
	Least Challenging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.0%	0.1%	0.0%
Scenario 2 (LC)	Extremely Challenging	37.8%	37.8%	37.8%	0.0%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%	37.8%
	Highly Challenging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Moderately Challenging	0.1%	0.1%	0.1%	7.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%	0.1%
	Slightly Challenging	51.4%	51.3%	51.2%	82.0%	52.6%	52.8%	45.1%	46.3%	54.8%	55.0%	54.5%	54.0%	43.7%	51.7%	42.4%	55.5%	51.6%	43.5%
	Least Challenging	10.7%	10.8%	10.8%	10.9%	9.4%	9.4%	17.1%	15.9%	7.3%	7.1%	7.6%	8.0%	18.4%	10.4%	19.7%	6.6%	10.4%	18.7%
Scenario 3 (LC)	Extremely Challenging	22.9%	22.9%	22.9%	0.0%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%	22.9%
	Highly Challenging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Moderately Challenging	0.0%	0.0%	0.0%	3.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	0.1%	0.0%	0.1%	0.0%	0.1%	0.0%	0.1%
	Slightly Challenging	54.6%	54.7%	54.3%	73.9%	58.0%	56.9%	34.2%	37.3%	61.1%	61.3%	61.4%	60.5%	41.5%	55.7%	38.4%	61.9%	56.2%	53.4%
	Least Challenging	22.5%	22.4%	22.8%	22.5%	19.1%	20.2%	42.9%	39.8%	16.0%	15.7%	15.7%	16.5%	35.6%	21.3%	38.7%	15.1%	20.9%	23.6%

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Table D.1 (continued)

Scenario	Assessment of road links (N=1,495)	Actual applied: Expert-weighted components (Wc_j)	Industry participants only weighted components (Wc_j)	Equal-weighted components (Wc_j)	Excluding penalties in RRI	Omitting a component from the Road Readiness Index													
						C1: Road Geometry Challenge	C2: Road Surface Condition	C3: Road Markings Condition	C4: Road Boundaries	C5: Traffic Signs Visibility	C6: Special Road Sections	C7: Road Lighting	C8: Speed Limit	C9: Number and Diversity of Road Users	C10: Roadside Complexity	C11: Facilities for Vulnerable Road Users	C12: Precautions for Roadworks and Incidents	C13: Localisation Challenging	C14: Communication Facilities
Scenario 1 (HC)	Extremely Challenging	73.8%	73.8%	73.8%	0.0%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%	73.8%
	Highly Challenging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Moderately Challenging	0.0%	0.0%	0.0%	10.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Slightly Challenging	22.0%	22.1%	21.1%	85.0%	20.3%	24.1%	18.5%	24.0%	16.9%	24.6%	24.5%	24.6%	20.6%	23.1%	19.9%	24.8%	15.7%	21.7%
	Least Challenging	4.1%	4.1%	5.0%	4.1%	5.8%	2.0%	7.6%	2.1%	9.2%	1.5%	1.6%	1.5%	5.6%	3.0%	6.3%	1.3%	10.5%	4.4%
Scenario 2 (HC)	Extremely Challenging	33.6%	33.6%	33.6%	0.0%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%	33.6%
	Highly Challenging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Moderately Challenging	0.0%	0.0%	0.0%	0.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Slightly Challenging	17.1%	17.7%	17.1%	44.0%	21.3%	17.0%	4.8%	7.6%	23.5%	23.7%	23.1%	23.7%	12.2%	20.5%	9.8%	24.4%	22.9%	12.2%
	Least Challenging	49.3%	48.7%	49.2%	55.3%	45.0%	49.4%	61.5%	58.7%	42.9%	42.7%	43.2%	42.6%	54.1%	45.8%	56.5%	41.9%	43.4%	54.2%
Scenario 3 (HC)	Extremely Challenging	18.2%	18.2%	18.2%	0.0%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%	18.2%
	Highly Challenging	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Moderately Challenging	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Slightly Challenging	8.9%	9.1%	9.7%	26.6%	13.6%	6.6%	2.5%	3.7%	15.1%	15.1%	13.0%	15.1%	7.0%	10.0%	4.8%	15.9%	13.5%	13.8%
	Least Challenging	72.9%	72.7%	72.1%	73.4%	68.2%	75.3%	79.3%	78.1%	66.8%	66.8%	68.8%	66.7%	74.8%	71.8%	77.0%	65.9%	68.3%	68.0%
		100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

SUPPLEMENTARY FILE 1

Supplementary files to Chapter 5

Supplementary materials 1.1 (SM-1.1)

This section provides the details of the road readiness index, including its components, subcomponents, and scoring systems. It also explains the rationale behind their selection and impact on the capabilities of automated vehicles.

1. Road geometry challenge

Road safety is highly linked to the geometric design and infrastructure features of the road, as they affect the human driving ability to operate a vehicle safely and effectively on the road (Papadimitriou et al., 2019). Similarly, road geometry affects the capabilities of AVs (Boggs et al., 2020) since having an impact on automated driving systems performance in terms of many aspects, such as the ability to detection of lane markings (Tao, 2016; Marr et al., 2020), precise localisation of vehicles on roads (Reid et al., 2019), and path planning control (Pendleton et al., 2017; Xu and Peng, 2020; Eskandarian et al., 2021). Mainly, sharp horizontal and crest vertical curves pose challenging situations for AVs as the field of view range of the camera-based (García et al., 2021) and LiDAR-based sensors are limited (S. Wang et al., 2022). This is because road curvatures not only affect the stability of vehicles but also affect the sight distance that AVs require to detect the objects and events surrounding the driving environment and react appropriately to them for safe driving. In addition to road alignment, studies reveal that cross-sectional dimensions of roads such as lane width have a considerable impact on the performance of AVs (García and Camacho-Torregrosa, 2020). Today's current ADS technologies may already be capable of overcoming the challenges posed by road geometry, but most AV manufacturers have yet to share or verify such data. Therefore, solutions which could involve additional countermeasures for AVs have still to be proposed and implemented. In this context, four equally weighted subcomponents are proposed to represent road section geometry challenges for AV operation. These are horizontal curvature, gradient level of a road segment, road or lane width consistency and presence of digital map of road geometry (see **Table S1.1**).

Table S1.1 Scoring scheme for road geometry challenge component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C1,1	Horizontal curvature	0.25	Straight or gently curving (Radius of curvature: R ≥ 400m)	1	1
			Moderate curvature (150 ≤ R<400m)	0.5	0.75
			Sharp curvature or corners (R<150m)	0	0.25
C1,2	Longitudinal gradient	0.25	Flat or gentle rise (0% to <4%)	1	1
			Moderate rise (4% to <8%)	0.75	1
			Steep rise (≥ 8%)	0.25	0.5
C1,3	Road width consistency	0.25	Constant or slight change in road/lane width (road width change rate less than 15%)	1	1
			Presence of moderate change (narrowing and widening) in road/lane width (road width change rate is 15 to 30%)	0.5	0.75
			Presence of high change (narrowing and widening) in road/lane width (road width change rate higher than 30%)	0	0.25
C1,4	Digital mapping of road geometry	0.25	Presence of digital map of road geometry	1	1
			No presence of digital map of road geometry	0	0

It is difficult to propose uniform objective thresholds for horizontal curvature since the degree of danger at a bend varies mainly with four factors: the speed of a vehicle, the radius of curvature, the superelevation, and the skid resistance of the road surface. For this reason, horizontal curvature was categorised based on the radius of curvature that can pose a risk for vehicles (Wang et al., 2020) and the highest score was assigned to straight or gently curve road sections. Moreover, the radius of curvature might reduce forward visibility; thus AVs need to slow down to perform their driving tasks. The minimum forward visibility required is equal to the minimum stopping sight distance, which is based on the design speed at the location being considered, deceleration rate of vehicle, and longitudinal gradient level of roads. According to the UK Design Manual for Roads and Bridges (DMRB) standard CD109, maximum longitudinal gradient level is 4% for motorways and 8% for all-purpose carriageways. In hilly areas, steeper gradients frequently are required, but a gradient of 8% is assumed as a practical maximum unless there are local difficulties. Therefore thresholds for longitudinal gradient subcomponents have been determined based on the current standard recommendations. Road width consistency is another important criterion because rapid changes in lane width on road segments can pose difficulties for AVs to navigate, particularly if there are large trucks or other vehicles nearby. Therefore road sections where sudden changes in lane width such as merging, narrowing, or widening are assigned the lowest score.

On the other hand, some studies proposed an automated speed concept, as the maximum speed that AVs can be achieved at a specific road section such as horizontal curves (García et al., 2020) and gradient conditions (Zhang et al., 2012; Gouda et al., 2021). This can be possible by a High-Definition (HD) map, which is a digital representation of the road environment. HD maps can have detailed road geometry information of the road ahead, allowing AVs to control braking and speed. Also, HD maps can help AVs develop some proactive speed control strategies at locations where visibility is limited (Easa et al., 2021). Therefore, the availability of HD maps is considered a critical subcomponent in the index to represent the redundancy of automated driving systems.

Vertical curvatures, such as sag or crest curvatures, also impact the operational speed of AVs and their perception ranges. However, evaluating vertical curvature is not straightforward and requires detailed information from road links. Additionally, vertical curvature is not commonly observed in urban streets, especially when road links are not lengthy. Therefore, in this index, vertical curvature was not included as a subcomponent.

2. Road surface condition

The condition of the road surface is crucial for road user safety, as it directly affects the stability and operation of vehicles. Research shows that poor road surface conditions increase the severity of road crashes (Lee et al., 2015). Similarly, road surface condition is expected to be an important factor for automated driving (Boudette, 2016). Potholes, cracks, ruts, and a wide variety of other imperfections on the road surface can affect AVs' ability to navigate safely, as they can change the way the vehicle responds to control inputs or cause the vehicle to change direction unexpectedly (Lee et al., 2021). While limited research has been done to date, studies noted that poor road conditions (including improper lane marking) were one of the main causes of disengagements of ADS during testing in the USA (Dixit et al., 2016; Lv et al., 2018). In addition, deterioration of the pavement in a traffic lane carrying vehicles in a platoon, where vehicles follow each other very closely, could be extremely dangerous for maintaining control of the vehicles, particularly at high speed (Johnson, 2017). Human drivers may react to sudden manoeuvres to avoid potholes, resulting in unpredictable driving situations for AVs. Potholes can also cause problems for AV sensors as water accumulates on the surface in rainy weather. Another challenging point stated in the literature for ADS is the presence of different colours or materials on the road surface such as gullies, manholes and metal grids. This is because different colour values on the road surface, for example by patching or in a combination of asphalt and concrete road condition pose problems for the perception systems of AVs (Lawson, 2018; Soteropoulos et al., 2020). Similarly, unpaved road surfaces such as gravel present challenging situations for the perception systems of AVs (Thorn et al., 2018), although some AVs are capable to operate in off-road areas (Van Brummelen et al., 2018).

A proper road surface quality largely depends on consistent monitoring and maintenance of conditions, but it is challenging for large cities with lots of city properties to consider (Chacra and Zelek, 2018). In recent years, automated road assessment technologies have evolved that can provide high-accuracy data without disrupting traffic (Osichenko and Spielhofer, 2018; Urano et al., 2019; Wright, 2020). For example, TRACS (TRAffic-speed Condition Surveys) survey vehicles are commonly used by Highways Agency in the UK to assess the road surface condition of motorways and major roads, known as the strategic road network (Department for Transport, 2021). On the other hand, local authorises have adopted a different type of survey vehicle which is the SCANNER (Surface Condition Assessment for the National Network of Roads). With this technology, each 10m length of the road section is assigned a condition category based on the Road Condition Indicator (RCI)[45]. RCI value is measured using many critical parameters such as ruth depth, longitudinal profile, texture, and cracking of road surface. The DMRB CS228 and CS230 standards define the detail of surface conditions measured by these surveys. Although motorways and trunk roads are periodically inspected with specialised vehicles, roads maintained by local authorities are relatively less inspected due to the lack of budget and personnel (Urano et al., 2019), thus surface conditions data for local roads is often not available.

Table S1.2 Scoring scheme for road surface component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C2,1	Road surface type	0.5	Asphalt or concrete and has a homogeneous appearance	1	1
			Pavers, bricks, or presence of different colours or materials on the road surface (e.g. patching, ghost markings, presence of lots of manholes etc.)	0.5	0.75
			Unpaved road surface (e.g. gravel)	0	0.25
C2,2	Road surface condition	0.5	No presence or low level of deterioration (e.g. potholes, cracks, rutting etc.) or RCI is Green	1	1
			Presence of moderate level of deterioration or RCI is Amber	0.5	0.75
			Presence of severe level of deterioration or RCI is Red	0	0

Table S1.2 illustrates the subcomponents representing the road surface component and their measurement variables. We considered the type and condition of road surfaces for evaluation of the compatibility of road segments for AV operation. These two factors have equal weight in the index component and are classified according to the level of challenge for the perception and control systems of AVs. We argue that the more homogeneous the appearance of the road surface, the less problems it will cause

[45] The categories of road condition are as follows: ***Green*** (Good condition - no further investigation or work is likely needed at this time); ***Amber*** (Likely to be some deterioration - work may be needed sometime in the future); ***Red*** (Likely to be in poor condition - further investigation may be required to determine whether this section of road should be considered for maintenance).

for AVs. Therefore, the highest score is assigned to road surfaces that are less confusing for the MV system. Similarly, a less degraded road surface is less challenging for road users and scores highest for this subcomponent. Two alternative scoring schemes have been proposed for the road surface condition based on the availability of automated surface conditioning survey data.

3. Road marking condition

AVs use different types of onboard sensors, cameras and artificial intelligence that detect and identify markings on the roads to perform driving tasks and navigation (Kuutti et al., 2018; I. Meneguette et al., 2018; Easa et al., 2021). Most studies suggest that ideal road marking should be readable by the machine-vision (MV) systems of AVs (Nitsche et al., 2014; Huggins et al., 2017; Transport Systems Catapult, 2017; Lawson, 2018). This is because improper delineation of road markings poses challenges for AV algorithms to predict where the vehicle is on the road. In recent years, trials of AV have been disengaged multiple times due to the faded or non-existent road markings (Favarò et al., 2018). Therefore, various studies have been conducted in order to develop algorithms that allow for real-time recognition of lane boundaries and vehicle guiding (Van Brummelen et al., 2018; Xing et al., 2018; Eskandarian et al., 2021). Most of these studies have tried to solve this problem by developing hardware and software, namely image recorders and detection algorithms. On the other hand, the physical conditions and configuration of road marking play an important role in the performance of ADS (García et al., 2021). For this reason, there is an increasing interest in identifying the design characteristics of road markings, which may affect the ability of MV systems such as dimension, colour, retroreflectivity (Ambrosius, 2018). However, determining the optimum road marking requirements precisely for AVs is challenging as it depends on many variables such as operating speed, road surface condition, lane width etc. So far, limited experimental studies have highlighted these factors and outlined the desired conditions and configurations of road markings for AVs to function properly (Marr et al., 2020; Konstantinopoulou et al., 2020). As sensor technology and software capabilities evolve, the minimum requirements for road marking conditions for AVs will likely change as well.

In addition, road markings are not always clear in natural environments, numerous dynamic factors such as shadows from trees, wet surfaces, dirt, rain or fog affect their clarity (Ye et al., 2018; Waykole et al., 2021). Moreover, non-standard road markings represent a major problem, confusing AVs and are also cited as a major problem facing human drivers (EuroRAP and Euro NCAP, 2013; Johnson, 2017; PIARC, 2021). Therefore, to deal with non-standard, damaged or poor-quality markings, AVs may need supplementary information via digital maps that provide a better location estimate (Van Brummelen et al., 2018; Marr et al., 2020). Some argue that digital maps will likely not be available or not be the desired level for many cities in the early stage of implementation (Tengilimoglu et al., 2023). Therefore, road markings still are an important factor and ADS technologies will likely continue to rely on them as a primary or secondary input.

However, there is presently no formal standard or benchmark to be used to assess the compatibility of road markings that support AV functions (Nayak et al., 2020). For this reason, current specification requirements for road marking were adopted to evaluate this component as AVs need distinguishable and readable road marking features. The UK Traffic Signs Manual gives guidance for authorities on the use of road markings and describes how the road marking configuration should be (Department for Transport, 2019). Additionally, the DMRB CS126 standard defines how to assess road markings and road studs and evaluates the road marking conditions based on five factors: wear, retroreflectivity in dry and wet conditions, colour, luminance factor or luminance co-efficient, and skid resistance.

Studies have emphasised that a minimum of 150 mm width is desirable for machine-vision (MV) systems (EuroRAP and Euro NCAP, 2013; ERF, 2013; Konstantinopoulou et al., 2020). Regarding the colour of road markings, few studies indicated that MV shows better recognition performance for white markings than yellow (Mihalj et al., 2022). However, a recent experimental study revealed that a 100 mm line width, which is the minimum requirement for most of UK roads (Department for Transport, 2019), can also be readable by MV systems and colour has a very limited impact on these systems (Marr et al., 2020). Another point emphasised in literature is that the optimal contrast ratio between markings and road surface need to be 3-to-1 during daytime (Mihalj et al., 2022). However, road marking visibility reduces significantly with rain conditions as the contrast ratio between the markings and road surface is reduced in wet conditions (Hadi and Sinha, 2011; Pike et al., 2019). In Europe, it is recommended that retroreflectivity of road marking should have a minimum performance level of 150 mcd/lux/m² in dry conditions, while it should be 35 mcd/lux/m² for wet conditions to be clearly detected by MV systems (EuroRAP and Euro NCAP, 2013; ERF, 2013). On the other hand, the CS126 standard evaluates the minimum requirement by considering lit and unlit areas. In illuminated areas, the design requirement is reduced to 100 mcd/lux/m² due to more favourable ambient lighting providing better visibility. In addition, road studs, which are small reflective elements used on the road to help increase the visibility of the lane boundary in poorly lit areas or in bad weather conditions, have potential to help MV systems (Siddiqi and Alrashdi, 2022).

Aside from the longitudinal road markings, warning markings, such as directional arrow markings, give way and stop lines also need to satisfy the minimum requirements of MV system. However, quality assessment of road markings, especially measuring marking visibility at the network level is challenging for road and city authorities. Recently, new technologies have emerged that can be combined with existing road evaluation equipment. For example, Highways England successfully launched annual network-wide surveys of road marking conditions in 2018 (Wright, 2020). However, this technology is not yet widely implemented by local road and city authorities and data is not publicly available.

Table S1.3 Scoring scheme for road markings condition component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C3,1	Digital mapping of road markings	0.25	Presence of digital map of road markings	1	1
			No presence of digital map of road markings	0	0
C3,2	Road marking configuration	0.25	Presence of both the centre lines and two edge markings	1	1
			Presence of centre lines and one-side edge markings	0.75	1
			Presence of only centre lines or two-sides edge markings	0.5	0.75
			Presence of only one-side edge markings	0.25	0.5
			No presence of road markings	0	0
C3,3	Road marking wear condition	0.50	Wear score is 50 (no obvious wear) to 40 (very little wear) according to CS126 standard	1	1
			Wear score is 30 (some visible wear, larger bare sports) to 20 (visible but has randomly spaced small bare spots)	0.5	0.75
			Wear score is 10 (barely visible) to 0 (non-existent, residue only)	0	0

In addition to existing road marking practices, in recent years, new road marking solutions have been proposed to support the positioning functions of AVs. Magnetic markings are one of these promising technologies that have the potential to improve the safety and efficiency of AVs on the road. Magnetic markings refer to a type of technology that uses magnets embedded in the road surface to provide guidance and navigation information to AVs (Sobanjo, 2019; PIARC, 2021; Gopalakrishna et al., 2021; Bezai et al., 2021; Mihalj et al., 2022). These markings can be used to define lanes, indicate turns, and provide other types of information that can help AVs navigate safely and efficiently. Another solution for guiding and keeping AVs in their lane is smart road markings. Smart road markings are a type of technology that uses intelligent sensors and other technologies to provide real-time information to drivers and other road users. Smart road markings can be implemented in a variety of ways (Browne, 2020; Gkemou et al., 2020). However, this subcomponent is considered in communication facilities components of the framework. Therefore, a scoring scheme is proposed for the assigning of road markings based on the current efforts in road marking alternatives for supporting automated driving (see **Table S1.3**). The main argument for the scheme is the availability of road markings in digital form and whether they are in good physical condition for the redundancy of perception systems. That is if road marking is worn, or its configuration is missing this would be challenging for AVs to detect and navigate properly. Meanwhile, if magnetic road markings are available on the road, this component score will be assigned as 1 for the road segment, without consideration of any other criteria.

4. Road boundaries

In addition to road markings that define the boundaries of the roads or lanes, continuous and detectable road edge condition is another key aspect of road infrastructure that contributes to the safe operation of AVs (Suleymanov et al., 2021). The road edges need to be easily noticeable by the AV's sensors to enable the vehicle to accurately determine its position and orientation on the road. A continuous and detectable road edge such as sidewalks, safety barriers or kerbs helps AVs make decisions and avoid obstacles and provides a reference for navigation and mapping. In rural areas, road edges are mainly used to form an edge restraint and drainage feature, but there are many rural roads and streets where there is no kerb and separate footway. For these areas, clear and well-defined boundaries between the road and its surroundings can be provided by creating surfaces with contrasting tones such as grass. In addition, property access points, where vehicles can enter or exit the roadway other than public roads, lead to discontinuity on the edge of roadways. This may include entries to large vehicle parks and rest areas. The presence of access points on the road requires additional attention for AVs to detect and identify potential objects from these points. Apart from this, on-street parking is a major impediment to the AV's ability to detect and interpret the road surface edge or lane boundaries. On-street parking can also cause a huge restriction on traffic flow that may leave insufficient space for two-way traffic in many places. In this case, drivers can decide among themselves who goes first, and this can often be communicated by a hand gesture or a flash of the headlights (Transport Systems Catapult, 2017). However, this might cause a significant challenge for AVs to navigate and localise on these roads.

Considering these issues, three different criteria with different weight were considered in the road boundaries component scoring scheme (see **Table S1.4**). In the first subcomponent, median types are categorised according to the condition that perception systems of AVs may struggle to detect the boundaries of the median side of the roadway. For example, some studies underline that cable or tall posts constructed median pose a challenging for camera systems of AVs (Konstantinopoulou and Ljubotina, 2020; P. Wang et al., 2022). Therefore, these physical medians are assigned a relatively low score. In the second subcomponent, the kerb side of the roadway is evaluated on the basis of continuity that mentioned above. Lastly, on-street parking condition is taken into consideration as a third subcomponent in the component. For this component, the reason the median type is given a higher weight than other subcomponents is that the median side can serve as a more efficient reference for AVs. For instance, when there is vehicle parking and discontinuous road edge, centrelines can assist AVs in localisation.

Table S1.4 Scoring scheme for road boundaries component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C4,1	Median type	0.5	One-way road, or two-way road with concrete/metal safety barrier, kerb stone or grass median	1	1
			Wide or double centre line or central hatching (two-way road)	0.75	1
			Centre line (two-way road)	0.5	0.75
			Cable barrier or flexible posts (two-way road)	0.25	0.5
			No presence of median (two-way road)	0	0.25
C4,2	Road edge condition	0.25	Continuous road edge (e.g. kerb stone, barriers, grass etc.) on both sides of roadway	1	1
			Discontinuous or damaged road edge (e.g. access points) on one-side of roadway	0.5	0.75
			Discontinuous or damaged road edge (e.g. access points) on both sides of roadway	0	0.25
C4,3	On-street vehicle parking	0.25	Parking or limited time waiting is not permitted	1	1
			Presence of parking or limited time waiting zone on one side of roadway	0.50	0.75
			Presence of parking or limited time waiting zone on two sides of roadway	0	0.25

5. Traffic signs visibility

Similar to road markings, traffic signs are one of the most crucial parts of road infrastructure, as they provide information about the direction and trajectories to be followed, the rules to be followed for safety and possible hazards ahead. AVs need to detect, read and understand traffic signs in order to operate safely. Existing traffic signs and signal recognition technology adopted in the vehicle industry works through onboard vision sensors and machine learning algorithms that detect and interpret the traffic sign's colour, shape, message etc. (Bruno et al., 2018). However, this technology has not yet reached the desired level of robustness (Nowakowski et al., 2016; Eskandarian et al., 2021). The concerns about false reading and real-time in-motion reading need to be addressed before their mass-scale implementations on road networks (Shladover and Bishop, 2015; Koopman, 2019). For this reason, the automation industry and scientific committees show great effort to develop more robust and reliable traffic signs and signal recognition systems (Chen and Huang, 2016; Jensen et al., 2016). However, this also depends on traffic signs and signals being visible and readable by MV technology (Lyon et al., 2017).

Several experimental studies have been carried out to understand what kinds of signs are suitable for AV applications and which criteria affect MV systems (Roper et al., 2018; Konstantinopoulou et al., 2020). Studies have indicated that there are numerous factors that can affect the traffic sign recognition system performance such as the position and orientation of traffic signs, variable lighting conditions, roadside obstruction etc. Also some research revealed that electronic dynamic signs such as variable message signs present hurdle for MV because they are using technologies and control systems designed for the human eye (Roper et al., 2018; PIARC, 2021).

Another frequently cited challenge for proper functioning of ADS is that differences in the characteristics of traffic signs, such as font size, colour, language, position, or style of delineation, from jurisdiction to jurisdiction (EuroRAP and Euro NCAP, 2013; Huggins et al., 2017). While some standards for traffic sign harmonisation, such as the US Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways and the Vienna Convention on Road Signs and Signals, it is common to have regional differences in traffic signs within countries and sub-jurisdictions (PIARC, 2021). Therefore, studies point out the necessity of harmonising on traffic signs but achieving this across the entire road network would be a long and costly process.

In recent years, there has been a growing interest in digital mapping, which provides additional information that can assist vehicles in safe navigation plans (Ulrich et al., 2020; Waymo, 2021). The information included in maps can cover many road features such as road alignments, lanes, road markings, traffic signs or traffic conditions (ERTRAC, 2019). In addition to the digital maps, most of the safety-critical information for AV operation can be provided via roadside devices or network connectivity (e.g. I2V, C-V2X). These additional data sources play a potentially important role in situations where an AV is unable to obtain a complete picture of its surroundings through its onboard sensors. More importantly, it allows the ADS system to work under different environmental conditions. As mentioned earlier, some researchers believe that all road networks will not be covered in the geographical database in the early stages due to the costs of the mapping and communication technologies (Mocanu et al., 2015). Similar to road markings, traffic signs will still play a prominent role in informing the decisions an AV needs to make in the case of a connection problem (Transport Systems Catapult, 2017). Moreover, there are additional benefits in redundancy from having both harmonisation and digitisation of traffic signs (PIARC, 2021)

The maintenance and inspection of each traffic sign installation is necessary to identify defects which can affect the safety or operational performance. This is also very important for their readability by on-board sensors of AVs. The UK Traffic Sing Manual and Manual for Streets (MfS) describe how the traffic signs configuration should be for the safe operation of road users. In addition, DMRB standards define how to inspect (CS125) and maintain (CM125) traffic signs. However, inspection frequency and the budget of authorities for the maintenance of traffic signs need to be addressed for this emerging technology. Similar to most of the components, there is presently no formal standard or benchmark to be used by authorities to assess the suitability of their traffic signs to support AV functions (Nayak et al., 2020). Therefore, it is assumed that traffic signs for AVs should fulfil existing standard requirements that require clearly visible and readable features. In this context, a scoring scheme is proposed for this component based on criteria that affect the perception capabilities of AVs (see **Table S1.5**).

Table S1.5 Scoring scheme for traffic signs component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C5,1	Digital mapping of traffic signs	0.5	Presence of digital map of traffic signs	1	1
			No presence of digital map of traffic signs	0	0
C5,2	Traffic signs conditions	0.5	Presence of visible and readable physical traffic signs (e.g. not obstructed, damaged, vandalised etc.) or absence of traffic signs on the roadway	1	1
			Presence of multiple signs in a single unit	0.5	0.75
			Presence of electronic signs such as variable message signs	0.25	0.5
			Unreadable, damaged, or obstructed traffic signs (critical defects according to CS125)	0	0

Clear and legible traffic signs and their digital representation are desirable for the safe operation of MV systems and redundancy. Therefore, these two subcomponents have equal weight in the index. The digital alternative to traffic signs with mapping technology provided by the automation industry, third-party service providers or government agencies is assigned to half of the whole component score. For the redundancy, the traffic signs condition, on the other hand, was categorised based on the functional requirements of MV systems. The highest score is given to signs that are in good condition and visible to road users and that meet the requirements of the standards and guidance. However, when lighting or weather conditions are bad, AVs may still have difficulties detecting and reading these signs. The relatively low score is given to multiple signs in a single unit as they represent a challenging situation for AVs to interpret relevant information. Dynamic electronic signs, which are often challenging for AVs, are scored one step lower. Lastly, the lowest score is given any critical defect identified according to CS 125 standard (e.g. significant obstruction of traffic signs by vegetation when viewed from minimum clear visibility distance, faded or damaged traffic signs).

6. Special road sections

Current literature points out that some special road sections such as slip roads (e.g. diverging or merging sections), tunnels, toll plazas or grade-separated interchanges are relatively complex road sections for automated driving, compared to ordinary straight-line road segments. Studies highlight that these critical road sections may require special attention at the initial stages of AVs implementation as requirements might be different than human-driven vehicles (Lu, 2018; Amelink et al., 2020). For example, some studies suggest that the length and width of slip roads need to be reconsidered for new driving scenarios such as vehicle platooning and high operating speed (Huggins et al., 2017; Farah et al., 2018). Therefore, a scoring scheme has been proposed for the special road sections based on their potentially challenging level for automated driving (see **Table S1.6**).

Table S1.6 Scoring scheme for special road sections component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C6,1	Special road sections	1.0	Not presence of any special road sections stated below	1	1
			Presence of grade-separated interchanges or presence of slip roads/ramps (e.g. merging or diverging sections)	0.75	1
			Presence of weaving areas (merging and diverging sections)	0.5	0.75
			Presence of toll plazas or gates on the roadway (e.g. chicane or road narrowing)	0.25	0.50
			Presence of dead-end roadway (with/out turning point)	0	0

The highest score is given to road segments that do not contain special road segments. A relatively lower score is assigned to grade-separated interchanges or bridges as they present relatively challenging road environments that AVs need to detect and react to properly. One step lower score is given to slip roads that require more attention and present a significant problem for AVs. This is because AVs in general have difficulty with merging that need to negotiate with other road users and the local perception given by their sensors is sometimes limited by a very short distance or by obstacles (Paulsen, 2018). By comparison, weaving sections, where vehicles frequently change lanes to enter or exit an adjacent lane, are more complex driving environment because AVs must coordinate the use of the common area with other road users. In general, weaving areas are considered a source of congestion, bottlenecks, and safety concerns, as vehicles changing lanes can cause disruptions in traffic flow and increase the risk of accidents. Similarly, toll plazas are quite heterogeneous in their planning and appearance making it possibly difficult for AVs to navigate safely. To address the problems likely facing AVs at these locations, many studies suggest cooperative driving strategies via communication supports such as V2I or V2V (Rios-Torres and Malikopoulos, 2017; PIARC, 2021). However, communication facilities alone might not be seen as a solution for AVs at low market penetration levels. ADS technologies need to prove their capabilities to operate safely in these sections. Therefore, these locations still present challenging and complex driving environments for AVs.

Lastly, the lowest score is given to dead-end streets, as AVs run into problems in these sections and sometimes even require human driver intervention. Dead-end streets can present challenges for AVs due to the lack of a clear path forward beyond the end of the street. Since AVs rely on detailed mapping and navigation systems to determine their route, they may struggle to identify the end of the road and the need to turn around or backtrack. Additionally, dead-end streets may not be a high priority for mapping and navigation systems, and therefore may not be accurately represented in the AV's data. As a result, AVs may require specialised programming and sensors to navigate and manoeuvre safely on dead-end road links. Some AVs may simply avoid dead-end streets altogether, choosing instead to reroute to a nearby road that provides a clear path forward. Apart from these, tunnels are another challenging road segments for AVs, as they often have different lighting conditions and visibility than normal roads. AVs need to be able to adjust their sensors and systems to account for these changes. However, tunnels and underpasses are considered in the lighting conditions and localisation challenge components of the index.

7. Road lighting

Lighting is highly correlated with the visibility conditions of the road environment and is one of the important factors that affect the safe operation of AVs. For example, poor visibility due to inadequate illuminations or glare is a challenging situation for current ADS and has been identified as having a negative impact on machine-vision-enabled, lane-guidance functions. Some OEMs have indicated that this will not be a serious issue for AV operations as vehicle headlights provide adequate illumination in the range at which vehicle systems attempt to detect objects and read road markings and traffic signs. However, the necessity of adequate illumination and density of streetlights to support AV visibility is mentioned by many experts and stakeholders (Marr et al., 2020; Gopalakrishna et al., 2021). In addition, it is expected that more frequent inspection and maintenance of road lighting equipment will be required for the initial stages of the automated driving deployments.

However, there is no solid evidence in the literature yet to assess the road lighting situation to support automated driving functions. For this reason, the scoring scheme for assigning lighting conditions of road sections for AVs considered the availability of lighting systems and whether occlusions that can affect the clear illumination of road segment (see **Table S1.7**). In addition, underpasses and tunnels were also considered challenging situations for MV systems due to the lighting conditions.

Table S1.7 Scoring scheme for road lighting component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C7,1	Lighting condition	1.0	Presence of road lighting systems and no obstacles around (e.g. trees in the surrounding)	1	1
			Presence of road lighting systems with obstruction around or short underpasses (L < 20m) on the roadway	0.5	0.75
			Presence of long underpasses (L > 20m) or tunnels	0.25	0.50
			No presence of road lighting systems or damaged lighting system	0	0.25

8. Speed limit

Speed limits are one of the most critical safety factors for road users, as it is highly correlated with traffic accident risk and the severity of injuries in accidents. Studies show that the number of accidents resulting in fatalities increases exponentially as vehicle speed increases (Elvik et al., 2019). There is a potential for to AVs dynamically adapt their operational speed based on the legal speed limit or external factors such as road geometric challenges, congestion, and weather. However, considering the operating aspect of AVs, current ADS technologies are not yet ready to safely perform all driving tasks at high speeds (Schwall et al., 2020). While AV sensors have a better angle of view than people, and a human cannot match a computer's response, humans are often considerably better at reading traffic and detecting potentially dangerous situations. High-speed traffic makes it difficult for computers to understand and predict situations occurring in the driving environment (Pendleton et al., 2017). At higher operating speeds, AVs need to perceive and react more quickly – e.g. detection of the environment by the sensors, the processing of the sensor data by the software, the achievement of a control decision etc. (Campbell et al., 2010). Higher speeds and therefore less response time increase the complexity of ADSs as they require much faster computation time and higher computational resources (Soteropoulos et al., 2020).

In general, AVs are required to obey posted speed limits and traffic laws, just like human-driven vehicles (HDVs). The current AV industry focuses on developing automated driving technology for different use cases with different operating speeds. Also, the speed limit for operation of AVs can vary depending on the location and the specific regulations in place. As of 2022, for example, driverless ride-hailing company Waymo can legally operate their vehicles on roadways with speed limits up to 45 mph in the East Valley region of the Phoenix, Arizona metropolitan area (Schwall et al., 2020). On the other hand, another robo-taxi company Cruise can operate their AVs at a maximum speed of 30 mph legally in San Francisco without safety driver control.[46] However, conventional vehicles travel much faster than these limits and this may lead to conflict between AVs and human drivers during the transitional period. As mentioned earlier, an analysis of traffic accidents involving AVs showed that rear-end crashes were generally caused by driver errors in conventional vehicles, such as unsafe speed or following too closely (Petrovic et al., 2020).

There is no solid evidence in the literature yet to determine the threshold values for speeds at which AVs can operate safely on public roads. Therefore, scoring for the speed limit of road segments has been determined based on the maximum operating

[46] More information about the legal operation speed limit can be found in: https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/autonomous-vehicle-deployment-program/

speed that AV can stop within the perception (object detection) range. AVs try to anticipate the traffic situation and the behaviour of the surrounding road users 2 to 3 seconds in advance and stop the vehicle when necessary (Yu et al., 2021). At current permissible speed limits, it is quite easy to stop a vehicle on a dry road surface in seconds without compromising too much passenger comfort when braking. At higher speeds, some researchers argue that onboard sensors may not suffice for safe operation on slippery roads since braking distance increases significantly, and reliable scanning becomes difficult. From a safety point of view, the stopping sight distance (SSD) should be less than the on-board sensor range and harder braking should also be avoided as it can pose a safety risk to the occupants. In other wors, it is necessary to ensure that the effective sensor range is greater than the required sight distance (Easa et al., 2021). In theory, since the response time of AVs will be less than the driver's perception and reaction time it is expected that the required sight distance for AVs would be shorter than that for HDVs. Sight distance parameters can be based on various models, such as stopping sight distance, overtaking distance or gap acceptance. UK design practices generally focus on SSD, which is the distance a driver needs to be able to see ahead to safely stop a vehicle travelling at design speed without collision with any other obstruction and should be provided continuously along each road. According to the DMRB CD 109 and MfS-2, the basic formula for calculating SSD (in meters) is:

$$\mathrm{SSD} = \mathrm{Vt} + \frac{\mathrm{V}^2}{2(\mathrm{d} + 0.1\mathrm{a})} \tag{1}$$

where, v is the speed of vehicle (m/s), t is the perception and reaction time of driver (seconds), d is the deceleration rate (m/s), a is the longitudinal grade of the road (%).

The standards recommend the perception reaction time (PRT) and deceleration rate as 2 second and 0.250g m/s to evaluate SSD for above the 60 kph design speed. We assume that the value of an LC AV's PRT is 0.8 seconds based on the findings of Dixit et al (2016), although studies commonly assumed 0.5 seconds – we assumed this is valid for HC AVs (Khoury et al., 2019; Othman, 2021). Regarding the longitudinal grade of the road, DMRB CD 109 indicate that the gradient level for motorways and all-purpose carriageways should not exceed 4% and 8%, respectively. For the sake of safety, the gradient level of roads is assumed as a 4% downgrade. On the other hand, the braking distance depends on the mechanical characteristics of the vehicle, so it is assumed that the mechanical performance of the HDVs and AVs will be identical. Besides, the maximum range of sensors varies by type and model of vehicle. For example, the range of Lidar and cameras that are commonly used sensors in AVs is in general up to 250-300 m (Wevolver, 2020; Vargas et al., 2021). The study assumed that the reliable view range of sensors in the early model of LC and HC AVs are 200 m and 300m, respectively; this is a reasonable assumption considering that the number of points detected or resolution decreases with increasing distance. Moreover, studies underline that the performance on-board sensors affected by adverse weather condition such as fog and rain, reducing the density point tracking (Neumeister and Pape, 2019; Zang et al., 2019; Vargas et al., 2021). Therefore, it is assumed that the effective sensor range of AVs can drop to 100 m for LC AVs and 150 m for HC AVs, during adverse weather conditions. Also side perception range of AVs is usually shorter than the front or rear range. For this reason, side view ranges are assumed 100 m and 150 m for AVs, respectively.

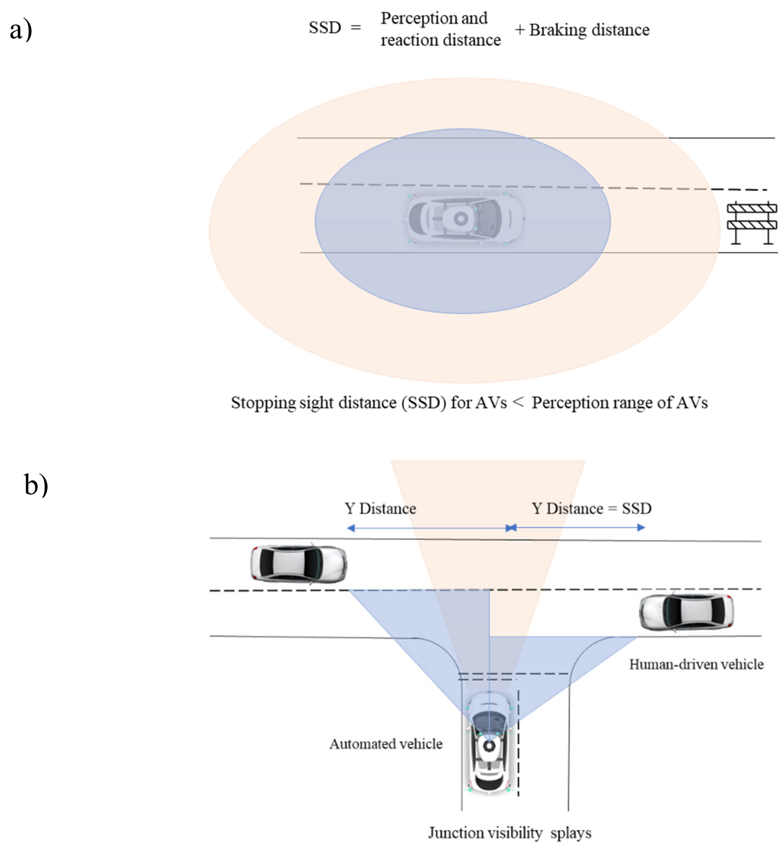

Figure S1.1 Required stopping sight distance for AVs (a), sight distance at priority-controlled intersection (b).

Given the assumptions, scoring for road speed limit were estimated according to the potential driving scenarios displayed in **Figure S1.1**. For the first scenario, the maximum operating speed limit at which an LC AV can stop within the 200 m perception range is calculated as 61-mph. This means that LC AVs may not stop safely on road sections that have higher than a 61-mph speed limit, so given the lowest score in the scoring scheme. On the other hand, this limit is calculated as 42 mph for 100 m, representing the adverse weather conditions range. Therefore, a relatively higher score is given to road sections between these two-speed limits. In addition, intersection sight distance is a critical parameter that needs to be considered in urban roads (Magyari et al., 2021). Therefore, in the second scenario, HDVs need to travel on the main road at a certain speed so that they can stop within the side view range of AVs. In other words, the stopping distance of HDVs should not exceed the sight distance of LC AVs to prevent any conflict in the mixed traffic situation. Therefore, the maximum speed limit for the road section is calculated as 37 mph. The highest score is given to road sections that have less than this speed limit. The same procedure was applied for HC AVs and the results are shown in **Table S1.8**.

Table S1.8 Scoring scheme for speed limit component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Value / Measurement variables	Score LC	Score HC
C8,1	Speed limit of road section	1.0	Speed limit < 37 mph	1	
			37 mph ≤ Speed limit < 42 mph	0.50	
			42 mph ≤ Speed limit < 61 mph	0.25	
			61 mph ≤ Speed limit	0	
			Speed limit < 47 mph		1
			47 mph ≤ Speed limit < 53 mph		0.50
			53 mph ≤ Speed limit < 76 mph		0.25
			76 mph ≤ Speed limit		0

9. Number and diversity of road users

The effectiveness of automated vehicles (AVs) as a reliable mode of transportation for society depends on their ability to communicate with other road users (Stanciu et al., 2018). This entails acquiring timely and accurate information about the intentions and actions of surrounding road users and being able to respond to them in a safe and efficient manner. However, in a driving environment with a high diversity and density of road users, the interaction between AVs and other road users can be challenging (Tabone et al., 2021). This is particularly true when it comes to detecting and correctly predicting the behaviour of dynamic objects, such as pedestrians, cyclists, animals, and other road users. As a result, the risk of misperception and unsafe driving situations can increase. Briefly, the more diverse and dense dynamic objects on the roadway, the greater the challenge for the AVs to accurately detect and identify different road users and predict their behaviour. However, the diversity and density of road users (e.g. cars, motorcycles, trucks, buses and pedestrians) differ significantly by the time of the day and the day of the week. Also, it requires significant efforts to measure or observe the flow of road user types at a specific time across the entire road network. While recent advances in artificial intelligence have made it possible to classify and count road users in real-time, these technologies have not yet been widely implemented by cities. Thus, publicly available data in this regard may not be sufficient to evaluate the entire road network of a city at the moment. Therefore, three indirect subcomponents have been adopted to represent this component of the assessment index (see **Table S1.9**).

Table S1.9 Scoring scheme for number and diversity of road users component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement Variables	Score ($Sc_{i,j,m}$) LC	HC
C9,1	Road access	0.5	Access control roads: VRUs (e.g. pedestrians and cyclists) are not permitted	1	1
			Mixed traffic roads without any public transit facilities (bus, tram etc.)	0.5	0.75
			Mixed traffic roads with public transit facilities	0.25	0.5
			Shared space roads: access to all road users	0	0.25
C9,2	Counterflow	0.25	No presence of counterflow traffic	1	1
			Presence of counterflow traffic	0	0.25
C9,3	No. of lanes	0.25	Total number of lanes on the road section ($N \leq 2$)	1	1
			Total number of lanes on the road section ($2 < N \leq 4$)	0.5	0.75
			Total number of lanes on the road section ($N > 4$)	0.25	0.5

Road access authorisation is adopted to represent the diversity of road users on road segments (i.e. half of the weight of the component). The highest score is assigned to sections of the road that are not allowed access by VRUs. Mixed traffic facilities shared between drivers, cyclists and sometimes pedestrians are given a relatively lower rating. If there are also public transport facilities on the roads, a score is given one step lower. Finally, shared space areas were assigned the lowest score as more diverse road users can be present compared to other roads. To evaluate the number of road users, two subcomponents are proposed: the presence of counter-flow traffic and the total number of lanes on the road sections. The number of road users can be expected to increase with the number of lanes on the road, so the highest score is assigned to road sections with fewer lanes. Finally, with counter-flow roads, AVs also need to detect and respond to dynamic objects in the reverse traffic direction. Therefore, physically segregated road sections received the highest score.

10. Roadside complexity

Roadside complexity and occlusions can have a significant impact on the ability of AVs to safely operate on roads. This refers to the presence of visual distractions along the road, such as signs, buildings, trees, and other physical features. These distractions can make it more difficult for AVs to accurately perceive their environment, potentially leading to unsafe driving behaviour. In other words, AVs not only need to detect, identify, and anticipate the behaviour of dynamic objects such as VRUs and animals but also need to perceive and classify stationary objects in the driving environment (Shladover, 2018). Research points out that the complexity of road environments for automated driving systems increases as the number of objects and obstacles increases, as it becomes more challenging to identify and understand the behaviour of these objects (Soteropoulos et al., 2020). Furthermore, roadside objects may cause a challenge for the detection capabilities of AVs as being potential physical obstacles (Koopman and Fratrik, 2019). On the other hand, some studies suggest that AVs should have a detailed prior knowledge of the road infrastructure and surrounding environments on their planned route before starting the journey (Huggins et al., 2017; Ulrich et al., 2020; PIARC, 2021). This can be possible with a detailed level of high-definition map of the road network and its surrounding environment (Ebrahimi Soorchaei et al., 2022). Additionally, advances in machine learning and computer vision can also help to improve the ability of AVs to deal with roadside complexity and occlusions. However, experts point out that HD maps need to be constantly updated and that this may not be possible for all operational areas in the early stages of implementation (Tengilimoglu et al., 2023).

Table S1.10 Scoring scheme of roadside complexity component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement Variables	Score ($Sc_{i,j,m}$) LC	HC
C10,1	Presence of trees	0.25	No presence of trees on two sides of roadway (or presence far from the road edges such as d >8-10m)	1	1
			Presence of trees on one side of roadway	0.5	0.75
			Presence of trees on both sides of roadway	0	0.25
C10,2	Street furniture density	0.25	Low density of street furniture (e.g. advertising display, benches, bicycle stands, billboards, bins, bus shelter, lamps, post boxes, etc.) on two sides of roadway	1	1
			High density of street furniture on one side of roadway	0.50	0.75
			High density of street furniture on two sides of roadway	0	0.25
C10,3	Proximity of buildings	0.25	No presence of close buildings (e.g. commercial, industrial, educational etc.) on two sides of roadway (not far from the road edge d < 2-3 m)	1	1
			Presence of close buildings on one side of roadway	0.50	0.75
			Presence of close buildings on both sides of roadway	0	0.25
C10,4	Digital mapping of roadside environment	0.25	Presence of digital map of the roadside environment	1	1
			No presence of digital map of roadside environment	0	0

In this context, four equally weighted subcomponents were taken into account in the scoring scheme for the roadside complexity component (see **Table S1.10**). The first subcomponent is the presence of trees on the sides of the road as this can pose challenges for MV systems. This is because trees cause shadows on the road surface, even dynamic changes in the shadows with the wind, accumulation of leaves or obstruction to the visibility of traffic equipment. The density of street furniture was another subcomponent to evaluate this component, as more roadside objects mean, a more complex driving environment for AVs. Thirdly, the proximity of buildings to the road can also increase the complexity of the environment as the high presence of pedestrians or other vehicles entering or exiting the buildings, especially commercial ones. Another potential challenge of the proximity of these buildings to the road is the presence of many billboards and digital screens that can affect the detection systems of AVs and complicate the decision-making process. Also, proximity may limit the visibility of the road ahead, which can impact the AV's ability to detect road users and safely navigate the road. The last subcomponent is the availability of digital representation of surrounding road environments that provide preliminary information for AVs to mitigate the risks as discussed above.

11. Facilities for vulnerable road users

As previously stated, one of the main barriers to the acceptance of AVs on public roads is the necessity of robust systems that can reliably interact with other road users. The perception and planning modules of AVs must be able to recognise VRUs precisely and timely, anticipate their trajectory and speed, and avoid colliding with them (Schwarting et al., 2018). This can only be possible with significant advances in both the software and hardware side of automated driving systems. This is because the perception systems and algorithms of current AV models are not yet able to respond to the subtle social aspects of driving as human drivers do (Rasouli and Tsotsos, 2020). For this reason, recent developments expand the idea of vehicle-to-everything (V2X) communication to include vulnerable road users (Hussein et al., 2016). For instance, smartphone-integrated systems are one of the research directions that partially address this limitation of AVs. In this way, both vehicles and VRUs are aware of each other's movements and receive warning signals in case of a possible accident when necessary (Miucic and Bai, 2019; Rasouli and Tsotsos, 2020; Eskandarian et al., 2021). However, the benefits of these solutions mostly depend on the rate of smartphone usage in societies. Therefore, relying solely on the connection cannot be a robust solution. In addition to technological developments in the vehicle and digital infrastructure, it is vital to consider the expectation of VRUs from the physical road infrastructure. This is highly correlated with the operational capabilities of AVs, as infrastructure-based facilities can help reduce the risk of conflicts between VRUs and AVs. For example, well-designed and well-maintained sidewalks, crosswalks, and segregated bike lanes are desirable due to mitigating the risk of conflict between road users. Regarding the index, four equally weighted subcomponents were considered in the scoring scheme of this component (see **Table S1.11**).

The first subcomponent is pedestrian crossing points that directly affect the safe operation of AVs due to the necessity of interaction between road users. So, the types of crossing in the UK were categorised based on their potential complexity level for AVs. Pedestrian crossing facilities can be evaluated regardless of whether they are at an intersection or not. If a crossing is located at an intersection, it can be assigned to the closest or responsible road segment. Sidewalks, the second subcomponent of the component, were evaluated according to their conditions and availability on the sides of the roadway. The highest score was assigned to physically separated sidewalks, and relatively lower scores were given to unseparated sidewalks based on their configurations. Similarly, cycling infrastructure on the road was categorised according to their level of complexity for automated driving and the safety perspective of cyclists. Finally, the configuration of public transport access points is an important factor affecting not only the safety or traffic efficiency of VRUs, but also the level of interaction between AVs and VRUs. In this regard, bus stop types (including school buses) on the roadway were categorised based on the same idea as the previous subcomponents. That is, higher scores were given to situations with less likelihood of interaction between VRUs with AVs. However, if the road segment is an access control road, which is a prohibited legal road for pedestrians and cyclists, this component score is assigned as 1, without consideration of any other criteria.

Table S1.11 Scoring scheme of facilities for vulnerable road users component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement Variables	Score ($Sc_{i,j,m}$) LC	HC
C11,1	Pedestrians crossing type	0.25	Presence of pedestrian bridges or underpasses on the roadway	1	1
			Puffin, Toucan, Pegasus crossing on the roadway	0.75	1
			Pelican crossing on the roadway	0.5	0.75
			Zebra crossing or surface marked crossing on the roadway	0.25	0.50
			Unmarked or No provision for pedestrians crossing on the roadway	0	0.25
C11,2	Pedestrian sidewalk	0.25	Physically segregated pedestrian sidewalk with barriers, buffer, or landscaping zones on the roadway	1	1
			Presence of sidewalk on both sides of the roadway	0.75	1
			Presence of sidewalk on one side of the roadway	0.50	0.75
			No presence of sidewalk for pedestrians on the roadway	0	0.25
C11,3	Cycling infrastructure	0.25	Physically segregated cycle lane on the roadway	1	1
			Segregation with lane markings or painting on surface on the roadway	0.50	0.75
			No presence of segregation on the roadway	0	0.25
C11,4	Public transit access point design	0.25	Not presence of bus route, stops, or Presence of dedicated bus lane on the roadway	1	1
			Presence of bus lay-by on the roadway	0.75	1
			Presence of bus shelter on the roadway	0.50	0.75
			Presence of bus stop with road marking and post on the roadway	0.25	0.5
			Presence of temporary bus stop or bus stop with simple sign or post on the roadway	0	0.25

12. Precautions for roadworks and incidents

Roadworks and construction sites are a significant source of danger, causing many accidents involving both vehicles and workers. AV manufacturers and system suppliers are particularly worried about roadwork and recognise them as a crucial aspect that needs to be addressed (P. Wang et al., 2022). Similarly, many experts in the field point out that roadworks and incidents are major inconvenience factors for AVs and the surrounding traffic (Tengilimoglu et al., 2023). This is because road works, temporary road closures and incidents change the road layout that requires AVs to interpret real-time changes, such as merging-lanes suggestions provided by temporary signs and cones. Changes in a predefined physical road environment may cause complex situations for AVs to navigate safely. Furthermore, effectively coordinating human-guided vehicles and AVs in these areas poses a significant challenge (Lytrivis et al., 2018). For this reason, roadworks need to become well-planned activities and real-time information, including physical changes in road layout, needs to be provided to

AVs (Huggins et al., 2017). In this regard, local authorities in the UK work closely with third-party service providers to provide real-time information on incidents and roadworks and to map their locations (e.g. One.network). This information in the map format is updated periodically, however, some emergency roadworks may not be listed as work often starts at short notice. Although the location and time of roadworks and incidents are provided, the lack of detailed information on the layout of the site makes it difficult for AVs to distinguish real-time changes from predefined maps, thus making it difficult to navigate (Liu et al., 2019).

Therefore, roadworks should be planned and implemented in a way that facilitates the safe negotiation of vehicle drivers and AVs. Guidelines for necessary equipment in roadwork zone need to be developed and lane layouts, temporary marking and other guiding elements described in greater detail. For AVs, harmonisation of roadworks management as well as related warnings and information requires standardisation activities on a national level, and preferably on the global level (Amelink et al., 2020). There is currently a uniform code and guideline for traffic management and control of roadworks at the national level in the UK. The Code of Practice for Safety in Street Works and Road Works is one of them, and this code applies to all roads, except motorways and any dual carriageways with a speed limit of 50 mph or more (Department for Transport, 2013). Further guidance on the safe operation of roadworks on highways, including in some cases not covered by this Code, is available in Chapter 8 of the Traffic Signs Manual. However, these specifications need to be re-evaluated or, if necessary, simplified for AVs to pass through such areas safely and efficiently. For example, there is a need to establish uniform signs, barriers, or cones and their locations at the roadworks in a manner easily detected and interpreted by the sensors and software of vehicles as well as human drivers (Transport Systems Catapult, 2017). For this, firstly, an agreement between stakeholders is needed on what road equipment and warnings (e.g. markings, cones and signs) will be used for roadwork or incident zone (P. Wang et al., 2022). Besides, new concepts on markings and signs can be considered so that AVs have a distinctive symbol to respond (Singh and Islam, 2020). Aside from the physical infrastructure, it is important to establish digital roadside communications to replace static facilities to provide timely roadwork and incident information to the AVs (Lytrivis et al., 2018). The standardised information exchange on location and layout together with defined communication protocols can be implemented in those areas to help AVs (Amelink et al., 2020; P. Wang et al., 2022).

Given the discussion above, the scoring scheme for assigning road sections considered the availability of real-time information systems and whether digital and physical warning signs and markings are implemented for AVs (see **Table S1.12**). If the roadwork or incident is on the evaluated road segment, a higher score is assigned to situations in that AVs access real-time layout level information and locate standardised digital and physical warning signs and markings. The lowest score is assigned to measures taken only for human-driven vehicles where AVs may have difficulty navigating.

Table S1.12 Scoring scheme of precautions for roadworks and incidents component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement Variables	Score ($Sc_{i,j,m}$) LC	HC
C12,1	Precautions for roadworks and incidents	1.0	No presence of roadwork or incident on the roadway	1	1
			Presence of roadwork or incident with real-time layout level information, and standardised digital and physical warning signs and markings on the roadway	0.75	1
			Presence of roadwork or incident with standardised digital and physical warning signs and markings on the roadway	0.50	0.75
			Presence of roadwork or incident with only standardised physical warning signs and markings	0.25	0.50
			Presence of roadwork or incident without any precautions for AVs	0	0.25

13. Localisation challenges

Accurate and robust localisation is essential in many transportation applications such as vehicle navigation, traffic monitoring, and tracking of commercial and public transit vehicles. The current state-of-practice positioning devices typically have an accuracy of 10 metres and can suitably meet the needs of the above applications (Kuutti et al., 2018; Meng et al., 2018). When it comes to an automated vehicle, knowing its absolute position on the ground is extremely important for performing dynamic driving tasks safely. However, the level of localisation accuracy required for automated vehicles depends on the level of automation (PIARC, 2021). Studies point out that centimetre-level positioning accuracy is needed for highly automated vehicles to be able to safely navigate on urban roads (Reid et al., 2019). This is because accurate knowledge of a vehicle's location is necessary for the planning and control functions to make correct driving decisions and take appropriate actions. A slight error of a few decimetres in determining the location can result in the vehicle being localised on the wrong side of the road or causing accidents involving vulnerable road users like cyclists and pedestrians. In addition, AVs must be able to determine their location accurately in regard to other static and dynamic objects even in challenging driving conditions, such as when road markings are not visible or in harsh weather conditions like snow. Therefore, robust localisation systems for AVs with centimetre-level accuracy in real-time are crucial (Kuutti et al., 2018; Reid et al., 2019).

The use of Global Navigation Satellite Systems (GNSS) has become prevalent in identifying the position of vehicles and other individuals on the road. GNNS systems (i.e. GPS, GLONASS, Galileo, BeiDou, etc.) utilize a receiver or an antenna to communicate with satellites through radio signals transmission and triangulate the vehicle’s global position. However, ordinary GNSS has several shortcomings, which prevent its stand-alone usage (Government Office for Science, 2018; Eskandarian et al., 2021). GNSS systems are easily affected by environmental factors such as cloud cover, and obstacles such as infrastructures, trees and tall buildings in the urban environment. These effects can be divided into two kinds: multipath, where the signal is received through a reflected path, and non-line-of-sight (NLOS), where the receiver cannot receive the satellite signal directly, which is blocked by obstacles (Eskandarian et al., 2021). Moreover, in some countries or regions, the signal might also be too weak for precise localisation of the vehicle (Wevolver, 2020). Many of these problems can be addressed using methods that augment basic GNSS. Some of the techniques that improve the accuracy are differential GNSS, satellite-based augmentation systems (SBAS), real time kinematic (RTK) solutions, precise point positioning (PPP) and more (Government Office for Science, 2018).

Aside from the augmentation of GNSS, to acquire more precise localisation, a variety of vehicle localisation techniques with different accuracy levels have been developed in the last few years (Kuutti et al., 2018; Van Brummelen et al., 2018). AVs use their own perception sensors to scan the environment, GNSS and real-time kinematic (RTK) for centimetre precision, and inertial measurement unit (IMU) and wheel odometry to assess vehicle dynamics and support positioning when GNSS is not available (Mihalj et al., 2022). Moreover, a HD map in combination with sensing can help in centimetre-precision longitudinal and lateral position predictions of AVs. Rather than rely on GNSS, some AV companies benefit cross-references their pre-built maps with real-time sensor data to precisely determine vehicle location on the road (Waymo, 2021). In short, AVs can use communication supports and sensor fusion that utilise the IMU, in-vehicle sensors, onboard sensors and digital maps to achieve precise localisation (Kuutti et al., 2018; Eskandarian et al., 2021).

Regarding localisation services that support the safe and efficient operation of automated driving, different subcomponents can be offered for localisation facilities components, including empirical evidence-based subcomponents. In this context, studies have evaluated the quality of GNSS signal strength and localisation accuracy on certain road segments by comparing different methods for automated driving through experimental measurements (Meng et al., 2018). For instance, Cucor et al. (2022) focused on three main criteria in the evaluation of road segments for localisation requirements of AVs: average number of satellites, number of using satellites and GNSS lateral localisation error. Another recent experimental study indicated that the service level subcomponent for positioning services could be the measured signal strength over 40 dB (i.e. Signal-to-Noise-Ratio) using five strongest satellites from each constellation (FTIA, 2021). However, these types of evaluation for all road network in a city requires significant effort in terms of budget and time. Also, the real accuracy for a user depends on local factors such as signal blockage, atmospheric conditions, and the quality of the adopted receiver. Therefore, two equally weighted subcomponents in the scoring scheme for the evaluated road segments have been taken into consideration: the presence of any obstruction challenges for GNSS signals and the presence of a digital map that can help the localisation of AVs (see **Table S1.13**).

Table S1.13 Scoring scheme for localisations challenging component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement Variables	Score ($Sc_{i,j,m}$) LC	HC
C13,1	Localisation challenges	0.5	Presence of landmarks or magnetic road markings on the roadway	1	1
			Presence of low-rise development on both sides of the roadway	0.75	1
			Presence of high-rise development or high-vegetation cover on one sides of the roadway	0.5	0.75
			Presence of high-rise developments (e.g. urban canyons) or valleys surrounding the roadway or high vegetation cover on both sides of the roadway or short underpasses (L < 20m) on the roadway	0.25	0.5
			Presence of long underpasses (L > 20m) or tunnels on the roadway	0	0
C13,2	Digital mapping of road environment	0.5	Presence of digital map of road and surrounding environment	1	1
			No presence of digital map of road and surrounding environment	0	0

14. Communication facilities

Despite some views that AVs should be capable of operating on roads without depending on connectivity, it is widely accepted that communication systems will play an important role in vehicle automation to address many challenges related to safety and gain network-wide benefits in efficiency through cooperation (Shladover, 2018). Communication technologies enable a vehicle to wirelessly connect with other road participants such as surrounding vehicles (V2V) and vulnerable road users (V2P), or infrastructure such as traffic equipment (V2I) and network (V2N) to exchange data (He et al., 2019). All these communication systems are commonly gathered under the umbrella of Vehicle-to-Everything (V2X). Applications of V2X are currently in consideration in many areas such as roadwork or warning of road obstacles ahead, traffic jam information, traffic signals phase and time, spot weather impact, merging support, queue warning, pedestrian detection and more (European Commission, 2017; PIARC, 2021). Briefly, communication infrastructure will likely be a key component of road networks for the safe operation of AVs. However, with the penetration of AVs, the issues such as data precision, latency and transmission data rate will become more critical for secure and efficient systems. Therefore, the network that provides these applications of communication should be highly reliable, efficient and capable of handling the data traffic load (Bagloee et al., 2016; Wevolver, 2020).

Various wireless communication technologies such as cellular, Wi-Fi, radio broadcast and satellite have been developed and used in many areas (Huggins et al., 2017). In simple terms, these communication facilities for AVs are commonly categorised as short-range and long-range broadcasts and are predominantly supported by two network standards, each with significantly different design principles (Eskandarian et al., 2021). For short-range communication, two main vehicular communication protocols have emerged in recent years: Dedicated Short-Range Communications (DSRC) in the USA and Intelligent Transportation System ITS-G5 in Europe (Mannoni et al., 2019; Mihalj et al., 2022). Both protocols are based on the IEEE 802.11p automobile-specific Wi-Fi standard and use channels of 10 MHz bandwidth in the 5.9GHz spectrum band. On the other hand, cellular is another promising technology for V2X and these technologies such as 4G/ LTE and 5G provide long-range communication facilities for vehicles and devices. Recently, there has been increasing debate about how much stakeholders should invest in these technologies (Khan et al., 2019). There is also much industry debate about which of these models will prevail and which is the best choice for AVs and cities. The discussion includes various factors such as performance, capabilities, deployment costs, and technology readiness level (Mannoni et al., 2019; Moradi-Pari et al., 2023). Ensuring the coexistence of the two technologies in a geographic region will require spectrum management and overcoming operational challenges (Wevolver, 2020). More information on C-V2X use causes and communication service level requirements for automated driving can be found in the 5G Automotive Association reports such as (5GAA, 2020).

Regarding communication facilities that support the safe and efficient operation of automated driving, two alternative subcomponents were considered in the scoring scheme (see Table S14). While these subcomponents are alternatives to each other, some studies argue that the presence of both dedicated channels and cellular connections along the road network would be a more reliable and robust solution for AVs. For example, AVs may need to connect to their manufacturer's or service provider's cloud to update their software or maps via a cellular connection, they also can share or receive safety-critical data with traffic management centres through Road-Side Units. The presence of both connectivity options (as a hybrid system) may provide a backup plan for AVs and redundancy in case of any breakouts and cyberattacks on one platform (European Commission, 2017). However in this study, communication options were considered not used as hybrid system in the early stages of the implementation due to investment cost. The first subcomponent is therefore whether Roadside Units are present along the road. These units can be any form of technology providing V2X connectivity and employing road structures such as road strips and traffic lights. The second alternative subcomponent is cellular network coverage. This subcomponent evaluates whether the presence of good cellular network service along the road segment. The highest score is given to 5G-based C-V2X since potentially better than 4G-based alternatives in terms of data rate, with much lower latency, and the ability to serve more devices (Wevolver, 2020). On the other hand, the lowest score is assigned to the roadway section, where there is a lack of cellular coverage areas or gaps in coverage in both (4G/LTE and 5G) options.

Table S1.14 Scoring scheme for supporting communication facilities component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement Variables	Score ($Sc_{i,j,m}$) LC	HC
C14,1	Roadside Units	1.0	Presence of Roadside Units (RSUs) along with the roadway (e.g. DSRC or ITS-G5)	1	1
			No presence of Roadside Units (e.g. DSRC or ITS-G5)	0	0
Or					
C14,1	Cellular network coverage	1.0	Excellent or good 5G NR coverage in operation area for C-V2X	1	1
			Average 5G NR coverage in operation area for C-V2X	0.75	1
			Excellent or good 4G/LTE coverage in operation area for C-V2X	0.5	0.75
			Average 4G/LTE coverage in operation area for C-V2X	0.25	0.5
			Below average, poor, limited cellular coverage or Network blackspots	0	0

According to a recent report, around 92% of the UK landmass is predicted to have good 4G coverage from at least one operator (Ofcom, 2022). However, there is disagreement on the accuracy of cellular coverage maps since much of the coverage data is generated by computer modelling rather than real-life testing. As such it may not always reflect the truth on the ground (Local Government Association, 2019). Moreover, the performance of cellular networks may change with the time of the day or day of the week due to fluctuating in vehicle density. Therefore, more solid, and empirical evidence-based subcomponents can be offered for communication facility components. Some studies have evaluated the quality of the cellular network for automated driving through experimental measurements (Meng et al., 2018; Somers, 2019). Among these, for example, a recent research measured download speed, upload speed and latency level of 4G and 5G on the road section named E12 between Helsinki and Tampere during different times of the day (FTIA, 2021). The study also considered the proximity of mobile base stations and fibre access points to road segments. A more detailed measurement for connectivity was proposed by Cucor et al. (2022) and focused on three main criteria in the evaluation of road segments: communication latency, message loss and bitrate per vehicle. However, such empirical-based assessments require an enormous effort from both the public and private sectors. In recent years, the Office of Communications (commonly known as Ofcom) has begun measuring mobile signal strength for 4G and 5G technologies from four main mobile operators on different roads across the UK. This data reflects measurements made at a height of 1.5m using an antenna mounted on the roof of a vehicle. The data comprises several technical parameters such as RSRP, RSRQ and SINR, which are three important parameters used to measure the quality and strength of a cellular network signal (Ofcom, 2021). Nonetheless, there are still many roads that need to be evaluated in the UK. Therefore, we have adopted signal coverage maps as a simple way to evaluate this component.

15. Intersections and roundabouts

Intersections are complex traffic situations for road users and represent critical points in terms of safety in networks (Montanaro et al., 2019). Similarly, these locations can be considered challenging areas for AVs in terms of dimensions, visibility, and complexity in the traffic situation, as AVs must detect, identify, and predict the behaviour of other road users and respond appropriately to them. Namely, current AV trials in mixed traffic conditions reveal that intersections are the most challenging road sections for automated driving. This is because the majority of the reported AV-involved accident happened around the intersections. However, most of these accidents are rear-end crashes involving human-driven vehicles (Favarò et al., 2017). A recent report indicated that nearly all collision events involved one or more road rule violations or other errors by a human driver or road user (Schwall et al., 2020). This brings many concerns about how the interaction between human drivers and AVs will be managed safely. In this context, research and development studies have accelerated in recent years on roadside units or cellular connection models (e.g. I2V, C-V2X) that aim to travel seamlessly and safely at intersections (Martínez-Díaz et al., 2019). Nevertheless, developments in ADS technologies and connectivity alone may not be sufficient for safe operation at these points, therefore serious efforts are also required to improve the infrastructure such as standardisation of rules for physical road separation, proper channelisation, and delineation of intersections (P. Wang et al., 2022).

One of the main obstacles to the adoption of AVs, especially in urban road networks, is the variation in intersection and roundabout types with different sets of rules and complexity. For this component, the intersection and roundabout types were categorised regarding their complexity levels for AVs operating functions (see **Table S1.15**). While some opposite views (Gill et al., 2015; Anagnostopoulos and Kehagia, 2020), many studies point out that signal controlled intersections are relatively easier for AVs to able to handle their operational tasks than other forms of intersections such as roundabouts (Transport Systems Catapult, 2017; Lawson, 2018). According to expert opinions, non-signal controlled intersections and roundabouts are the most dangerous and challenging road sections for AVs (Lu et al., 2019). This is mainly because signal-controlled junctions provide more predictable elements of stop-and-go manoeuvres and more closely defined turning manoeuvres (Morando et al., 2018). Therefore, signal controlled intersections, including railway crossings, are probably the relatively least complex junction types for AVs, as there is no need to negotiate priority with other road users or predict their intentions. Among the signal-controlled intersections, the highest score is given to signal-controlled intersections with protected turn lane as the relatively less confusing driving situation between vehicles for turning movements. However, the main concern with MV technology is reliability in accurately identifying traffic lights and status without connectivity support (Jensen et al., 2016). Therefore, it becomes more and more important to the communication infrastructure at the intersections and mapping system that support the traffic signal time and status for the safe operation of vehicles. These factors were considered in the other components of the parameters such as digital mapping of traffic signs, communications facilities, and information management systems.

Table S1.15 Scoring scheme for intersections and roundabouts component.

Item ($C_{i,j}$)	Subcomponents	Weight ($Wc_{i,j}$)	Measurement variables	Score ($Sc_{i,j,m}$) LC	HC
C15,1	Intersection and roundabout type	0.25	Signal controlled intersections with protected turn lane	1	1
			Signal controlled intersections, or Priority-controlled intersections with protected turn lane	0.75	1
			Priority-controlled intersections, or Mini or single-lane roundabouts	0.50	0.75
			Uncontrolled intersections, or Median crossing points	0.25	0.5
			Multi-lane roundabouts	0	0.25
C15,2	Number of arms	0.25	N = 3 (e.g. T or Y intersections)	1	1
			N = 4 (e.g. Cross / staggered)	0.5	0.75
			N > 4 (e.g. multi-armed)	0	0.25
C15,3	Regularity of layout	0.25	Regular form of intersection	1	1
			Irregular form of intersection	0	0.25
C15,4	Delineation (marking) conditions	0.25	Clear visible marking or Availability of HD mapping	1	1
			Some visible wear on the markings	0.5	0.75
			Barely visible or non-existent markings	0	0.25

On the other hand, priority (non-signal) controlled intersections represent a relatively high challenge for automated driving systems as they involve many traffic relationships, and the behaviour of AVs depends on detecting and predicting the movements of other road users. By comparison, uncontrolled intersections are more complex because AVs must coordinate the use of the common area with other road users as there is no signal or signage within the intersection. Similarly, the complexity is quite high at roundabouts for automated driving (Soteropoulos et al., 2020). Successfully navigating a roundabout requires an understanding of the choice of entry and exit lanes, how to apply priority rules, how to interpret other drivers' intentions, and the current traffic itself (Cuenca et al., 2019). Therefore, mini, and single-lane roundabouts are assigned to relatively higher score in the scheme as they have low traffic volumes, speeds, and simple geometric design for AV operation. On the other hand, tracking vehicles on a circulatory road segment with multiple lanes of traffic present additional challenges in the path planning of AVs, so the lowest score in the scheme was given to multi-lane roundabouts.

In addition to intersection types, three other important factors: the number of arms in the intersection, regularity in the layout of intersects and delineation condition are included in the component. This is because these three subcomponents are correlated with the complexity of intersections, posing challenges for automated vehicles and human drivers. Therefore, the highest score is assigned to less-armed intersections, relatively regular layouts and good condition in the delineation markings. More information about the regularity in intersection form can be found in Fig 7.9 in the Manual for Streets (Department for Transport, 2009).

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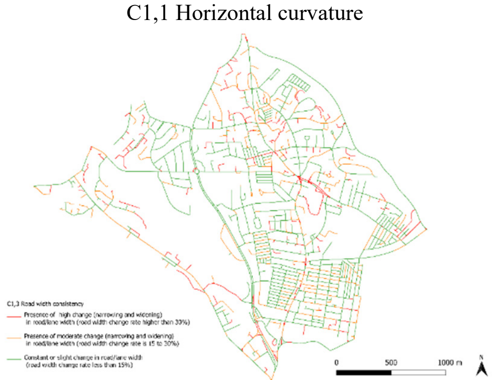
Supplementary materials 1.2 (SM-1.2)

The following figures illustrate the outcomes of the evaluation conducted on the road links, considering the measurement variables within the subcomponents of the corresponding index components.

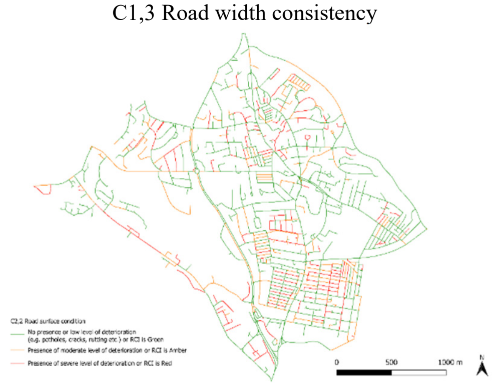
C1,1 Horizontal curvature

C1,2 Longitudinal gradient



C1,3 Road width consistency

C2,1 Road surface type



C2,2 Road surface condition

C3,2 Road marking configuration

C3,3 Road marking wear condition

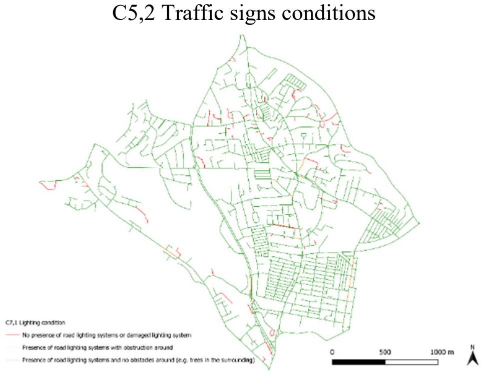
C4,1 Median type

C4,2 Road edge condition

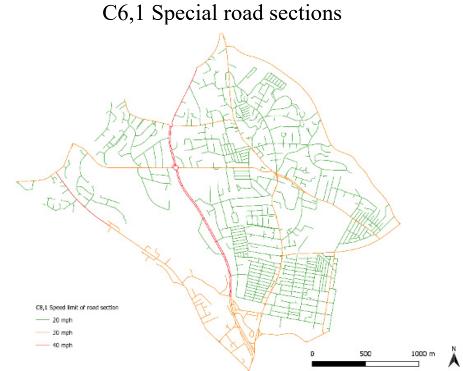
C4,3 On-street vehicle parking

C5,2 Traffic signs conditions

C6,1 Special road sections



C7,1 Lighting condition



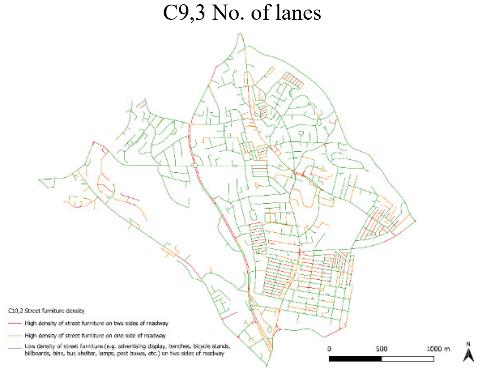
C8,1 Speed limit of road section

C9,1 Road access

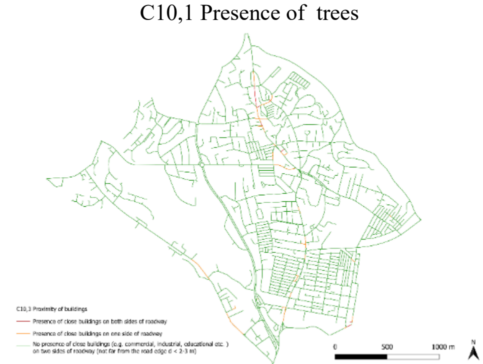
C9,2 Counterflow

C9,3 No. of lanes

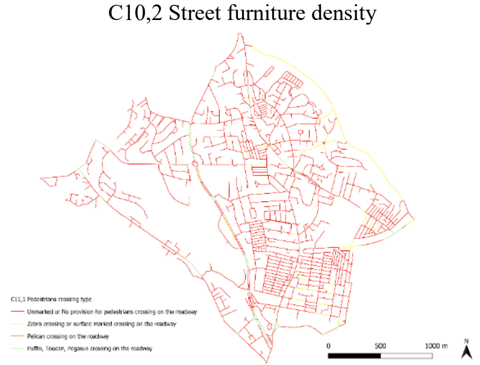
C10,1 Presence of trees



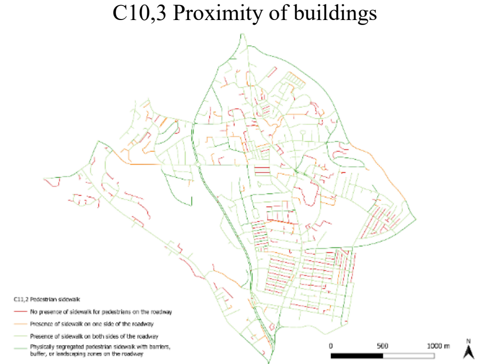
C10,2 Street furniture density



C10,3 Proximity of buildings



C11,1 Pedestrians crossing type



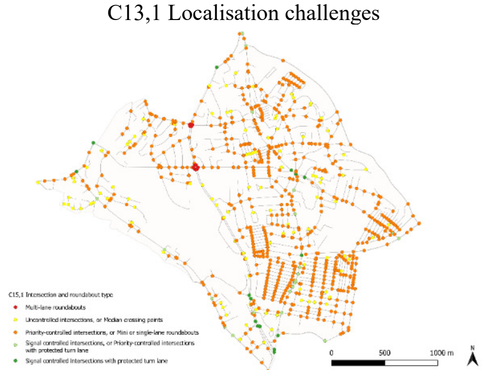
C11,2 Pedestrian sidewalk

C11,3 Cycling infrastructure

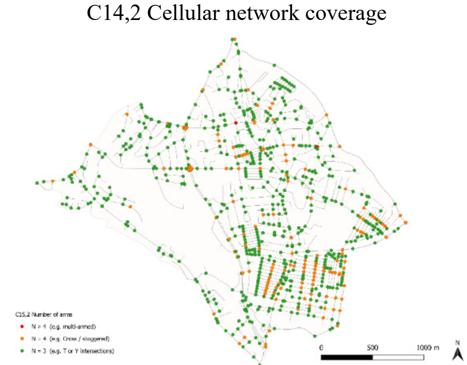
C11,4 Public transit access point design

C13,1 Localisation challenges

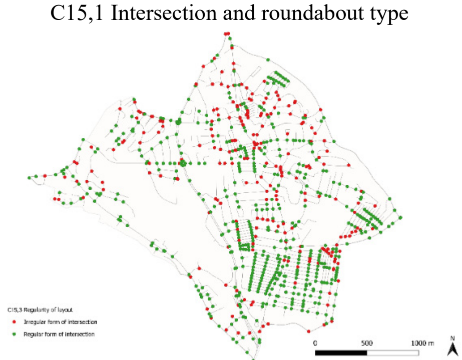
C14,2 Cellular network coverage



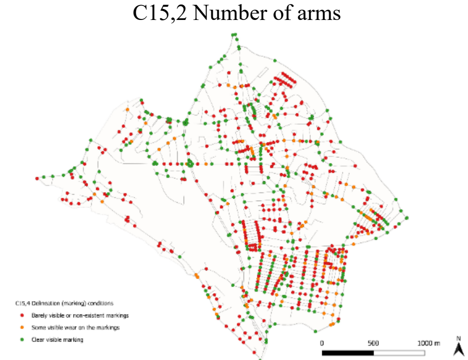
C15,1 Intersection and roundabout type



C15,2 Number of arms



C15,3 Regularity of layout



C15,4 Delineation (marking) conditions

SUPPLEMENTARY FILE 2

Supplementary files to Chapter 6

Supplementary materials 2.1. (SM-2.1)

The supplementary material of the related chapter refers to Appendix B of this thesis.

Supplementary materials 2.2 (SM-2.2)

Table S2.1 provides an overview of the data sources used in evaluation process of road links and evaluates the quality and representativeness of the collected data for each component.

Table S2.1 Overview data collection method for representation of subcomponent of framework and general assessment of collected data quality, adopted from Tengilimoglu et al. (2024)*

Ci	Framework components	Ci,j	Subcomponents	Source of data/ method of data collection	General assessment of collected data quality/representation
C1	Road Geometric Challenges	C1,1	Horizontal curvature	It was initially calculated by using ROCA (ROad Curvature Analysis) toolbox in ArcGIS Pro developed by (Bíl et al., 2018)** . It was then revised by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C1,2	Longitudinal gradient	It was initially calculated by using the data provided by the Ordnance Survey MasterMap. Elevation differences of road link ends were divided into the length of the road link. However, this method has limitations for long or non-straight road links. To address these limitations, the method involves recalculating slopes for smaller segments of the road links, utilizing a Digital Elevation Model (DEM) from the Ordnance Survey and the road network.	Good
		C1,3	Road width consistency	It was initially calculated the change rate of width in road links using the data provided by the Ordnance Survey MasterMap. The difference between average road width and minimum road width was divided by average road width. A score of 1 was given if the ratio was less than 0.15, 0.5 if it was between 0.15 and 0.3, and 0 otherwise. Also, it was revised by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C1,4	Digital map of road geometry	An assumption was made according to scenarios (NS1: no HD maps, NS2: available for all network).	Poor
C2	Road Surface	C2,1	Road surface type	It was evaluated by visual inspection using street view services.	Good
		C2,2	Road surface condition	The condition of the road surface was categorised based on the available RCI data provided by the Department for Transport. The data is available at: https://maps.dft.gov.uk/road-condition-explorer/index.html. Also, it was evaluated by visual inspections using street view services for places where automated inspection data collected by specialised vehicles is not available.	Fair
C3	Road Markings	C3,1	Digital map of road markings	An assumption was made according to scenarios ((NS1: no HD maps, NS2: available for all network).	Poor
		C3,2	Marking configuration	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C3,3	Marking condition	It was roughly evaluated by visual inspection using street view services according to examples in Appendix C of the DMRB CS 126 standard.	Fair
C4	Road Boundaries	C4,1	Median type	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services.	Good
		C4,2	Road edge condition	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, the continuity of road edge conditions was controlled from: https://www.leedstraffweb.co.uk/main.html and Ordnance Survey MasterMap Topography Layer.	Fair
		C4,3	On-street vehicle parking	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, parking locations on the network were controlled from: https://www.leedstraffweb.co.uk/main.html	Fair

(continued on next page)

Table S2.1 (continued)

Ci	Framework components	Ci,j	Subcomponents	Source of data/ method of data collection	General assessment of collected data quality/representation
C5	Traffic Signs	C5,1	Digital map of traffic signs	An assumption was made according to scenarios (NS1: no HD maps, NS2: available for all network).	Poor
		C5,2	Traffic signs conditions	It was roughly evaluated by visual inspection using street view services according to examples in Appendix E of the DMRB CS 125 standard.	Fair
C6	Special road section	C6,1	Special road sections	It was evaluated by using the data provided by the Ordnance Survey MasterMap. In addition, it was checked by visual inspection using aerial photography/satellite imagery or street view services.	Good
C7	Road Lightning	C7,1	Lighting condition	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Detailed information on the location and unit type of streetlights is available at: https://datamillnorth.org/dataset/street-lights-unmetered. However, the limitation of this method cannot consider whether the lighting systems work properly at night.	Poor
C8	Speed Limit	C8,1	Speed limit of road section	It was evaluated based on the interactive map providing traffic orders of roads that are under the control of Leeds City Council. (https://www.leedstraffweb.co.uk/main.html). Also, it was roughly controlled by visual inspection of speed limit signs on the roadway using street view services. Alternatively, Open Street Map can be used for this indicator.	Fair
C9	Number and Diversity of Road Users	C9,1	Road access	It was initially evaluated by considering road hierarchy. Also, public transit (bus) route was controlled from: Open Streep Map and https://www.geopunk.co.uk/timetables/town/leeds. Then it was controlled by visual inspection using aerial photography/satellite imagery or street view services.	Fair
		C9,2	Counterflow	It was evaluated by using the data provided by the Ordnance Survey MasterMap. Also, it was controlled form traffic orders data of the city from https://www.leedstraffweb.co.uk/main.html	Fair
		C9,3	No. of lanes	It was initially estimated by dividing the average road width by the approximate lane widths by type of road hierarchy. It was then revised by visual inspection using aerial photography/satellite imagery or street view services.	Fair
C10	Roadside Complexity	C10,1	Presence of trees	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Detailed analysis for this indicator can be done by using Tree Detection toolbox (deep learning model to detect trees in high-resolution imagery) in ArcGIS Pro by aerial photography/satellite imagery.	Fair
		C10,2	Street furniture density	It was roughly evaluated by visual inspection using street view services.	Poor
		C10,3	Proximity of buildings	It was evaluated considering Point of Interest (POI) and building data provided by Ordnance Survey. Then buffer analysis was carried out in QGIS. Moreover, commercial facilities control with visual inspection by using street view services.	Good
		C10,4	Digital mapping of surrounding road environment	An assumption was made according to scenarios (NS1: no HD maps, NS2: available for all network).	Poor

(continued on next page)

Table S2.1 (continued)

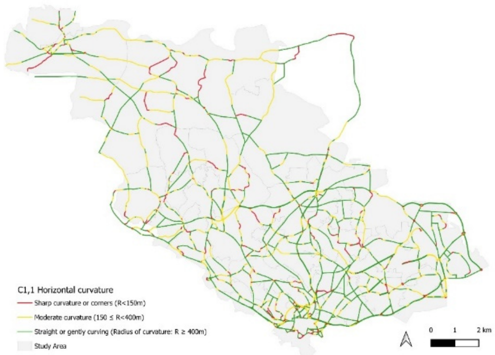
Ci	Framework components	Ci,j	Subcomponents	Source of data/ method of data collection	General assessment of collected data quality/representation
C11	Facilities for Vulnerable Road Users	C11,1	Pedestrians crossing type	It was initially evaluated by using data provided by Data Mill North and Ordnance Survey MasterMap. It was then revised by visual inspection using aerial photography/satellite imagery or street view services.	Good
		C11,2	Pedestrian sidewalk	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, it was controlled from: https://www.leedstraffweb.co.uk/main.html	Good
		C11,3	Cycling infrastructure	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, it was controlled from: Google Maps Cycling and Open Street Map.	Good
		C11,4	Public transit access point design	It was evaluated by visual inspection using aerial photography/satellite imagery or street view services. Also, public transit (bus) route was controlled from: Open Streep Map, and https://www.geopunk.co.uk/timetables/town/leeds. Additional information was based on data from National Public Transport Access Nodes (NaPTAN) by the Department for Transport.	Good
C12	Precautions for Roadworks and Incidents	C12,1	Precautions for roadworks and incidents	As this indicator requires a dynamic evaluation, it was assumed that there was no roadwork or incident on the network. Detailed information on live roadworks and incidents are available at https://one.network/uk/leeds.	Poor
C13	Localisation Challenges	C13,1	Localisation challenges	It was evaluated by visual inspection using street view services. Also estimated roughly by using the data provided by the Ordnance Survey MasterMap, such as building heights and average road width.	Poor
		C13,2	Digital mapping of road environment	An assumption was made according to scenarios (S1: no HD maps, S2-3: available for all network).	Poor
C14	Communication Facilities	C14,1	Roadside Unit or	There is no publicly available data for this indicator. Therefore, it was assumed that there were no roadside units on the network.	Poor
		C14,1	Cellular network coverage	It was simply evaluated by using service provider coverage maps or third-party web pages (e.g. https://www.cellmapper.net/). Only one service provider, EE Mobile, which has widely available network coverage data in the study area, was selected for the assignment. The band category chosen specifically for evaluating 4G LTE was B3-DCS 1805-1880MHz FDD. In contrast, for 5G, all band categories were considered. For sections of the road where data is unavailable, an average 4G signal strength is assumed.	Fair

* Tengilimoglu, O., Carsten, O., Wadud, Z., 2024. Are current roads ready for highly automated driving? A conceptual model for road readiness for AVs applied to the UK city of Leeds. Transportation Research Part A: Policy and Practice 186, 104148. https://doi.org/10.1016/j.tra.2024.104148

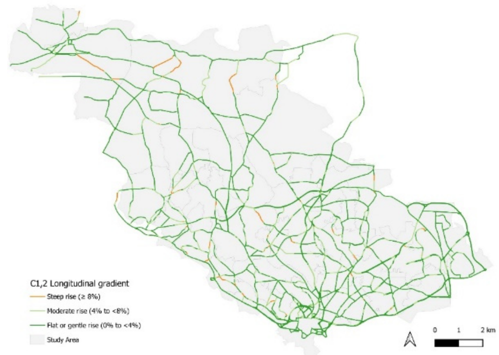
** Bíl, M., Andrášik, R., Sedoník, J., Cícha, V., 2018. ROCA – An ArcGIS toolbox for road alignment identification and horizontal curve radii computation. PLoS ONE 13, 1–15. https://doi.org/10.1371/journal.pone.0208407

Supplementary materials 2.3 (SM-2.3)

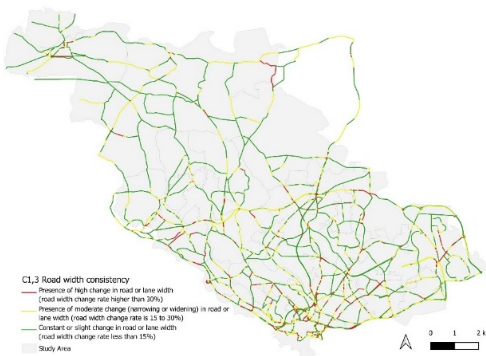
The following figures illustrate the outcomes of the evaluation conducted on the road links, considering the measurement variables within the subcomponents of the corresponding index components.



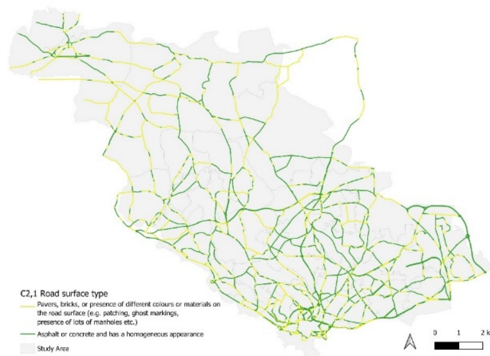
C1,1 Horizontal curvature



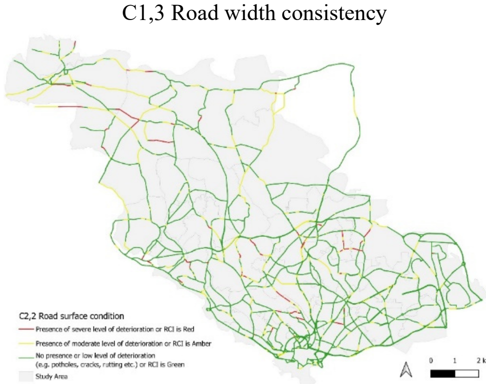
C1,2 Longitudinal gradient



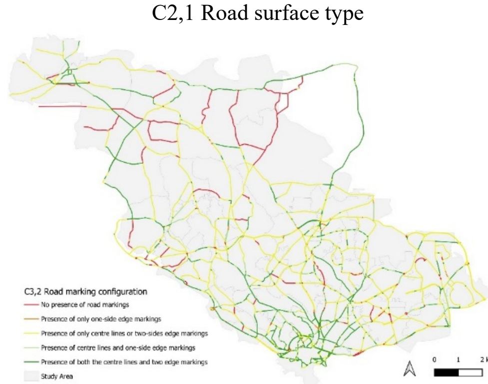
C1,3 Road width consistency



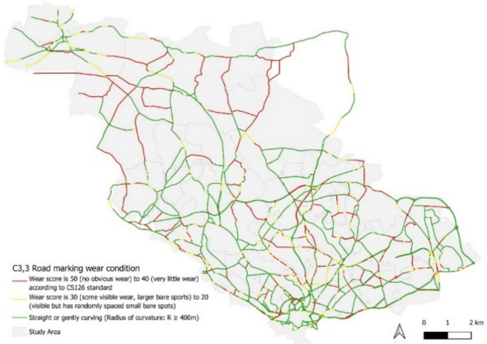
C2,1 Road surface type



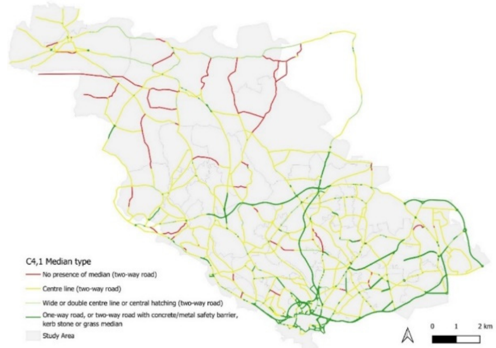
C2,2 Road surface condition



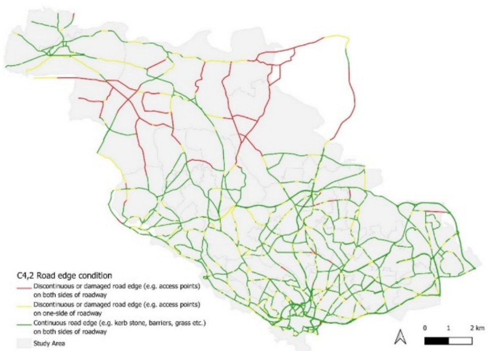
C3,2 Road marking configuration



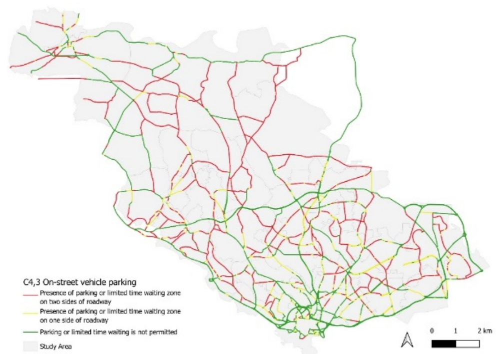
C3,3 Road marking wear condition



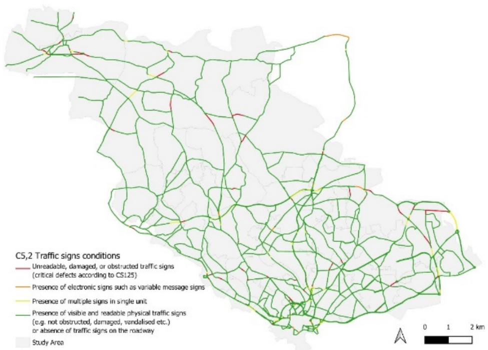
C4,1 Median type



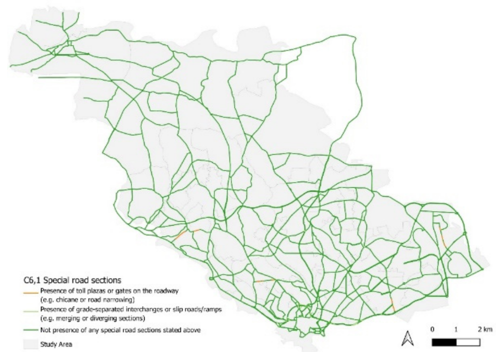
C4,2 Road edge condition



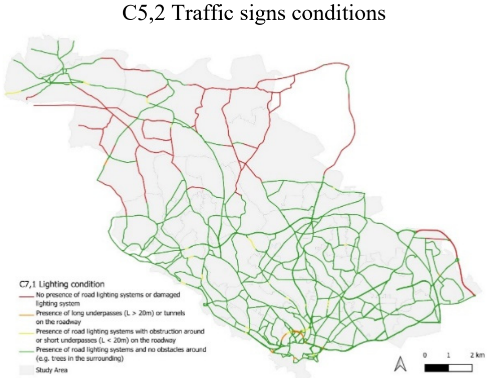
C4,3 On-street vehicle parking



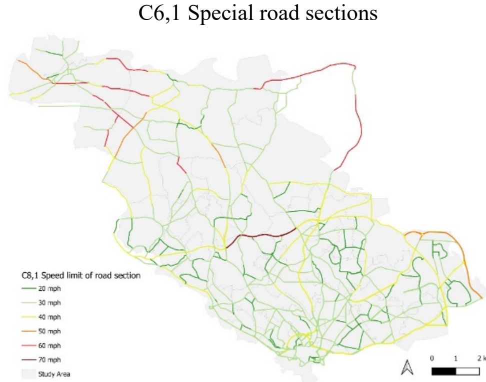
C5,2 Traffic signs conditions



C6,1 Special road sections



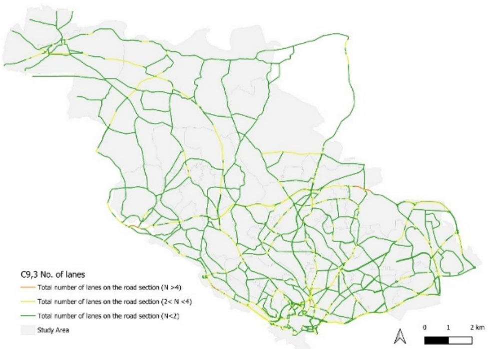
C7,1 Lighting condition



C8,1 Speed limit of road section

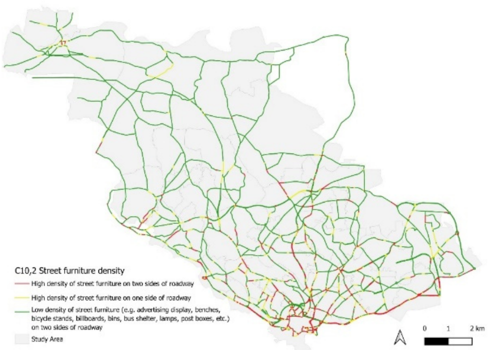
C9,1 Road access

C9,2 Counterflow

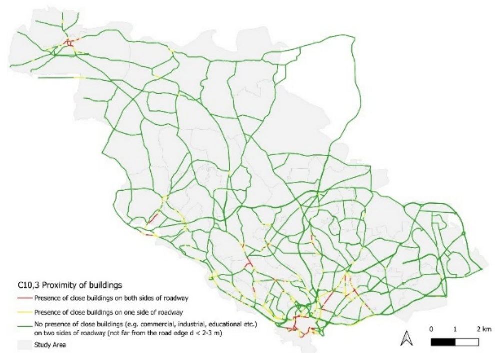


C9,3 No. of lanes

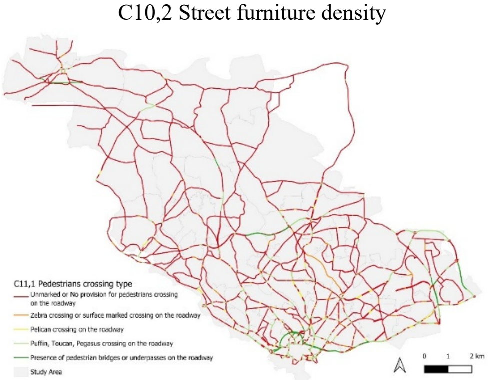
C10,1 Presence of trees



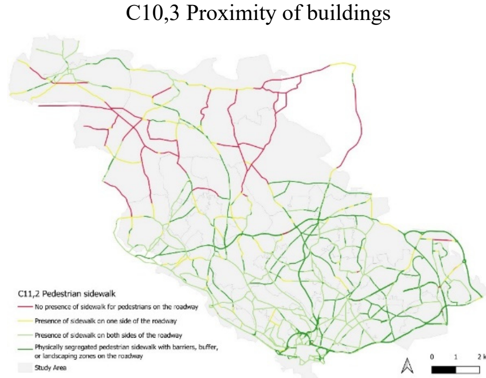
C10,2 Street furniture density



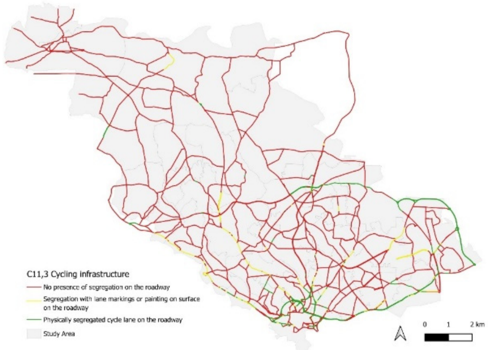
C10,3 Proximity of buildings



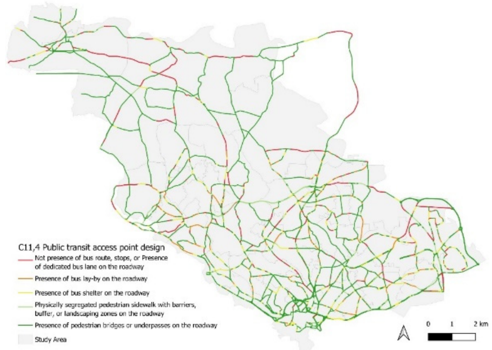
C11,1 Pedestrian crossing type



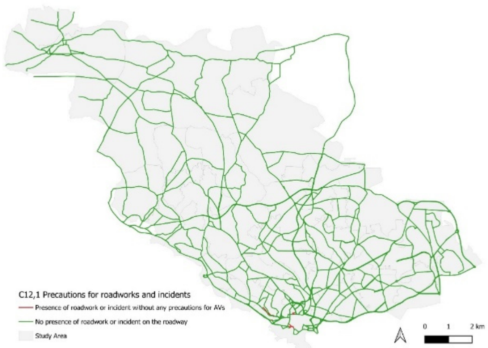
C11,2 Pedestrian sidewalk



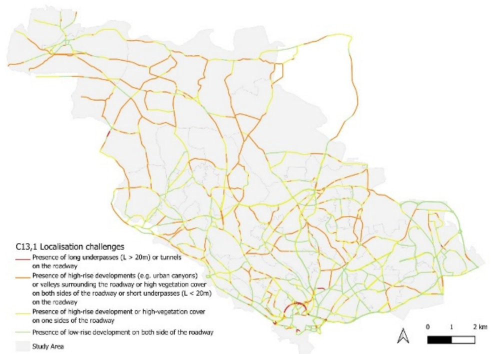
C11,3 Cycling infrastructure



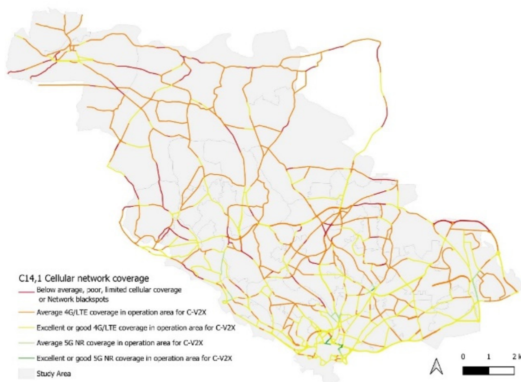
C11,4 Public transit access point design



C12,1 Precautions for Roadworks and Incidents



C13,1 Localisation challenges



C14,2 Cellular network coverage

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