Credible Speed Limit Setting

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The candidate confirms that the work submitted is her own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

Speed is at the core of the problem of road safety, and speed management is a tool for improving road safety. Speed limits that are credible encourage drivers to comply with them, with consequent benefits for road safety. Credible speed limits have been found to be affected by the features surrounding the road by previous research in the Netherlands. However, not a great deal of empirical work has been done evaluating what a credible speed limit is for a given road layout and roadside environment based on motorists' perceptions. This thesis builds a research model to link road environment, speed limit credibility, risk perception and speed limit compliance as a whole. The research presented here aims to verify the model. To do this, three separate experiments are used.

Experiment 1 investigates, using a questionnaire, whether the current national speed limit is credible for a variety of UK road environments, and what the difference is between the speed limit and the chosen, self-reported, driving speed. The survey results reveal that road layout and roadside environment affect the intrinsic perception of the appropriate speed and speed limit. Chosen speed limit and chosen speed are not identical in terms of compliance, but are correlated.

Experiment 2 provides various measurements of credible speed limits, and examines how to set more credible speed limits in order to improve driver compliance. A picture questionnaire, a driving simulator in automated conditions, and manual driving in a simulator are used for measurement. The experiment investigates how the layout of single carriageway roads and roadside environmental factors affect speed limit credibility, subjective risk perception and compliance with speed limits. Five indicators: the most common choice of speed limit by drivers; the highest credible rating score value; indication of comfort with speed in automated driving; risk rating in the range from feeling safe to very safe; arousal indicated by skin conductance, are used to evaluate a credible speed limit for a given road layout, which is used to define a credible speed limit. The method used for setting credible speed limits can be applied to other types of roads. The study develops the relationship between speed limit credibility, risk perception, and compliance with the speed limit.

Experiment 3 investigates how road warning signs affect perception (credibility, safety and necessity) and driving behaviour for a given road layout and roadside environment, using a questionnaire and driving simulator. The study finds that road warning signs affect driving speed, specifically by slowing down the driving speed and reducing the proportion of time spent driving in excess of the speed limit.

Combining the results of the three experiments, the research confirms that speed limit credibility is useful for speed management. The findings indicate that there exists a credible speed limit for each specific type of road that would lead to better speed management. As the credibility of the speed limit increases, drivers become more compliant with it. In terms of practical implications for road design, the research provides advice to local highway authorities on matching credible speed limits to rural single carriageway infrastructure in order to provide safe conditions for all road users. Speed limit compliance can be reinforced by using the most effective combination of warning and speed signs.

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Chapter 1 Introduction

1.1 Research background

"*Ultimately the goal for speed management policies must be for drivers to take responsibility for their own actions and abide by speed limits. For limits to be respected they not only need to be appropriate for the road, but also to be understood. Inappropriate limits are often ignored and make drivers less willing to comply with the system generally*" (DETR, 2000)

1.1.1 Speed as a risk factor

Speed is an important risk factor in road safety, influencing both road crash risk and the severity of injuries caused by crashes, more than almost any other known risk factor (WHO, 2008; Elvik et al., 2009). Vehicle speed control can prevent crashes, reduce their impact, and lessen the severity of injuries sustained by the victims when they do occur (WHO, 2008). There is a need to ensure driving speeds which allow people to survive if a crash does happen. A proposed safe speed to lower the fatality rate in collisions between pedestrians and cars would be 30km/h, 50km/h for side impacts at junctions, and 70km/h for head-on crashes (Richards, 2010), meaning it would be necessary to reduce speed limits to 30km/h wherever pedestrians are not restricted from using roads. More details are given in the literature review. Actually, injury severity is directly dependent on the change in velocity during the crash, more especially the pre-crash speed (O'Day and Flora, 1982). The relationship between impact speed and risk of fatality can be used to derive rules for safer speed limits that minimise fatality risks. This would reduce the number of speed-related crashes and their severity, while also bringing benefit for economic productivity (KiwiRAP, 2010).

Speed management can limit the negative adverse effects of inappropriate speed in the transport system (OECD, 2006). Setting and enforcing speed limits are two of the most effective measures for reducing road traffic injuries (WHO, 2008). Achieving compliance with the speed limit is, however, a separate issue (Department for Transport, 2013a).

1.1.2 Speed management

Speed management can be defined as a set of measures to limit the negative effects of excessive or inappropriate speed (exceeding speed limits or not matching the driving conditions) in the transport system (OECD, 2006). There are a range of measures to address speed management, including enforcement, engineering, education and publicity, depending on the prevailing circumstances. Department for Transport (2013a) stated that:

> "*Speed management actions is to deliver a balance between safety objectives for all road users and mobility objectives to ensure efficient travel, as well as environmental and community outcomes. So every effort should be made to achieve an appropriate balance between actual vehicle speeds, speed limits, road design and other measures. This balance may be delivered by introducing one or more speed management measures in conjunction with the new speed limits, and/or as part of an overall route safety strategy*. "

Effective speed management involves many components designed to work together to encourage, help and require road users to adopt appropriate speeds (Department for Transport, 2013a). To achieve wide public acceptance of enforcement, speed limits need to be set appropriately. Speed enforcement and sanctions are always needed to ensure compliance with speed limits (WHO, 2008) because some drivers will always be non-compliant. There should be a focus on setting credible speed limits in order to improve effective speed management. Traffic calming is another widely-used measure for speed management. This consists of physical road design features being implemented with horizontal and vertical alignment on lower speed roads, improving safety for pedestrians and cyclists. Other traffic calming measures on higher speed roads include speed enforcement and education.

1.1.3 Vision Zero and Safe System

The Safe System is a complex, dynamic interaction of various layers, actors and activities. Humans, vehicles, speed, road layouts and roadside environments are the factors used in the design and operation of road transport systems, as shown in the centre of Figure 1-1. Speed management is an important part of the Safe System. The Safe System aims to reduce the number of crashes and the severity of injury by reducing crash forces to survivable levels through an interaction of safer speeds, safer roads and roadsides and safer vehicles, which is an appropriate approach to guiding road safety (Alicandri et al., 2008). Vision Zero focuses on traffic systems, placing responsibility for safety on system design, management and leadership. This is similar to the Netherland's National Sustainable Safety which takes a human-centred approach to engineering, education and enforcement measures (WHO, 2008).

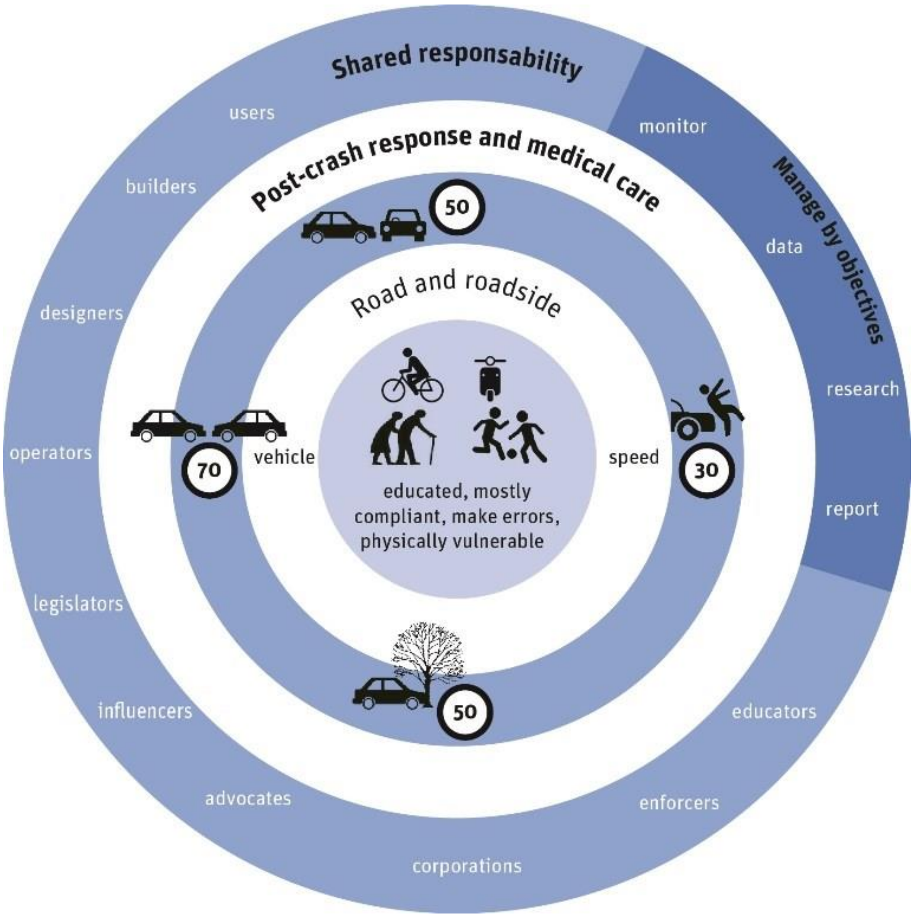


Figure 1-1: Conceptualisation of the safe system
Source: ITF (2016)

Vision Zero emphasises that speed must be limited to a level commensurate with the inherent safety of the road system. Higher speeds can be accepted if roads and vehicles become safer (Tingvall and Haworth, 2000). This brings a human impact focus to the determination of speed limits in road networks. Setting and enforcing appropriate speed limits is an important part of the Safe System, to persuade drivers to choose appropriate speeds. The more widespread the measures, the greater compliance results (WHO, 2008). Therefore, Vision Zero describes the end product of a safe road transport system and an inherently safe system with no serious or fatal injuries, which should be the goal of all speed management.

1.1.4 Self-explaining road and forgiving road

The term 'self-explaining road' (SER) means a road which drivers can easily recognise as requiring specific kinds of driving behaviour. SER design is more identifiable than normal road design, leading to a significantly more uniform mean driving speed, due to the road characteristics being an important determinant of homogeneity in driving speed (Houtenbos et al., 2011).

The term 'forgiving road' refers to a road the components of which have been improved that any error has less chance of causing fatalities. Forgiving road aims to lay out the road that driving errors are not immediately punished by serious injuries. Human errors are inevitable, and human beings are vulnerable. If human-error related accidents are relatively high, a system based on environmental or mechanical factors can compensate for road users' behaviour so as to avoid severe or fatal outcomes. Effort is needed to prevent human error through the design of more error-tolerant systems (Lenne et al., 2004). For example, a rumble strip along the road or a wide road shoulder creates an opportunity to mitigate driving errors and leads to crashes which are more survivable for everyone (La Torre et al., 2012). Roads that guide and inform drivers of what is coming up, e.g. intersections, can minimise crashes, even when things go wrong. Both SERs and forgiving roads aim to achieve driver self-compliance with speed limits, which is the best way to ensure that crash outcomes are not fatal or serious (Houtenbos et al., 2011; SWOV, 2012a). They also take into consideration the nature of information processing and human perception (Ihs and Linder, 2012).

1.2 Research focus

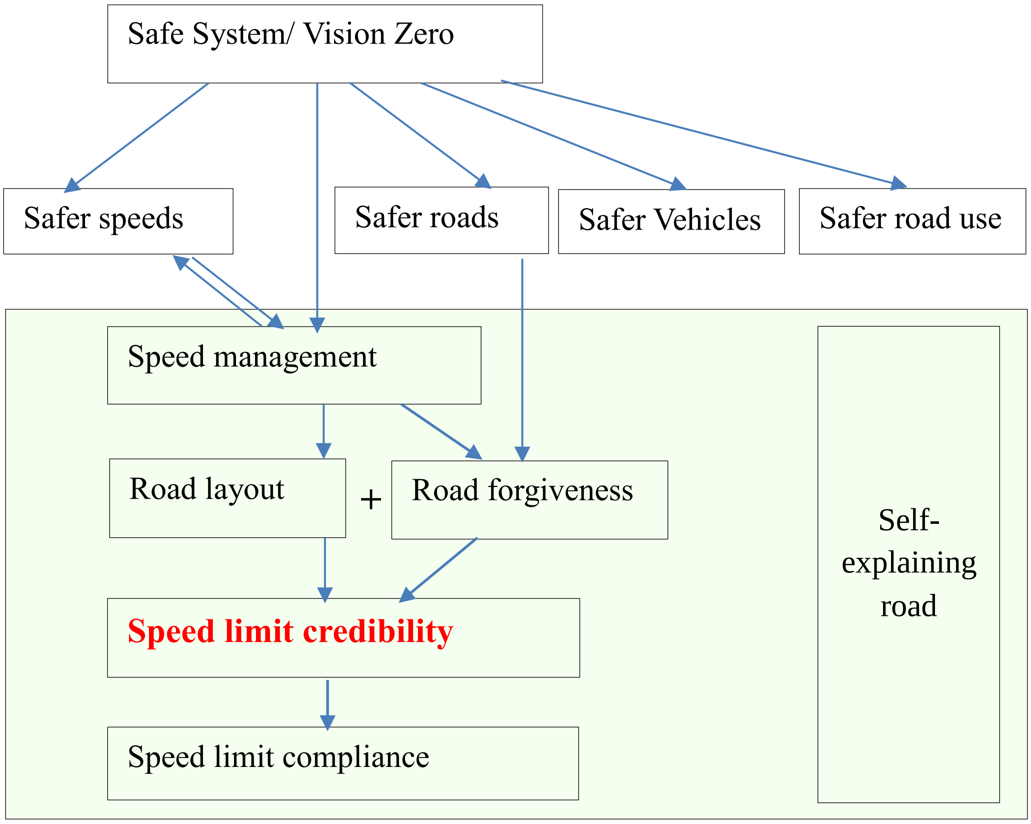


Figure 1-2: Research background and focus

Figure 1-2 shows the research background, and how the Safe System and credible speed limits are related. Based on Safe System principles, this thesis focuses on setting credible speed limits that encourage compliance for better speed management, and achieving forgiving roads where crash forces are survivable for most people. Setting a credible speed limit is a core element of the thesis, which addresses a knowledge gap in the road safety field. The implementation measurements are depicted by the vertical arrows. Vision Zero/Safe System has a long-term goal for road traffic systems which is ultimately to be free from death and serious injury through the interaction of safe speeds, safe roads and roadsides and safe vehicles (PACTS, 2015). This target can be achieved in part by effective speed management. Speed management is a central part of a safe system, which can be manipulated by providing a more (or less) forgiving road layout. A credible speed limit is one that matches the road characteristics and is acceptable for most road users. Forgiving road layouts can be used to make speed limits more credible, and this can be measured by specific indicators. The output of credible speed limits would be speed limit compliance. Obtaining speed limit compliance by drivers is a crucial element in speed management. Thus, road design should be clear and intuitive and in accordance with the speed limit. Credible speed limit is one component of self-explaining roads.

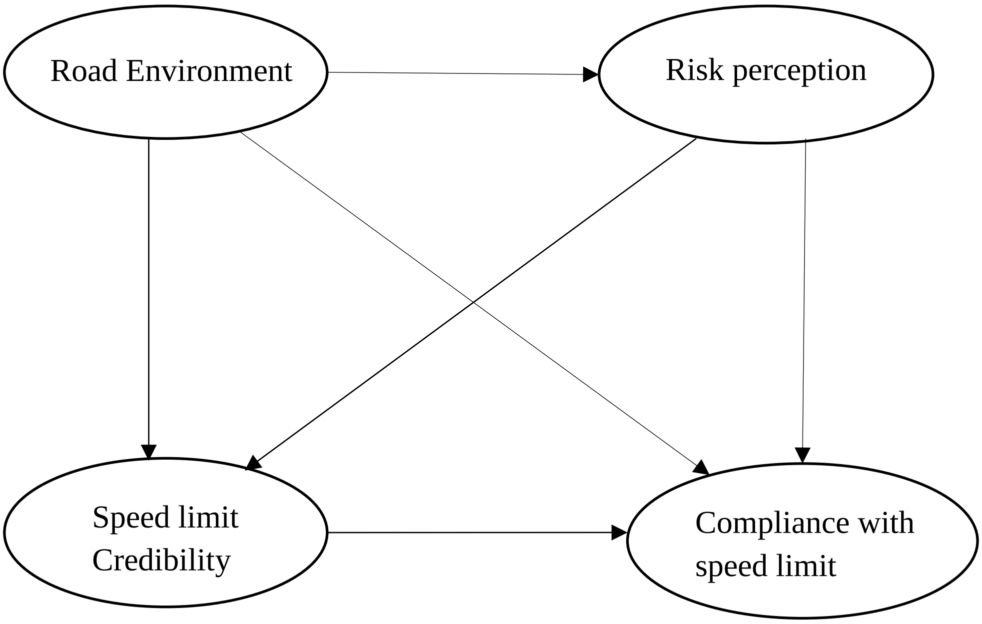


Figure 1-3: Research scope conceptual model

In order to investigate the relationship between credible speed limits and speed limit compliance for a given road layout and roadside environment, the research builds a conceptual model linking road environment, risk perception, speed limit credibility and compliance with the speed limit (Figure 1-3). Each factor needs to be supported by various indicators. There is a knowledge gap concerning the relationship between the factors, so links need to be built between each pair of factors. The model needs to be built step-by-step, as described in the following chapters.

1.3 Structure of the thesis

Chapter 1 gives an introduction to road safety issues caused by speed. Speed limits and speed management should provide effective measures to reduce risk. Self-explaining roads and forgiving roads can achieve the Vision Zero and Safe System strategies.

Chapter 2 is the literature review, which provides evidence of the relationship between speed, speed limits and accidents. It discusses various factors affecting credible speed limits, risk perception and compliance with speed limits. As such, the literature review focuses on three main variables from previous studies and provides a definition of each. Finally, it reveals the gaps in previous literature. The research questions are built to fill the gaps.

Chapter 3 covers Experiment 1, which explores the relationship between speed limit credibility and compliance with speed limits, using a questionnaire study methodology. The road layouts and the roadside environments are based on current UK roads, including motorways, rural single carriageways and urban roads.

Chapter 4 starts with a justification of the methodology used in Experiment 2, which focuses on the measurement of three variables, speed limit credibility, risk perception and compliance with speed limits. Both subjective and objective measurements are used. Experiment 2 investigates road layout factors affecting these three factors, focusing on the road layout and the roadside environment of rural single carriageways using synthetic photos, automated driving conditions and manual driving.

Chapter 5 investigates the relationship between speed limit credibility, subjective risk perception and compliance with speed limits, using a multilevel regression model and logistic regression model.

Chapter 6 uses a two-class classification method to predict driving behaviour using the perception/attitude results from Experiment 2.

Chapter 7 covers Experiment 3, which tests road warning signs and their effect on credible speed limit. Based on the research results, it is possible to determine and apply the best measurement tools for persuading drivers to adapt to the speed limit. It provides recommendations for road sign management strategies for various road types.

Chapter 8 summarises, draws conclusions and suggests the expected contribution of this research.

Chapter 2 Literature review

2.1 Structure of the literature review

Given the proposed conceptual model, this literature review focuses on the factors identified and the relationships between them. It is structured by each major factor. By way of the research background, the role of speed in risk and the purpose of speed limits are discussed. As speed is the main risk factor in road safety (Elvik et al., 2009), the relationship between speed and accident risk is reviewed. Speed variation also plays an important role in road accidents, and the relationship between speed variation and risk of fatality is reviewed. Section 2.2 discusses the literature on the close relationships between speed, speed limits and road safety. Section 2.3 focuses on speed limit setting, based on existing evidence of current speed limit setting. Sections 2.4 to 2.7 review the literature with the aim of developing a comprehensive understanding of credible speed limits, compliance with speed limits, risk perception and road layout and roadside environment, leading to the choice of road layout and roadside environment in the following experiments. Section 2.8 presents conclusions and reveals the gaps in the current research. Section 2.9 outlines the research aim and objectives and Section 2.10 highlights the research questions which address the knowledge gap.

2.2 Theoretical evidence of speed, speed limit, and road safety

2.2.1 Why do we set speed limits?

There are two general rules about why speed limits are set, obtained from Finch et al. (1994). Firstly, a change in the speed limit results in a change in average speed, which is roughly 1/4 of the value of the change in the limit. Secondly, small changes in speed limits are proportionately more effective at changing average speeds than substantial changes (Taylor et al., 2000; Finch et al., 1994). Following traffic law, speed limits should reflect an appropriate safe speed under normal conditions.

Speed limits can enhance road safety in two main ways. Firstly, speed limits are effective tools for speed management and regulating the maximum speed, especially of those who violate speed limit rules (OECD, 2006; Elvik, 2012). They aim to establish an upper bound of speed on the road and provide a regulatory function for enforcement and sanctions for drivers who exceed the limit, endangering others. Secondly, the speed limit is a key element of road safety, reducing the risk imposed by drivers' speed choices and reducing speed distribution and potential vehicle conflicts. The speed limit provides information to drivers about the type of road environment and makes the public aware of traffic speeds, affecting the choice of appropriate speed in the prevailing circumstances. Speed limits should be evidence-led and self-explaining and seek to reinforce motorists' assessments of a safe speed of travel (Department for Transport, 2013a). If the speed limit is reasonable, it should encourage self-compliance.

Speed limits must be matched to the characteristics of the road and the surrounding environment. There should be a clear difference between speed limits on different road types. Considering that higher speeds lead to an increase in accident severity, adverse environmental impacts and energy consumption, it is not advisable to set the speed limit too high (OECD, 2006). Therefore, speed limits are the basis for guiding the desired and appropriate speed, depending on various factors including road function, traffic composition, type of potential conflicts, design characteristics, etc. (Department for Transport, 2013a).

2.2.2 Speed impact on road safety

The power model

Nilsson's power model was first published in 1981. Sweden changed from left to right hand side traffic in 1967, followed by speed limit changes in rural areas, and a speed limit increase on motorways. The result of these changes provided the evidence for the power model. The power model describes the relationship between speed and road safety, which was empirically derived based on speed changes and crash effects resulting from a large number of rural speed limit changes rather than urban speed limit changes (Nilsson, 1982). The equation is used to predict the safety effect of speed limit changes for speed management.

To be specific, the increases in fatal crashes (those resulting in death), serious casualty crashes (those resulting in serious injury) and casualty crashes (those resulting in any injury) are each related to the 4th, 3rd and 2nd powers of the increase in mean traffic speed, respectively. Another explanation of the power model is that a 1% increase in speed results in approximately a 2% change in the injury crash rate, a 3% change in the severe crash rate, and a 4% change in the fatal crash rate (Nilsson, 2004). The relationship is widely used in OECD countries to estimate the effect of speed reduction on accident reduction, as is shown in Figure 2-1. The increases in fatalities, serious casualties and total casualties each include a component related to the 8th, 6th and 4th power of the increase in mean speed. The equations referring to the various levels of accidents are:

Number of fatal accidents: $\left(\frac{\text{Speed after}}{\text{Speed before}}\right)^4 * \text{ Fatal accident before}$

Number of fatal and serious injury accidents: $\left(\frac{\text{Speed after}}{\text{Speed before}}\right)^3 * \text{KSI accident before}$

Number of injury accidents (all): $\left(\frac{\text{Speed after}}{\text{Speed before}}\right)^2 * \text{ Injury accident before}$

Number of fatalities:

$$\left(\frac{\text{Speed after}}{\text{Speed before}}\right)^4 * \text{ Fatal accident before} + \left(\frac{\text{Speed after}}{\text{Speed before}}\right)^8 * (\text{Fatal accident victims before} - \text{Fatal accident before})$$

Number of fatal or serious injuries:

$$\left(\frac{\text{Speed after}}{\text{Speed before}}\right)^3 * \text{ KSI accident before} + \left(\frac{\text{Speed after}}{\text{Speed before}}\right)^6 * (\text{KSI accident victims before} - \text{KSI accident before})$$

Number of injured road users (all):

$$\left(\frac{\text{Speed after}}{\text{Speed before}}\right)^2 * \text{ Injury accident before} + \left(\frac{\text{Speed after}}{\text{Speed before}}\right)^4 * (\text{Injury accident victims before} - \text{Injury accident before})$$

Elvik argues however, that each severity of crash needs to be addressed separately rather than cumulatively. Elvik's meta-regression analysis shows that the powers of changes in mean speed need to be raised to estimate changes in road accidents at varying levels of injury severity, compared to Nilsson's power model (Cameron and Elvik, 2010). This is because Nilsson's power model assumes that serious injuries are cumulative with fatalities, rather than modelled separately (Cameron and Elvik, 2010). The model is also not applicable to traffic speed changes on urban arterial roads.

Although the power model has been strongly criticised by various researchers, it reveals the fundamental relationship between changes in speed and changes in road accidents at various levels of injury severity.

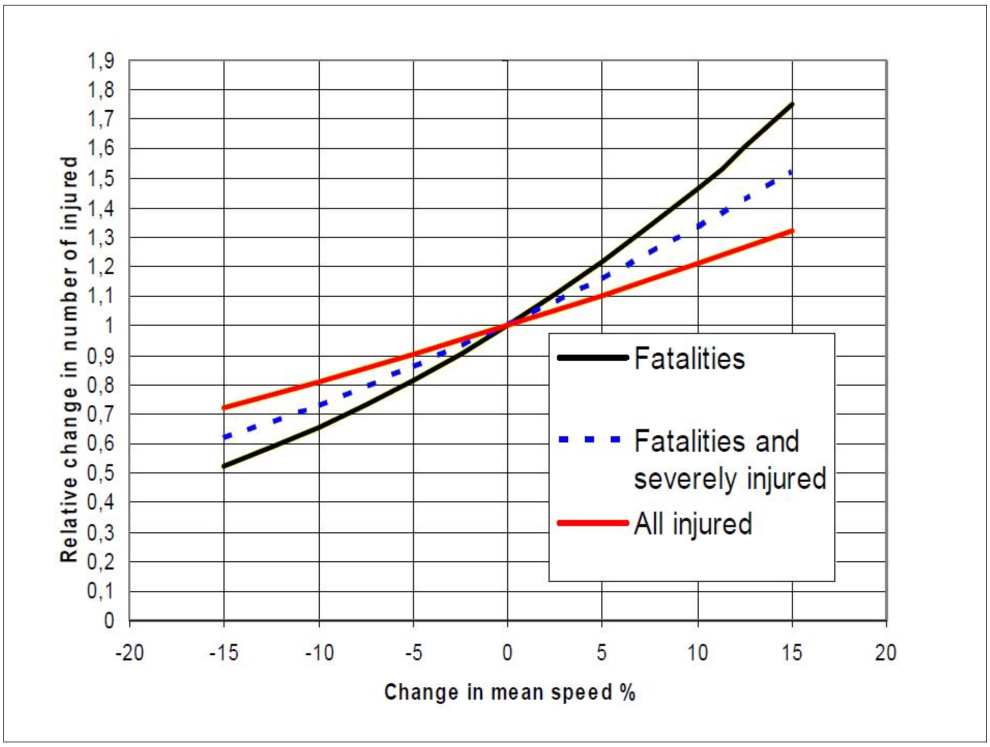
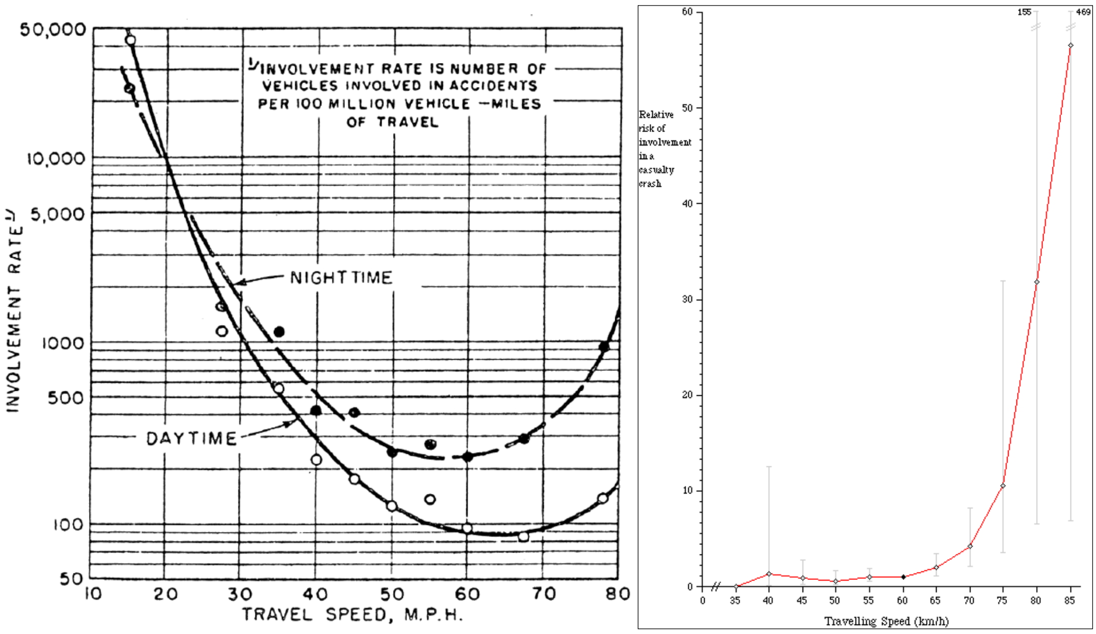


Figure 2-1: Illustration of the Power model and the relationship between percentage change in speed and relative change in the number of injured

Source: WHO (2008)

Speed Variation

Speed variance is an important factor which is a determinant of the risk of involvement in a casualty crash at a given site. Speed variance can mean individual vehicles speeding up or slowing down along a road or traffic travelling at different speeds (fast and slow vehicles) mixing. Solomon (1964) uses a case-control study (an observational study comparing two groups' outcomes on the basis of some supposed causal attribute) including 10,000 cases and 290,000 controls, to find the mean speed/speed dispersion and crash rate of individual vehicles (Figure 2-2 (a)). Specifically, the average speeds along each study section were measured by a driver-observer-recorder team, moving with the normal flow of traffic and recording the speed at periodic intervals (Solomon, 1964). Spot speed observations at selected sites were collected for 290,000 drivers. The speed data obtained were representative of the speed of daily traffic at typical locations on rural highways. The accident data came from reports of 10,000 drivers of vehicles involved in accidents on the 600 miles of rural highways studied. By using the number of accident-involved drivers and the total mileage for each range of speed, accident involvement rates were calculated. The crash risk U-shaped curve shows that drivers with speeds higher or lower than 10km/h above or below the mean speed had an increased crash involvement rate; the lowest crash risk being at 10km/h above the mean speed. However, this value almost reaches the 90th percentile of driving speed. Above the 90th percentile, drivers had a significantly higher risk of crashing as a consequence. A variety of other contributing factors (i.e. vehicle heterogeneity, drivers' lane changing behaviour, number of lanes) also affected the variance of traffic speed (Kweon and Kockelman, 2005). Kloeden et al. (2001); Kloeden et al. (1997); Kloeden et al. (2002) use case-control studies to find speed/speed dispersion and crash rates on urban roads with a 60km/h limit (151 cases, 604 linked controls) and rural 80-120km/h roads (83 cases, 830 linked controls), using accident reconstruction to identify the pre-crash speeds of the case vehicles. Figure 2-2 (b) shows the crashes requiring hospital admission or that were more severe. The involvement risk for a casualty crash increases exponentially as the individual vehicle speed increases above the mean speed.



(a) (b)

Figure 2-2 Accident involvement rate by travel speed: (a) from Solomon (1964) and (b) from Kloeden et.al., (1997) for 60km/h speed zone

Comparing Kloeden's model with Solomon's, shows two different curves. The reason Solomon's U-shape curve has higher risk involvement, injury and property-damage rates at very low speeds is as follows. Firstly, Solomon includes both daytime and night-time data while Kloeden does not calculate night-time road risk. Accident rates are higher at night. Secondly, Solomon only measures crashes that include material damage or are more severe, but Kloeden evaluates only more severe outcomes involving ambulance attendance. Thirdly, Solomon emphases rear-end collision and angled collision, while Kloeden does not. If Solomon's data are disaggregated by crash type, the U-shaped curve is only replicated for head-on collision crashes at night (Shinar, 2007). Fourthly, Solomon lacks characteristics matches between case and control vehicles, while Kloeden links each case vehicle with 10 or more control vehicles. Fifthly, Kloeden evaluates the case vehicles only with free travelling speed through intersections to join traffic streams, while Solomon does not restrict the speed. For these reasons, although the validity of the risk estimates can be questioned, travelling speeds are associated with accident involvement rates.

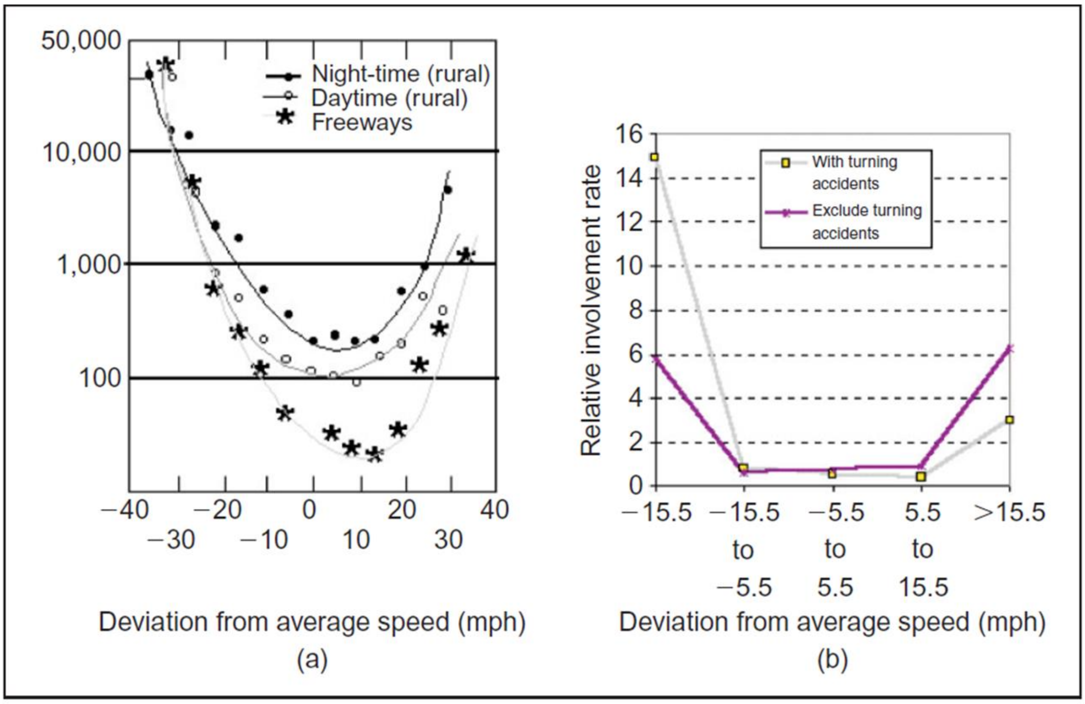


Figure 2-3 Crash involvement rate by deviation from average travel speed: (a) from Solomon, 1964 and Cirillo 1968 and (b) from West and Dunn, 1971

Safety problems are greatly affected by variation from mean speed, because individual drivers make different speed choices. For example, if a driver wishes to drive in an eco-friendly manner, they maintain a constant speed. Due to individual drivers' need to interact with other vehicles and the changing road environment, their speed goes up and down to avoid collisions. Acceleration and deceleration increase the risk of crash involvement. Figure 2-3 shows the expected increase in the risk of accident associated with variation from the mean speed for free-travelling traffic on rural roads. It shows that the risk of crash involvement increases exponentially in relation to the variance of speed. Similar studies for urban roads show an even greater increase in risk in relation to speed variance. West and Dunn (1971) investigate the relationship between speed and crash involvement with a result similar to Solomon's U-shaped relationship. Excluding turning vehicles, the U-shaped curve becomes flattened, and the elevated crash involvement rates at the low end of the speed distribution disappear. The characteristics of the road are responsible for creating the potential for vehicle crashes when driving too slowly for the conditions (Wilmot and Jayadevan, 2006). However, it cannot be judged which study is more correct because each has a different methodology and incomparable datasets. It can be concluded that both travelling speeds and speed deviation are associated with accident involvement rates.

The relationship between impact speed and risk of fatality

Impact speed is an important risk factor for severe and fatal injuries. The impact speed is determined by the weight and speed of both vehicles involved. The following presents the relationship between impact speed and risk of fatality based on datasets from Ashton and Mackay, collected in Birmingham in the 1970s; the On the Spot (OTS) project and police fatal file data 2000-2009; and Rosen and Sander's German In-Depth Accident Study (GIDAS). The data are weighted so they can be directly compared with other studies (Richards, 2010). The various datasets give somewhat different curves.

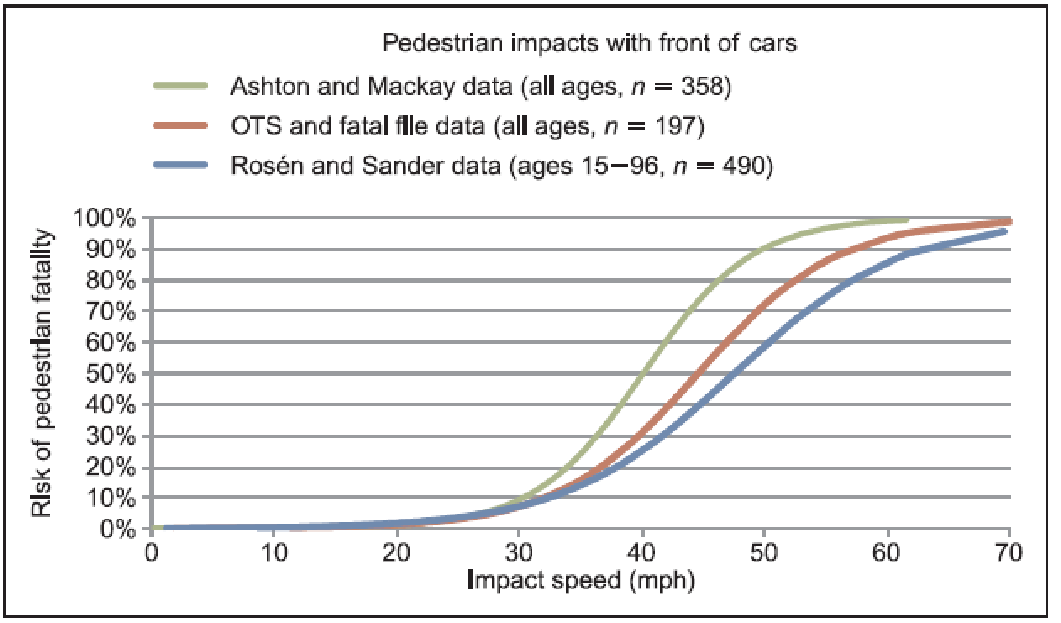


Figure 2-4: Comparison of risk of pedestrian fatality calculated using logistic regression from Ashton and Mackay data, OTS and police fatal file, and Rosen and Sander datasets

Source: Richards (2010)

Figure 2-4 shows a comparison between impact speed and risk of pedestrian fatality using British and German data from in-depth studies, calculated using the logistic regression method. The risk of pedestrian fatality from the OTS and police fatal file dataset shows that an impact speed of 30mph has an approximately 7% fatality risk, and an impact speed of 40mph has an approximately 31% fatality risk (Richards, 2010). With an impact speed 30mph, there is a 90% probability of survival. Comparison between the 1970s Ashton and Mackay data and more recent data shows a decreasing trend in the risk of pedestrian fatality for impact speeds of 30mph or greater. The reason may be that pedestrians are more likely to survive injuries because of improved medical care and improved car design. The Rosen and Sander's dataset does not include any children under 15 or impacts with sports utility vehicles (Richards, 2010). Considering the need to maximise the survivable rate for pedestrians and cyclists, the current speed limit of 30mph on urban road and 20mph in some low-speed zones is reasonable for road safety. Speed limits should be credible in light of the road and road environment and take into account the physical resistance of the human body (OECD, 2006).

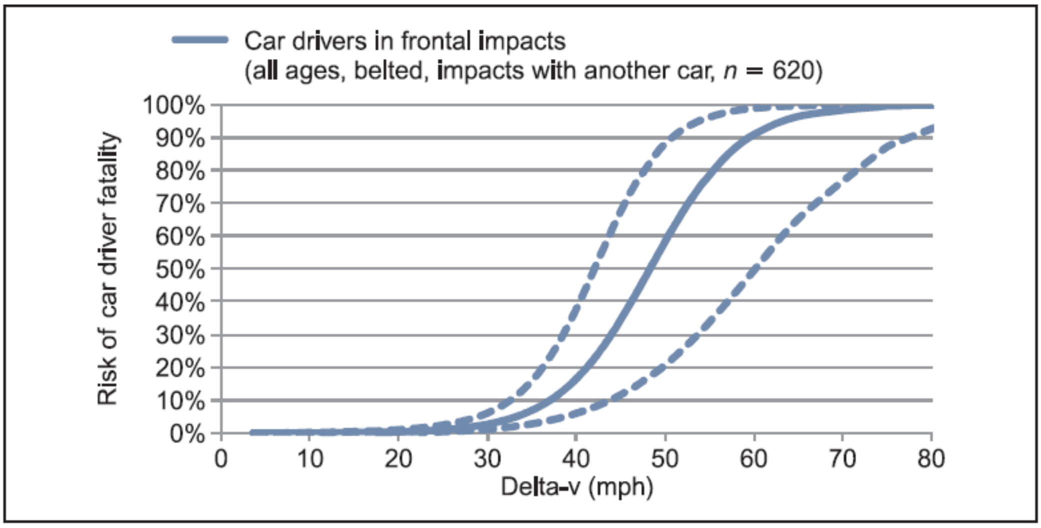


Figure 2-5: Risk of car driver fatality in frontal impacts calculated using logistic regression from the OTS and CCIS dataset.

Source: Richards (2010)

Figure 2-5 shows the risk of car driver fatality in frontal impacts, by the delta-v (V_{after}-V_{before}, a measure of impact severity) of the impact. This figure shows that the risk of car driver fatality in an impact with a delta-v of 30 mph is approximately 3%, at 40 mph the risk is approximately 17%, and at 50 mph the risk is approximately 60%. In addition, driving on motorways require drivers' shorter reaction time and require a longer distance to come to a stop due to a higher speed. The risk of car driver fatality reached almost 100% at Delta-V greater than 60mph. In addition, due to the different types of vehicles such as car-derived vans, dual-purpose vehicles, towing caravans or trailers and HGV driving on the high-speed road have 10mph lower than normal car speed limit, the speed variation between different types of vehicles will cause more potential conflicts.

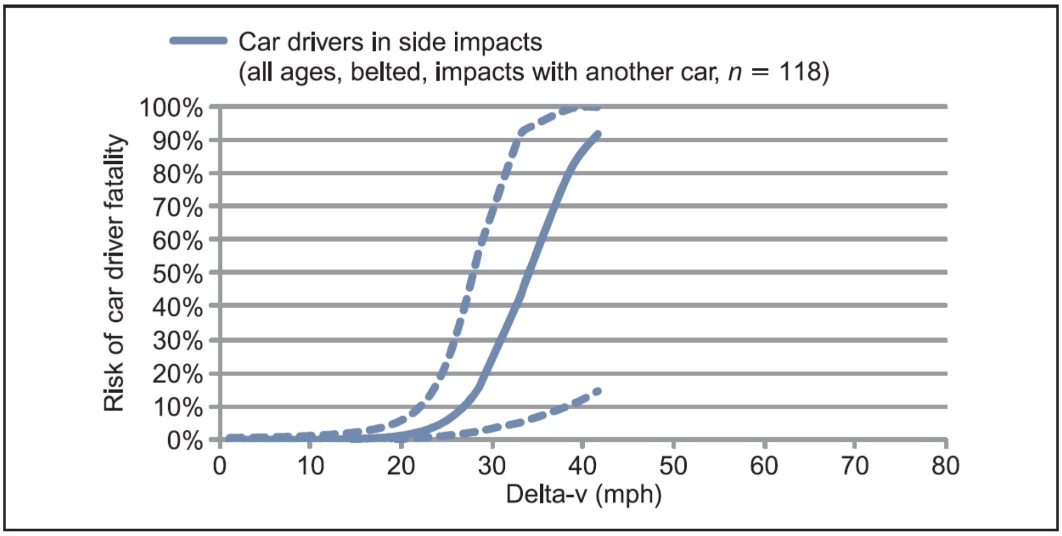


Figure 2-6: Risk of car driver fatality in side impacts calculated using logistic regression from the OTS and CCIS dataset

Source: Richards (2010)

The risk of car driver fatality in side impacts is much higher than in frontal impacts. Side collisions typically occur at intersections. Intersections usually provide a wide range of information signs, and motorists concentrate on identifying which road they should go to. Neuman et al. (2003) show that intersection-related crashes make up more than 30% of all crashes in rural areas and more than half in urban areas. Figure 2-6 shows collision speed and the risk of driver death in side collisions. It is immediately apparent that the risk in side impacts is much higher than frontal impacts. For a side impact with a delta-v of 30mph, the risk of fatality is approximately 25%. For a delta-v of 40mph, the risk of fatality is approximately 85% (Richards, 2010).

The probability of fatality increases exponentially as the impact speed increases, especially the severity of side impact accidents with vehicles emerging from road junctions being higher than head-on collisions. Side collision outcomes are more severe than other types of collision because most vehicles struck from the side do not have the physical space to avoid side intrusion. When crashes occur, although airbags and seatbelts may help, the human body is vulnerable and can only absorb so much force. When the force exceeds the body’s ability to assimilate it, injuries happen, ranging from sprains to fractures, organ damage and even death (Calisi, 2010).

Table 2-1 presents possible long term maximum travel speeds related to infrastructure and traffic. The potential frontal conflict road situation should be directed towards more forgiving roadsides where speeds exceed 70km/h. For pedestrian safety, vehicle speeds should be restricted to 30km/h where there are potential vehicle-pedestrian conflicts.

Table 2-1: The Sustainable Safety proposal for safe speeds, given possible conflicts between road users

Road types combined with allowed road users	**Safe speed**
Roads with possible conflicts between cars and unprotected road users	30km/h
Intersections with possible transverse conflicts between cars	50km/h
Roads with possible frontal conflicts between cars	70km/h
Roads with no possible frontal or transverse conflicts between road users	≥ 100km/h

Source: Tingvall and Haworth (2000)

Most pedestrians survive if they are hit by a car travelling at 30km/h, and most are killed if they are hit by a car travelling at 50km/h, but single carriageway roads in the UK have limits that are typically too high. Currently, the Safe System has not been adopted by the UK government as a whole (Brake, 2015). Most urban and rural roads in the UK have higher speed limits than recommended speed limit by Sustainable Safety. UK speed management cannot meet the requirements of Vision Zero, reducing the speed limit to a safe level and sacrificing mobility functions to have fewer people killed on the roads (Tingvall and Haworth, 2000). Mobility should follow from safety and cannot be achieved at the expense of safety because safety is a more important issue than other functions of the road transport system. In addition, the speed limit cannot be increased or decreased by 5mph, because the UK has not implemented this type of speed limit.

Two aspects of policy are affected by this research. The first is reducing speeds to a level where accidents do not cause serious injuries. Speed limit setting on UK roads should consider safety. The other is providing safer road environments to reduce the risk of serious human injury. Safer road environments can be achieved with forgiving road layouts. Highways England was set up to operate and improve the strategic road network (motorways and major A roads). Improving safety on the basis of Vision Zero may result in changes to road safety policy and the approach taken.

Road safety classified by road classes

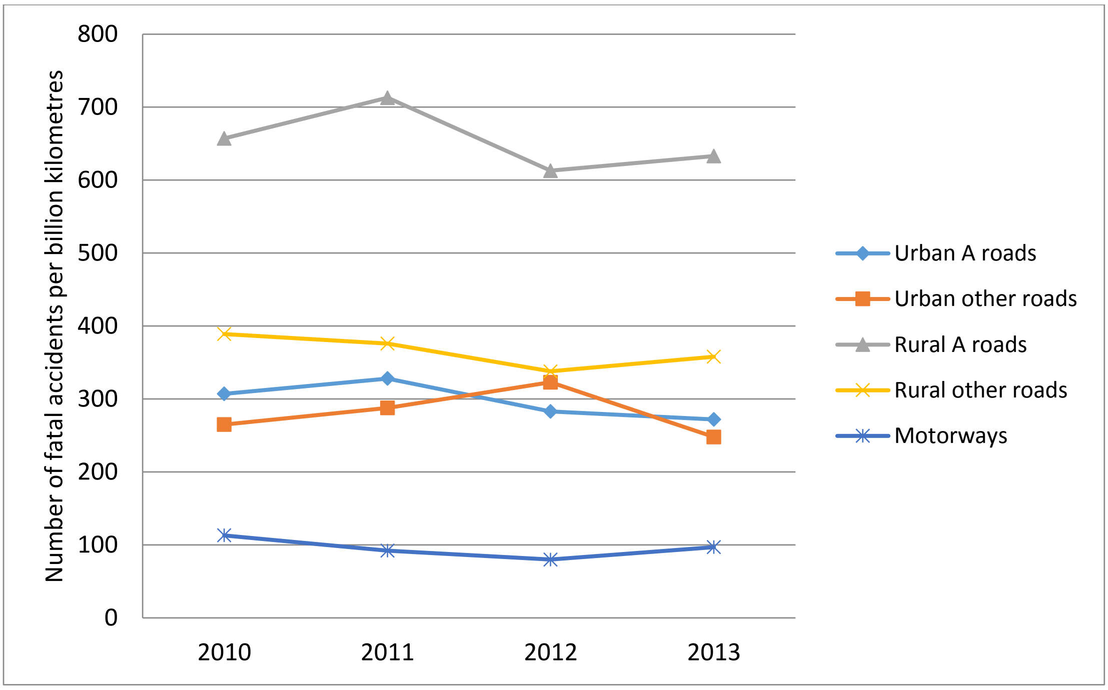


Figure 2-7: Reported number of fatal accidents per billion kilometres by road class in Great Britain (Department for Transport, 2014)

Road safety can be represented by two statistical measurements, crash risk probability and crash severity. The following figures summarise road safety statistics by road class. Figure 2-7 summarises the reported fatal accidents numbers per billion kilometres driven by road class in Great Britain from 2010 to 2013. It shows that rural A roads have a much higher number of fatal accidents than other types of road. Rural roads carry 53% of traffic but account for around two-thirds of road deaths (RRCGB, 2013). Rural roads tend to be less safe than urban roads. There is a need to conform to higher safety requirements for handling higher speeds safely on rural road (Aarts et al., 2009). High speed is a fundamental risk factor on rural roads (Herrstedt, 2006). Reducing speed is one way to reduce outcome severity and enhance road safety on rural roads. Therefore it can be concluded that rural A roads are the most dangerous in Great Britain.

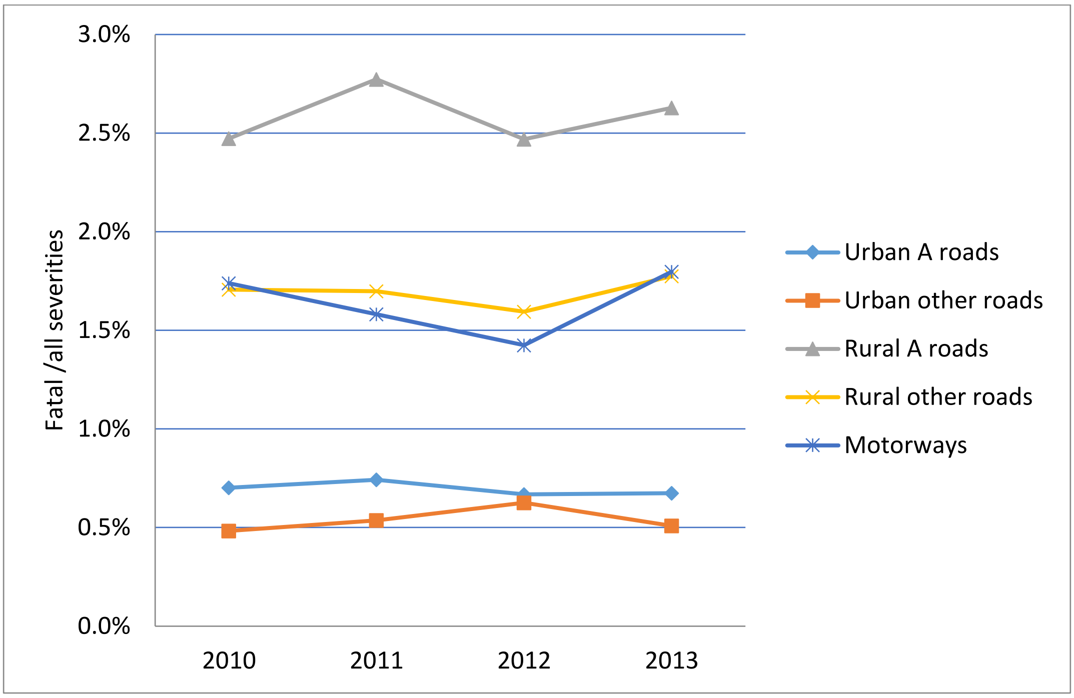


Figure 2-8: Risk of fatal accident given an injury crash (Fatal /all severities) by road class and severity in Great Britain (Department for Transport, 2014)

Figure 2-8 summarises the risk of fatality in crashes by road class in Great Britain from 2010 to 2013. It shows that accidents on rural single carriageways are more severe than on other types of road (Taylor and Barker, 1992; Transport Scotland, 2013). Rural single carriageways have greater severity collisions for both side impacts and head-on impacts. Jamson et al. (2008) show that of all road categories, motorways are twice as safe as dual-carriageways and five times safer than single-carriageways. Levett et al. (2008) show there is less severity for motorway road departure crashes. However, the risk of driver fatality based on delta-v relationship shows that the higher the impact speed, the more severe the collision outcome. Other evidence for the risk of car driver fatality (fatal/all severities) in 2013 shows a higher level on motorways (1.797%) than urban A roads (0.674%), but lower than rural A roads (2.628%). As speeds get higher, crashes result in more serious injury for both vehicle drivers involved (SWOV, 2012c). The relationship between congestion and crashes on arterial roads and motorways shows that more crashes occur on links with higher annual average daily traffic (AADT), which is associated with low flow velocity. Fatal accidents can, of course, still happen on lower speed roads.

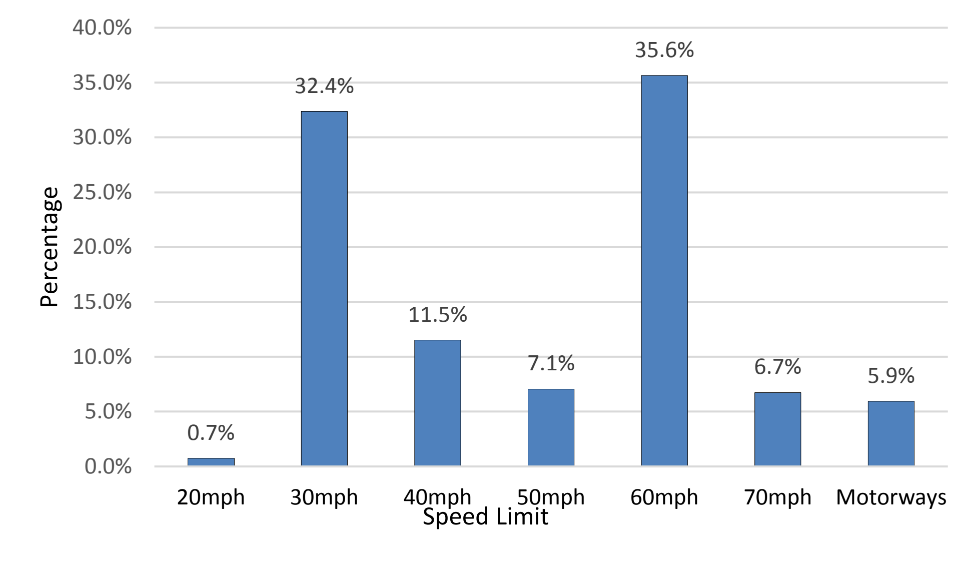


Figure 2-9: Reported Fatal accidents as a percentage of all accidents by speed limit, Great Britain, 2015

Source: RRCGB, 2015, Table RAS10001

Figure 2-9 shows fatal accidents classified by speed limit. While motorways carry around 21% of UK road traffic, they are responsible for only 6% of fatalities. Built-up area roads (urban roads) account for 44.6% of fatalities, but non-built-up area roads (rural roads) are the most dangerous with almost half the country's road deaths. Per mile driven, car drivers and occupants are nearly twice as likely to be killed on rural roads as urban roads.

An innovation is the 2 + 1 lane highway with a median barrier, a road type developed in Sweden, as shown in Figure 2-10 (Bergh and Carlsson, 2001). The 2 + 1 road is a specific category of three-lane road, consisting of two lanes in one direction and one lane in the other, alternating every few kilometres and separated, usually by a steel cable barrier. The reason for using a 2 + 1 road is that the 13m wide road can improve traffic safety, with a 90km/h speed limit in the 1-lane part and a 110km/h speed limit in the 2–lane part. Most people drive at 90km/h on the 1-lane road section and 110km/h on the 2–lane road section. Safety has been shown to improve, with a reduction of 55% in fatal and injury accidents, with the implementation of 2 + 1 roads using a cable barrier (Potts, 2003). The real innovation is the crash barrier between the lanes, which saves approximately 50 to 60 fatalities per year in Sweden.

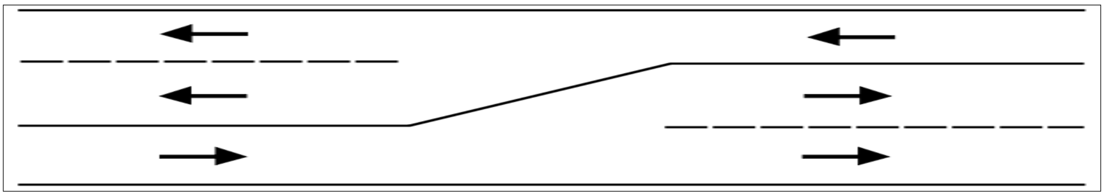


Figure 2-10: Sweden “2+1” road with cable barrier

It can be concluded that speed is a contributory factor in a large number of accidents. Traffic speed significantly affects all the important consequences of road transport, such as accidents, environmental impact, time and vehicle operating costs (Kallberg and Toivanen, 1998). The general rule obtained from Finch et al. (1994) is that a 1mph change in the average traffic speed is associated with a 5% change in injury accidents. Driving at a higher speed means limited time to identify and react to what is happening, thus causing accidents. Speed is a central factor in fatalities, the greater the speed the greater the likelihood of death (Nilsson, 2004; Richards, 2010). Higher speed is associated with more accidents and more severe outcomes. Taylor et al. (2000) show that reducing the speed of the fastest drivers brings greater accident benefit than reducing the overall average speed of all drivers, especially on urban roads. Therefore, speed management strategies not only need to control the distribution of driving speed but also the proportion of excess speeding behaviour.

The relationship between speed and crash frequency

Figure 2-11 shows the speed distribution of vehicles involved in casualty crashes on 60km/h roads, based on 151 cases (Kloeden et al., 1997). Driving speed and crash frequency are closely related. Although lower speed crashes have a much higher frequency than high-speed crashes, most are survivable, on lower speed roads, based on the impact speed and risk of fatality curve. Higher speeds mean a lower number of crashes but a higher risk of fatality. The higher the collision speed, the more serious the consequences in terms of injury and material damage. Although vehicles become ever better equipped to absorb the energy released in a crash in order to protect the occupants, collision speed is still very important to the crash outcome. Thus, for a given set of road traffic conditions, a reduction in average driving speed and speed variation results in a reduction in the number and severity of accidents. Achieving lower and more even speeds is an effective measure to reduce the number of accidents and mitigate the outcome of collisions (MASTER, 1998).

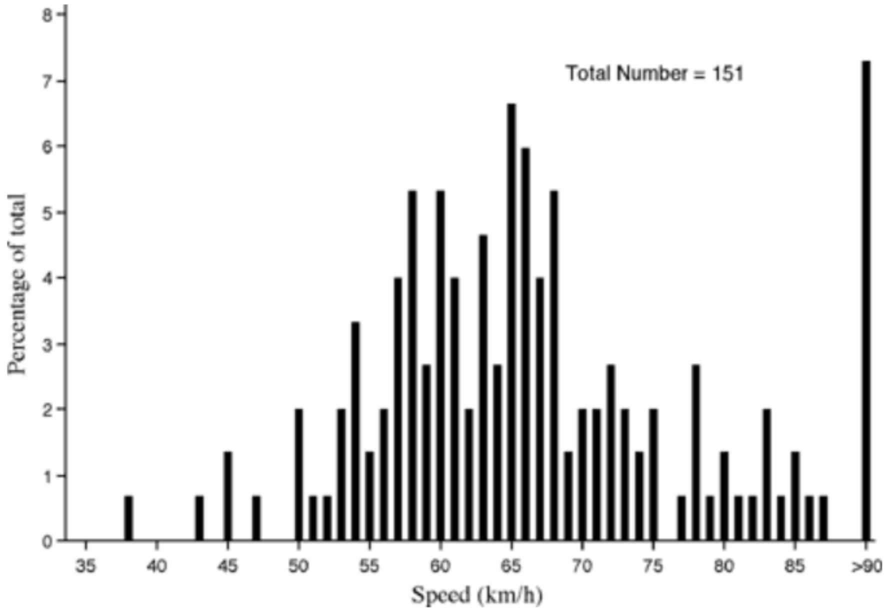


Figure 2-11: Travelling Speed Distribution of Casualty-Crash-Involved Vehicles Source: Kloeden et al. (1997)

2.2.3 Exceeding speed limit impact on road safety

Mosedale and Purdy (2004) show that excessive speed is a contributory factor in twice as many rural road accidents (18%) as urban road accidents (9%). Overtaking and curve negotiation are two of the riskiest manoeuvres on rural roads and can involve excessive or erroneous speed choices (Jamson et al., 2010). Figure 2-12 presents the percentage of cars exceeding the speed limit, by road category, from 2002 to 2012 in Great Britain. Motorists exceed the speed limit most on motorways (Department for Transport, 2013a). In European studies, SafetyNet (2009) and OECD (2006) show that almost half of drivers drive faster than the speed limit, and 10% to 20% exceed the speed limit by more than 10km/h. Reasons for intentional speed limit violations include intention, careless, reckless or in hurry (external non-permanent influences) and aggressive driving (Björklund, 2008; Kanellaidis et al., 1995; Christensen and Amundsen, 2005). Due to the strong relationships between speed, crash risk and crash severity, it can be inferred that most casualties could be prevented if drivers had better compliance with speed limits.

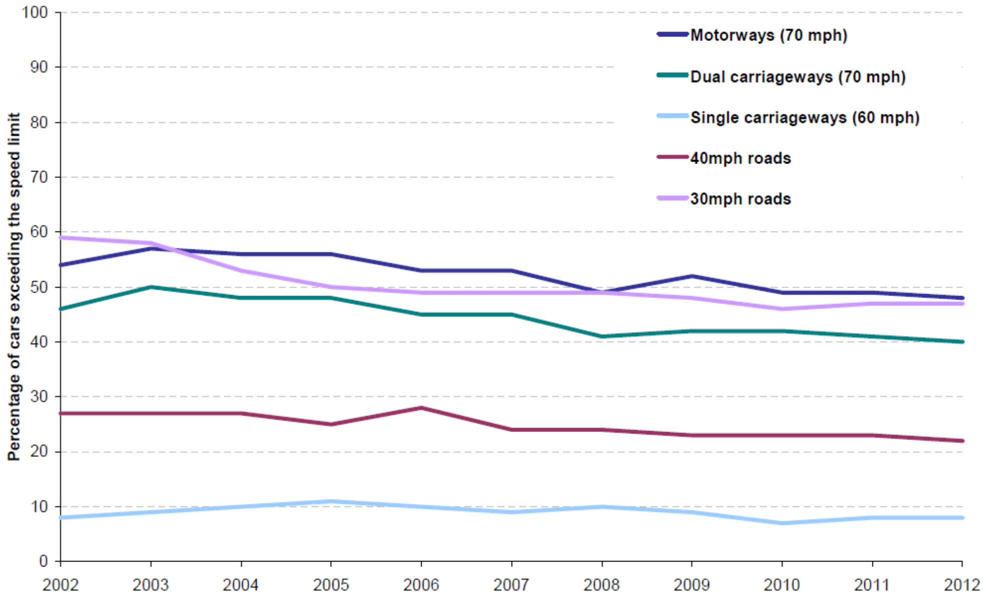


Figure 2-12: Percentage of cars exceeding the speed limit by road category in Great Britain from 2002

Source: Department for Transport (2013b)

There are four reasons drivers unintentionally violate the speed limit. Firstly, motorists can underestimate their driving speed in specific situations or when they don't know the speed limit on that road (SWOV, 2012a). For example, drivers often don't decelerate sufficiently in transitional zones (transfers between adjacent road segments with different curve radii). This situation happens in the transition from high-speed motorways to urban roads and where a long stretch of straight road is followed by a series of bends. Secondly, modern comfortable, quiet cars, in particular road circumstances, can lead to unintentional speeding (SWOV, 2012a). Increasing engine power allows cars to be driven faster. Higher comfort levels mean less discomfort at a high speed. The development of effective crashworthy design criteria and protective equipment installed inside cars increases human tolerance to crashes. Thirdly, drivers may be unaware of speed limit signs or they may be absent (European Road Safety Observatory, 2007). Fourthly, the current UK speed limit lacks credibility, meaning the majority of drivers exceed the speed limit on motorways and dual carriageways (Figure 2-12). There exists a contradiction between road design and speed limits (OECD, 2006). For example, a motorway layout presents a safe environment, and drivers often drive at 80mph unintentionally. Archer et al. (2008) state that the majority of the driving public must perceive limits as legitimate and comply with them voluntarily, otherwise they are likely to be disregarded. The characteristics of roads should be sufficiently informative about the speed limit. In terms of credibility, speed limits can be too low or too high. Speed limits can have high compliance but low credibility, which often occurs on rural single carriageways.

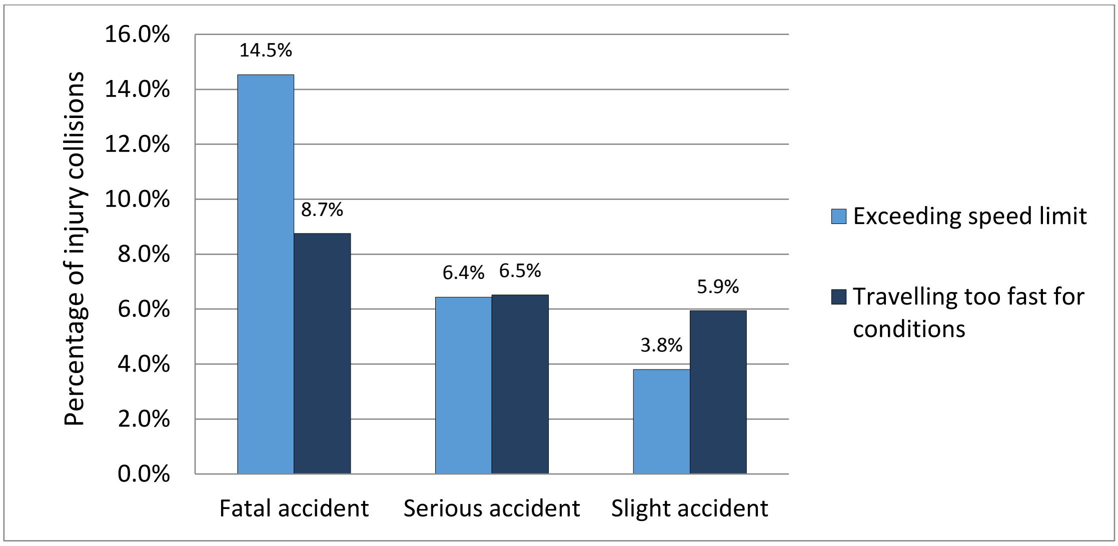


Figure 2-13: Speed as a contributing factor for road safety 2013 Source: STATS19

Speeding, in South Australia, contributes to around 12% of all crashes reported to the police and about one-third of fatal crashes (Kloeden et al., 2001). Two factors contribute to speeding behaviour, exceeding the speed limit and driving too fast for the conditions. Figure 2-13 shows a breakdown of drivers exceeding the posted speed limit and driving too fast for the conditions by severity of accident. Exceeding the speed limit contributes to most fatal accidents, but exceeding posted speed limits is common among drivers for various reasons in US (Sandberg et al., 2006). A recent survey in UK shows that one fifth of motorists think driving 10mph over the speed limit is acceptable (DailyMailReporter, 2011). In terms of exceeding speed limit criteria, drivers caught at speeds up to 10mph over the limit are classed as band A, with band B relating to offences where motorists are clocked at 11-21 mph over the limit. The most serious category of offence is band C, which applies to drivers exceeding the speed limit by more than 21 mph, also called excessive speeding (Pemberton, 2018). The speeding buffer by which a driver is allowed to exceed the speed limit is normally 10% plus 2mph (Pemberton, 2018). Driving too fast for the conditions means exceeding a ‘reasonable standard’ for safe driving. In other words, road conditions are such that even the posted limit is too high (UK Government, 2018). Drivers are required to slow down in the following conditions, wet roads, reduced visibility from fog or mist, uneven roads or loose paving such as gravel, sharp curves, unusual traffic patterns, roadwork areas, and heavy traffic.

Drivers' obeying speed limit regulations and adjusting their speed to the road conditions can improve road safety. To tackle speeding, enforcement can be effective for drivers who intend to exceed the limits but also wish to avoid being punished. If drivers are compliant with speed limits, enforcement measures are not necessary. Therefore, a proper solution would be for speed limits and road characteristics to match. Appropriate road layouts, credible speed limits and speed limit enforcement can work together to prevent intentional and unintentional speeding offences (SWOV, 2012a).

2.2.4 Consequence of speed limit change and road safety

Depending on local conditions, the following speed limit changes have an effect on speed and road accident rates, as explored in previous studies worldwide (Table 2-2). Both speed and crash severity generally decline when limits are lowered. Restricting speed to appropriate levels contributes to a reduction in serious and fatal injuries (Archer et al., 2008) which is the most valuable issue in road safety. Speed limit research only considers the effect of average speed change and accident risk change without considering unobserved personal characteristics or environmental road factors.

Table 2-2: Road speed limit reduction for road safety

Reference	**Country**	**Speed limit change**	**Results for speed change**	**Results for accidents change**
Nilsson (1990)	Sweden	110km/h to 90km/h	Speeds declined by 14km/h	Fatal crashes declined by 21%
Engel (1990)	Denmark	60km/h to 50km/h		Fatal crashes declined by 24% Injury crashes declined by 9%
Peltola (1991)	UK	100km/h to 80km/h	Speeds declined by 4km/h	Crashes declined by 14%
Sliogeris (1992)	Australia	110km/h to 100km/h		Injury crashes declined by 19%
Stuster et al. (1998)	Switzerland	130km/h to 120km/h change on motorways	Speeds declined by 5km/h	Fatalities declined by 12%
Stuster et al. (1998)	Switzerland	100km/h to 80km/h change on rural roads	Speeds declined by 10km/h	Fatalities declined by 6.2%
Engel and Thomsen (1988)	Denmark	60km/h to 50km/h change on built-up areas	Speeds declined by 3-4km/h	Fatalities declined by 24.1%
Scharping (1994)	Germany	60km/h to 50km/h	Crashes declined by 20%	
Parker Jr (1997)	USA	Small rural community roads 55m/h to 45m/h, small urban area roads 35m/h to 25m/h	No significant change in speeds	
Kloeden and McLean (2001)	Australia	110km/h to 100km/h		Casualty crashes declined by 9%
Hoareau et al. (2006)	Australia	60km/h to 50km/h	Mean speeds reduced by 2-3km/h	Serious injury crashes declined by 3% Minor injury crashes declined by 16%

Other external factors also influence speed limit changes, which in turn affect road safety. For example, in response to the 1973 oil crisis, US Congress enacted the

National Maximum Speed Law (NMSL) that created the universal 55mph (89km/h) speed limit. As a series of evaluation studies have shown, the 1973 reduction in the speed limit resulted in reduced fatalities, a fact which may have affected other aspects of driver behaviour. The speed limit was increased to 65mph (105km/h) on certain roads in 1987. Research (Transportation Research Board, 1984) shows that the speed limit increasing from 55mph to 65mph on rural roads led to a 25% to 30% increase in deaths. In 1995, the law was repealed, returning the choice of speed limit to each state (Patterson et al., 2000; Patterson et al., 2002). The full repeal in 1995 led to a further 15% increase in fatalities (Transportation Research Board, 1998). States that raised the speed limit to 70mph saw a 35% rise in fatality level in the four years after 1995. Those that raised it to 75mph saw a 38% rise. It is estimated that these speed limit increases were a key factor in 1,900 extra deaths (Patterson et al., 2002). The NMSL reduced fuel consumption by 0.2% to 1.0%. Rural interstates accounted for 9.5% of the US vehicle-miles-travelled in 1973, and were more fuel-efficient than conventional roads (Transportation Research Board, 1998).

Generally, the research shows that increasing speed limits leads to increasing accident numbers or accident severity, and decreasing the speed limit results in decreasing accident numbers or severity. However, there is one exception to this. Griffin (2014) concludes that increasing the speed limit actually has a positive effect on the number of road accidents. A two-year study shows that increasing speed limits on rural road from 80km/h to 90km/h brings the benefit of decreasing accident numbers. This is due to faster drivers driving slower and more drivers being compliant with the new speed limit. The speed distribution changed in a positive way, with less overtaking caused by a large differences between speeds. However, the report focuses on only one rural Danish road and does not indicate how the accident severity changed. The effect of increasing speed limits on road safety has not been evaluated on UK roads.

2.3 Theoretical evidence of speed limit setting

As speed is the main risk factor, speed limit setting is the main way to strengthen speed management. Speed limit setting is a complex process which needs to consider various factors. The following section introduces the current speed limit setting rules, criteria and procedures in the UK.

2.3.1 Traffic law

UK national speed limits are set out in Schedule 6 of the Road Traffic Regulation Act of 1984 and are summarised in Regulation 124 of the Sept 2007 version of the Highway Code. It should be noted that many factors influence the establishing of speed limits in effective road management. Speed limits are designed for the safety of all road users. The following government consideration list covers the important factors to be considered when speed limits are set for a road (Agent et al., 1998; Department for Transport, 2012):

- history of collisions (accident rate), including frequency, severity, types and causes
- road geometry and engineering (width, sightlines, bends, junctions, access, safety barriers etc.)
- road function (strategic, through traffic, local access etc.)
- the composition of road users (including existing and potential levels of vulnerable road users)
- existing traffic speed
- road environment (rural, level of roadside development, shop frontages, schools etc., impacts on residents)
- visibility restrictions
- pedestrian activity
- roadside development
- location of speed zone
- health criteria perspective, such as noise.

Speed limits can be adjusted based on vehicle type and road conditions to improve road safety. Although new roads can provide improved safety levels, the real challenge is to find an effective way to set and enforce speed limits on the existing road network. Posted speed limits often differentiate between cars and goods vehicles. Speed limits for goods vehicles are consistently slightly below those of cars for a given type of road (Department for Transport, 2013a). The main reason for these lower speed limits is that goods vehicles tend to take longer to slow down than cars travelling at the same speed. As speed limits bear strong implications for enhancing road safety, the feasibility of variable speed limits (i.e. night-time speed limits, school zone speed limits etc.), and motorway dynamic speed limits depending on traffic volumes, are also taken into account. Local governments sometimes impose variable speed limits according to time of day or time of year (OECD, 2006). Combining all these factors, along with previously recommended speed limits and road crash data, highway agencies make a final decision on speed limit setting.

2.3.2 Speed limit setting as a trade-off

Considering the implications for speed management, speed limits are a trade-off between safety, environmental and energy costs, and mobility and economic costs (OECD, 2006). Figure 2-14 shows the relationship between speed and balanced cost on single carriageway rural roads which are generally well within the national 60mph speed limit. As speeds increase, travel costs decrease but accident costs increase. Therefore, the solution adopted here is to identify the mean speed at which the total of the accident and travel costs are minimised (Department for Transport, 2006a). The concept of the optimum speed for a class of road is minimising the total social costs of the impacts of speed. To be specific, it is minimising the total of vehicle operating costs, travel time, road trauma and emissions for cruising speed on residential streets (Cameron, 2001). Therefore, the legal speed limit is a compromise which balances road traffic safety with travel time and mobility to ensure efficient travel and acceptable environmental and community outcomes. Drivers must not drive faster than the legal speed limit for the type of road and type of vehicle.

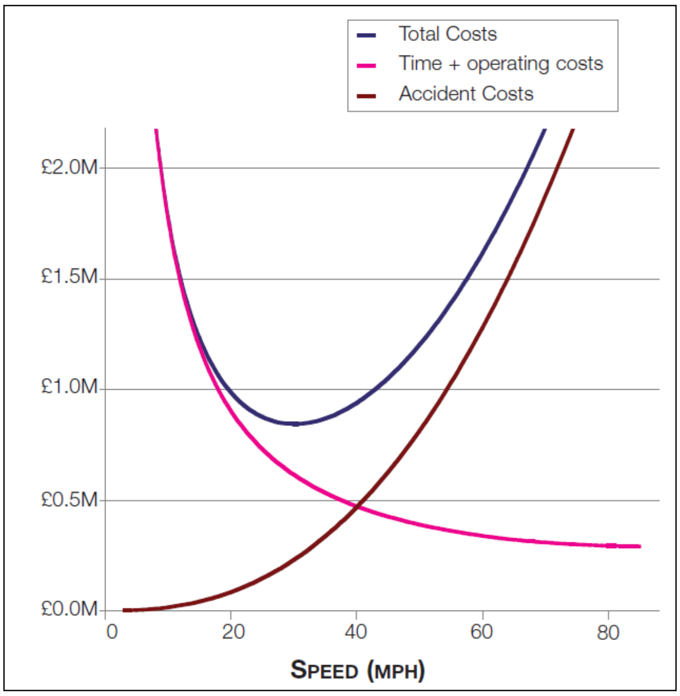


Figure 2-14: Speed and balanced cost

Source: Department for Transport (2006a)

2.3.3 Speed limit setting changed from 85 percentile to mean speed

In the past, 85th percentile speeds have traditionally been used as the basis for setting speed limits (Department for Transport, 2013a). This is the speed that most (85%) drivers are travelling at or below. The 85th percentile speed is adopted by most traffic engineers as the optimum level to set speed limits. Setting speed limits mainly concerns risk relating to infrastructure based on the Safe System approach based on the speed at which crashes are survivable, not fatal or serious, because human life comes before everything else. The 85th percentile speed limit setting approach is no longer viewed as appropriate because it only considers the motorists' perspective, ignoring safety, the environment and pedestrians (Box, 2012). Therefore, for safety considerations, the UK has moved from 85th percentile criteria for speed limit setting to mean speed (Department for Transport, 2013a; OECD, 2006).

2.4 Credibility

This section reviews existing credible speed limit studies as credibility is the most important factor in this research. Road layout and the roadside environment are assumed to be the main factors affecting speed limit credibility. The limitations of the current credibility research are presented.

2.4.1 Definition

SWOV (2012a) report that a credible speed limit is one that matches the image evoked by the road and traffic situation. Goldenbeld and van Schagen (2007) claim that certain specific road and environment combinations influence the credibility of speed limits. They define credibility as the speed limit drivers consider logical or appropriate in light of the characteristics of the road and its immediate surroundings, through specific consistency and continuity of road design. Each road should have a speed limit which is accepted by most drivers.

2.4.2 Road layout and the roadside environment factors affecting speed limit credibility

Credibility research was developed by a small number of Dutch researchers in the last decade. SWOV (2012d) summarises the credibility of a speed limit as being influenced by specific features of the road environment. The road environment refers to road design and road layout based on engineering. Table 2-3 shows the credibility factors based on three studies. van Nes et al. (2007) list five road and road environment characteristics influencing the credibility of speed limits. Road layout features which influence credibility on 80km/h rural roads in the Netherlands are summarised (Goldenbeld and van Schagen, 2007). Differences between characteristics of the road environment, such as the presence or absence of curves, and sight distance and clarity, lead to different perceptions of preferred and safe speed limits. There are large differences between subjects related to age, the degree of sensation seeking, the number of speeding tickets and the part of the country they live in. Subjects are influenced by, more or less, the same road features. Thus, credible speed limits are influenced by characteristics of the road itself and drivers' personalities. Aarts et al. (2009) find five road layout factors influence speed behaviour and credibility. Depending on which speed limit applies, road layout and the roadside environment encourage higher or lower speeds; the authors call them 'accelerators' and 'decelerators'. Accelerators are elements of the road or environment that intuitively elicit higher speeds, while decelerators elicit lower speeds. For example, a wide road is an accelerator, encouraging drivers to drive at higher speeds, whereas a narrow road is a decelerator, encouraging drivers to drive at lower speeds (SWOV, 2012d). Other factors include long tangents, physical speed limits not being present, open roads, clear road environments and smooth road surfaces, all identified as accelerators (SWOV, 2012d). Applying the concept to the UK road environment, credibility should be linked to both road environmental factors and human factors, Further studies should consider the match between road characteristic factors, human factors and speed limit setting.

Table 2-3: Summary of credibility factors based on three studies

	van Nes et al. (2007)	**Goldenbeld and van Schagen (2007)**	**Aarts et al. (2009)**
Road width		✓	✓
Road curve		✓	
Road surface			✓
Road openness			✓
Road marking	✓		
Road view		✓ (view ahead, view to the right, road clarity, buildings, trees on the right)	

Parking facilities	✓		
Pedestrian facilities	✓		
Cyclist facilities	✓		
Physical speed limiters			✓
Sight distance		✓	
Intersection type	✓		
Tangents length			✓

Road layout characteristics related to speed limit safety and credibility are shown in Table 2-4, which lists the criteria for safety features and credibility features for 60km/h, 80km/h, 100km/h and 120km/h speed limits in the Dutch road system. The comparison shows different emphases in terms of road layout and road environment. However, the ideal features from the table mainly come from the common advice from road design guidelines and current knowledge. The evaluation of the credibility features does not come from motorists' speed limit credibility perception, and is not empirically derived.

Table 2-4: Overview of the characteristics associated with safety and credibility per speed limit (Aarts et al., 2009)

Speed limit	**Safety features**	**Credibility features**
60 km/h	Road without vulnerable road users; Obstacle-free zone > 2.5m or forgiving roadside; Parking on the road not allowed; Stopping sight distance 64m.	Pedestrians hardly present or not at all; Cyclists on the road or bicycle lanes present; Parking in the road shoulder; One carriageway without lanes; Non-signalled junctions at grade; Mix of decelerators and accelerators. Medium long straight stretches (max. 60km/h at the end of a stretch); Physical decelerators on road sections and junctions; Rural area with some buildings; Road width ≤ 5m; Lane width ≤ 4m; Even or uneven road surfacing.
80 km/h	No access for slow traffic; Physical separation of driving directions; Obstacle-free zone > 6m or forgiving roadside; (Semi-) hard shoulder;	No pedestrians and cyclists or separate bicycle track; No parking facilities; One or two lanes per driving direction with centre line marking or separator that is impossible or difficult to cross;

	Parking on the road not allowed; Stopping sight distance 105m.	Priority junctions at grade (right of way, traffic lights, roundabout); Mix of accelerators and some decelerators; Short or long straight stretches; Raised junctions or roundabouts; Sparse rural area; Road width ± 7.5m; Lane width ± 2.8m.
100km/h	Physical separation of driving directions; Obstacle-free zone > 10m or forgiving roadside; Hard shoulder; Stopping sight distance 170m. No access for slow traffic; No lateral conflicts; Parking on the road not allowed	One or two lanes per driving direction with centre line marking or separator that is impossible or difficult to cross; Grade separated junctions; Long road straight stretches 463m; Sparse rural area; 18m < road width < 22.0 m; 2.9m < lane width < 3.6m No pedestrians or cyclists; No parking facilities; No physical speed limiters.
120km/h	Physical separation of driving directions; Obstacle-free zone > 13 m or forgiving roadside; Hard shoulder; Stopping sight distance 260m. No access for slow traffic; No lateral conflicts; Parking on the road not allowed	Two or more lanes per driving direction with separator that is impossible to cross; Grade separated junctions; Long road straight stretches 657m; Sparse rural area; 21.6m < road width < 26.4 m; 3.2m < lane width < 3.9m No pedestrians or cyclists; No parking facilities; No physical speed limiters.

The review of each road safety and credibility feature takes into consideration factors such as the road function, the road geometry, the level of adjacent development and the presence of vulnerable road users. The reason for using credible speed limit is that road layout is a direct way of communicating with drivers. SafetyNet (2009) claims that, “the principle of credibility implies that any transition from one speed limit to another must be accompanied by a change in the road or road environment characteristics”. Clearly, speed limits that are exactly supported by the road layout achieve credibility (SWOV, 2012a). Another explanation by Aarts et al. (2009) is that if there are an equal amount of accelerators and decelerators on a road section (a continuous or unbroken length which has one set of similar characteristics) the speed limit is considered credible.

Based on existing credibility studies, no standard tools are available to measure speed limit credibility because it lies in the subjective perception of the situation and is difficult to capture. The concept is only based on a theoretical viewpoint, and has not been made concrete or applicable from a practical viewpoint. Questions can be raised. How do road environment changes affect speed limit credibility? How does driving behaviour change from a non-credible speed limit to a credible one? What do motorists think about speed limit credibility? What is their attitude towards a credible speed limit in a given road environment? What factors affect credibility? These questions are investigated by the following experiments.

2.4.3 Credible speed limits for speed management

Speed limit setting on UK roads should consider safety outcomes. Setting appropriate, safe and credible speed limits is an absolute priority for good speed management policy (ETSC, 2010). Setting credible speed limits can achieve self-explaining roads (SER) which encourage self-compliance (Department for Transport, 2013a). SER can distinguish different road functionalities by means of consistent design elements, such as roadway widths, intersection controls and crossing types (Charlton et al., 2010). Drivers can easily recognise the road based on typical road layouts, and be guided into safe behaviour simply by its design (Theeuwes and Godthelp, 1995). Thus, credible speed limits, with forgiving road layouts and roadside environments, can achieve self-explaining characteristics and lead to better speed management.

Although speed choice and compliance are physically constrained by road layout and roadside environment, speed limit credibility factors need to be taken into consideration. The credibility of a speed limit should have an impact on drivers' choice of speed. SWOV (2012d) say that credible speed limits are supposed to result in drivers obeying (safe) speed limits. The premise for compliance is the credibility of the speed limits. Setting credible speed limits to achieve higher compliance rates can be achieved through modification of the road environment. Previous research into the relationship between speed limit credibility and compliance is limited. Whether speed limit credibility positively affects compliance, and by how much, should be investigated.

2.5 Compliance

Numerous factors influence drivers' compliance with speed limits. This section summarises the main factors that affect choice of speed and speed limit compliance. Road environment credibility, driver factors, dynamic factors, vehicle factors and social factors are all taken into consideration.

2.5.1 Definition

Compliance refers to driving speed behaviour. Generally, if driving speed is less than or equal to a given speed limit, drivers are compliant with that speed limit.

2.5.2 Road layout and the roadside environment factors affecting speed limit compliance

There is some evidence from previous research showing road geometry features related to speed choice. SWOV (2012a) say that road and roadside surrounding features have an effect on speed choice, categorised by cross-section, alignment, and direct road environment, based on Martens et al. (1997) and Aarts and Van Schagen (2006), summarised in Table 2-5.

Table 2-5: Factors affect higher speed behaviour

Cross section		
Number of lanes	more lanes	higher speed
Road width	wider	higher speed
Width of the obstacle-free zone	wider	higher speed
Presence/Absence of emergency lane	present	higher speed
Presence/Absence of cycle track or service road	present	higher speed
Presence/Absence of road marking	present	higher speed
Alignment		
Bendiness of the road (sight length)	fewer bends	higher speed
Sort and state of road surface	level road surface	higher speed
Road environment		
Buildings alongside the road	fewer buildings	higher speed
Vegetation alongside the road	less vegetation	higher speed

Design attributes, such as horizontal and vertical road alignment, the number of lanes, the presence of shoulder lanes etc. have all been studied to evaluate their effect on levels of compliance. Higher speeds are chosen on roads which are wide, with emergency lanes, fewer bends, a smooth surface, clear road markings, fewer buildings and less vegetation (Elliott et al., 2003; Goldenbeld and van Schagen, 2007; SWOV, 2012a). York et al. (2007) state that road width and forward visibility have an impact on speed choice. Research also shows that long straight roads can encourage drivers to speed and take risks (ROSPA, 2010). Road surface features also affect speed choice. A rough road surface reduces speed, and can be seen as a reduction in driver comfort (Martens et al., 1997). Research shows that a smooth road surface followed by a rough surface results in a 5% reduction in mean driving speed, but there is no increase in speed going from a rough surface to a smooth surface (Te Velde, 1985). Thus, physical measures typically force road users to reduce speed better than persuading them to reduce speed voluntarily. Designing a self-explaining road that provides a speed image that accords with the actual speed limit is a preferable solution (MASTER, 1998).

Psychology and the perception of road features have an impact on drivers' speed choices. Previous research investigates the trade-off between keeping speed limit rules and maintaining lane discipline behaviour. For example, features such as edge markings that visually narrow the road, the close proximity of buildings, reduced carriageway widths, obstructions in the carriageway and pedestrian activity, all tend to reduce speed (Kennedy et al., 2005). Drivers may reduce their speed because of 'perceptual narrowing', increasing the width of the central line and edge line or moving the position of edge lines closer to the centre (Jamson et al., 2008). Decreasing visibility distances by increasing the amount of curvature, gradients, buildings or overgrowths may increase drivers' uncertainty about the road and encourage them to slow down.

2.5.3 Driver's demographic characteristics and personality

Apart from the road and road environment characteristics, other factors contribute to drivers' speed choice according to previous literature, including drivers' personality characteristics, vehicle characteristics, driving task difficulty and driving capability. Speed choice is highly affected by demographic characteristics and driver characteristics (Stradling, 2000; French et al., 1993; Stradling et al., 2003). Generally, studies find that male drivers drive faster than female drivers (McKenna et al., 1998). Most older drivers and female drivers tend not to speed because they believe compliance is easy and common and treat speed limit compliance as a moral issue (Elliott, 2001). Research also shows that males who tend to display more aggressive behaviour and sensation-seeking characteristics drive fast for the thrill, and exceed speed limits significantly (Jonah, 1997; Cestac et al., 2011). Male drivers from 21 to 26 years old, who sustain engagement in risky driving behaviours, are more likely to be persistent risky drivers and cause severe injury traffic crashes, than female drivers (Begg and Langley, 2004). This is because females may be more concerned about risk and consider the probability of risk to be greater than males. Drivers' attitudes and motivations play a key role in their choice of speed.

2.5.4 Road dynamic factors

The following evidence shows how road dynamic factors affect speed choice. Road environmental factors, which relate directly to the road or weather conditions, are additional factors in road safety. Generally, individuals tend to be more cautious when using roads in rainy or icy conditions because of the higher perceived risk (Edwards, 1999b; Edwards, 1999a). Decreasing visibility distance is another impetus to reduce driving speed, increasing driver uncertainty, leading to speed reduction. Decreased visibility distance can be achieved through physical measures such as curvature, gradients, buildings etc. (Martens et al., 1997). A driver's choice of speed on a section of road is also dependent on the traffic flow. In a low traffic flow situation, speed can be maintained well, but as the traffic flow increases the road situation changes. There is less possibility for drivers to drive at free-flow speed and other vehicles' rhythms affect the individual driver's speed (Aronsson, 2006). The above road dynamic factors affecting speed choice can be explained by risk compensation and risk homeostasis, which describe drivers' tendencies to react to traffic system changes, including roads, vehicles, weather conditions and their own skills (Summala, 1996). For example, motorists slow down when they come to a sharp bend in the road (Adams, 1993). Thus, speed adaptation can be identified using simple control mechanisms.

2.5.5 Vehicle factors

There are a few vehicle factors affecting drivers' operating speeds, directly or indirectly. A vehicle's mechanical condition and manoeuvring characteristics including its accelerating, decelerating, braking and turning capabilities, affect safe operating speed. On curvy road sections, the body roll angles of cars also affect their safe operating speed. Along with vehicle technology, driving comfort has increased significantly, which affects speed performance (SWOV, 2012a). Drivers may drive in a risky manner if the vehicle they are driving is equipped with the antilock brake system (ABS) (Jonah et al., 2001). Electronic stability control (ESC) is another active safety measure which can prevent skidding and loss of control (Høye, 2011). However, the types of crashes that are typically affected by ESC are often more serious than other crashes, especially for SUVs which have a higher centre of gravity and are therefore more prone to rolling than passenger cars (Khattak and Rocha, 2003). Intelligent Speed Assistance (ISA) vehicle safety technology was developed to help drivers keep to the current speed limit and discourage speeding behaviour (ETSC, 2017).

2.5.6 Social factors

Surrounding vehicles and car passengers also influence drivers' speed behaviour. For instance, peer pressure is one issue that makes young people drive more dangerously. Adapting the vehicle's speed to the speed of other traffic is another important reason for exceeding the speed limit. Empirical data shows that speed choice is strongly influenced by how fast drivers think other drivers are going, with drivers generally overestimating other vehicles' speeds (Haglund and Åberg, 2000). The perceived threat of enforcement, driver motives and attitudes, time pressure and mood are all underlying psychological mechanisms affecting speed choice. Community approaches to reducing traffic speed show that drivers' choice of speed is often based on their subjective assessment and beliefs about the associated costs and benefits rather than research-based knowledge (MASTER, 1998). These factors can work together to determine the mean speed of traffic on a road which reflects 'average' road and traffic conditions.

Social factors for speed choice also make a contribution to speed management. For example, Australian rules state that novice drivers should not carry passengers who are younger than 25 unless supervised. This is because young adults (aged 17-24) are one of the most at-risk groups on the road and the crash risk for drivers is highest in the first 6-12 month of solo driving (CARRS-Q, 2015). This is one reason why Australia continues to expand their lead over the US in terms of safety outcomes (Marshall, 2018).

2.6 Risk perception

As risk comes from the road and the roadside environment, drivers' risk perception in a given road environment needs to be known. This section reviews existing theoretical risk models in order to link risk perception, driving behaviour, emotional feeling and drivers' demographics and personalities.

2.6.1 Definition

There are various definitions of risk perception presented in previous research. McKenna (1982) argues that subjective probabilities are the likelihood of some potential aversive stimulus or threat, to which some avoidance response may have to be made sooner or later. Slovic (1987) uses risk perception to examine subjective risk assessment in evaluating hazardous activities and technologies. Summala (1988) proposes that subjective risk in traffic refers to a driver's own estimate of the subjective probability of a consequential accident. Sjöberg et al. (2004) define risk perception as the subjective assessment of the probability of a specified type of accident happening. Both the probability and the consequences of negative outcomes should be considered.

As perceived risk is influenced by both psychological and social factors (Schmidt, 2004), in this research, risk perception can be defined as the individual's intuitive risk judgement (psychological consciousness) when evaluating potential hazards coming from road layouts and roadside environments. Thus, risk perception is quantifiable and predictable and can be transferred to a scaled value. How people think about and respond to risk needs to be considered from both a perception and behaviour point of view.

2.6.2 Risk perception theoretic model

Risk coming from various road situations brings potential hazard to drivers. Drivers' perceptions of risk changes their behaviour by leading them to take avoidance action based their instinctive tendencies. This is why risk perception is involved in the investigation of driving behaviour and speed limits. To be specific, the traffic risk factors affecting driving behaviour have been debated extensively for many years, with theoretical models including risk homeostasis theory (Wilde, 1982; Wilde, 1994; Wilde, 1998), zero-risk theory (Näätänen and Summala, 1974), threat avoidance model, task-capability interface model and risk allostasis theory (Fuller, 2000). Although zero risk is impossible to achieve in driving situations, drivers balance the risk by optimising their behaviour in accordance with the risk perception theoretical models. These models are used by traffic researchers to show the relationship between risk perception and driving behaviour. However, the models are based at a theoretical level and do not have much direct experimental support.

Wilde's risk homeostasis theory (RHT)

Wilde's risk homeostasis theory (RHT) (Wilde, 1998) is that people adapt their behaviour to a lower or acceptable level of risk so that the number of accidents remains unchanged. Drivers compare the amount of perceived risk with their target risk and try to adjust their behaviour to eliminate discrepancies between them, which indicates that they select a non-zero level of risk with which they feel comfortable. Most motorists seek to optimise the risk behaviour they engage in. However, Elvik et al. (2009) state that the target level of risk has not been measured and it cannot be known how it can be influenced. Risk estimation plays a small role in the process, due to drivers not being able to get feedback about their risk (Hole, 2014). Elvik (2004) proposes that risk homeostasis theory is too vague to explain the specific underlying behavioural mechanisms, which makes empirical testing extremely difficult.

Summala's zero-risk theory

Summala's zero-risk theory proposes that drivers do not behave in such a way as to maintain a preferred level of risk (Summala, 1996). Drivers' risk control is based on maintaining safety margins around themselves, operationalised as the distance they keep from a hazard. For example, motorists avoid experiencing risky situations by controlling their driving speed and their time-to-line crossing (TLC), which refers to the time duration available before crossing any lane boundary, to ensure that they are not subject to experiencing risk (Summala, 1996). However, zero-risk cannot be controllable as there is no zero-risk situation, especially when driving. Drivers need to minimise the risk to avoid any harmful situations.

Fuller's threat avoidance model

Fuller's threat avoidance model (1984) proposes that drivers take measures to avoid accidents happening. By continuous learning, they pre-estimate the risk of a situation. As Fuller argues, "the experience of subjective risk is aversive and so drivers are motivated to escape from situations which elicit the experience or to avoid those situations". However, this theory does not explain the driver's risk information processing so that it cannot explain the decision making used when facing complex traffic situations.

Fuller's task-capability interface model

Fuller (2000) points out that driving task difficulty arises out of the degree of separation between driver capability and task demand. He questions whether drivers can perceive risk in advance or use it consistently when driving. Risk feeling as an input to the decision mechanism can determine speed choice. The upper boundary of a driver's target task difficulty is presented as the driver's risk threshold (Fuller, 2007). Whether drivers can accept risk is dependent on the gap between the traffic environment risk and the driver's ability to deal with the risk. Speed as a decisive factor can control task difficulty in the task-capability interface model (Fuller and Santos, 2002) in order to maintain the current workload below their capacity. This leaves a margin of capability which the driver can call on if an increase in task demand should unexpectedly arise (Fuller et al., 2008). Its modification and adaptation enable the driver to control task difficulty to a large extent, as the reference criterion in a closed feedback loop of task difficulty homeostatic control. For example, drivers attempt to balance task demand and driving capability. If a feeling of uneasiness comes from the expected risk possibility and the severity of the potential outcome, drivers reduce their speed until their feelings reach a comfortable level. Under this assumption, drivers adjust their behaviour to maintain the current workload below their capacity. The selected speed is therefore optimal for drivers' preferences and subjective judgement of safety and risk. However, this risk model is only based on a theoretical view and has not been tested on motorists in given road environments. It does not consider dynamic traffic situations or pedestrians' presence. The theory does not analyse risk information processing, and thus cannot explain behavioural decisions made when facing complex traffic situations.

Fuller's task difficulty homeostasis

Task difficulty homeostasis is proposed as a key sub-goal in driving and speed choice, and is argued to be the primary solution to the problem of keeping task difficulty within selected boundaries (Fuller, 2005). The chosen driving speed makes the difficulty of the task fall within the range the driver can accept, not exceeding their risk threshold, by ongoing comparison between perceived task difficulty and the range of acceptable difficulty. Variation in speed is the principal method of homeostatic control. Risk homeostasis is a special case of task difficulty homeostasis.

Fuller's risk allostasis theory

Following on from the task-capacity interface (TCI) model, risk allostasis theory states that a feeling of risk, as an indication of task difficulty, is the primary controller of driving behaviour (Fuller and Santos, 2002; Fuller et al., 2008). Drivers seek to maintain a feeling of risk within a preferred range in which they operate and they can alter their behaviour to maintain the feeling of risk within this preferred range (Fuller, 2008c). Homeostasis is the process by which a target condition is maintained in the face of external variation in a negative feedback loop, whereas allostasis refers to adapting to a dynamic target condition and is defined as maintaining certain levels of biological conditions that vary according to an individual's needs and circumstances (Fuller, 2011).

Fuller's model has undergone development and a new emphasis has been put on the model's properties, hence the revised nomenclature (Fuller, 2008a). The theoretical model can be used to emphasise the potential importance of its contribution to driver safety and explore some of its implications for calibration.

To sum up, risk perception theories are based on individuals' psychology and ability to make judgements about subjective risk. As drivers have risk feelings based on road situations, subjective risk reactions or feelings of risk are important determinants of driver behaviour (e.g. speed change and behaviour adaptation). Drivers are able to anticipate, and make adjustments to account for, upcoming hazards (Summala, 1988; Jamson et al., 2008; Hu et al., 2014; Hatfield et al., 2005; Wilde, 1982). These subjective risk feelings can be estimated in order to evaluate the perceived risk of collision in a given road scenario. One example is that driver perceived accident risk is higher on narrow lanes (Godley et al., 2004) and therefore speed is reduced. Based on Taylor (1964) conclusion, driving behaviour can be interpreted as a self-paced task governed by the level of tension/anxiety a driver can tolerate. Charlton (2011) explains that drivers keep a critical distance threshold around them, with strong emotional characteristics associated with perceived risk. If perceived hazards are removed or reduced, drivers may readjust their behaviour to restore anxiety levels. However, the theoretical models neglect the influence of the surrounding environment, individual variability and social effects. Risk perception has a close relationship with other psychological factors such as attitude and emotion. Drivers' risk perceptions cannot be assumed to be the same as the objective risk, for instance, they may underestimate safety margins under high speed conditions, or they may not anticipate sudden changes in direction by other vehicles or the sudden emergence of pedestrians.

2.6.3 Risk perception and emotion

The emotional effects that play a part in risk perception decision-making need to be emphasised, as they are generally underestimated (Damasio and Sutherland, 1994). The risk-as-feelings hypotheses indicates that responses to risky situations result, in part, from direct emotional influences, including feelings such as worry, fear, dread or anxiety (Loewenstein et al., 2001). Emotions can be seen as objective physiological and mental states (Damasio and Sutherland, 1994; Lewis-Evans and Rothengatter, 2009). Emotional feelings in decision-making can be used to characterise driver type by risk threshold (the point above which the risk is too great), as elements with strong somatic markers are prioritised in attention automatically (Fuller, 2007). According to Damasio and Sutherland (1994), emotions are responses predisposed to react in certain ways that prepare the body for action, but emotional responses are also directed towards the brain through neurotransmitters in the brain stem which lead to changes in mental states (Vaa, 2001). Neurobiology confirms that emotions guide individuals in monitoring of risk, processing of information and decision-making (Vaa, 2001), which suggests that Damasio's somatic marker is an important mechanism in driver behaviour control. An individual's objective emotional feeling can be measured by psychophysiology, as explained in Chapter 4 (Section 4.2.2).

2.6.4 Risk assessment affected by demographic and personality

Some research explains how people assess the riskiness of driving and the individual differences in how drivers take risks. Drivers' perceptions of hazardousness or subjective risk depend on both their amount of experience with various sorts of driving hazards and the information load of the situation. Higher information loads lead to higher levels of subjective risk (Charlton, 2011). Deery (2000) studies hazard and risk perception among young novice drivers and observes that these drivers, in general, underestimate accident risk in hazardous situations. Young male drivers tend to rate dangerous traffic situations as less risky than older male drivers (Tränkle et al., 1990). Educational measures designed for young drivers should focus on aspects of their risk perception and risk tolerance.

Taubman-Ben-Ari et al. (2004) propose that risky driving behaviours incorporate personal and environmental factors. Reckless driving is related to both personal and environmental factors. Ulleberg and Rundmo (2003) investigate the relationship between five personality measures and perception of risk, attitude toward risk-taking, how often people engage in risky driving behaviours and accident record. The interaction approach to risk perception assessment, along with other factors, seems to have potential for future research. This evidence explains why risky drivers do not show risk compensation (Fuller, 1984).

Research into drivers' perceptions of risk shows that drivers do form judgements about the risk of the road and traffic situations they encounter (Sjöberg et al., 2004). Exposure in traffic, negotiation with other drivers' driving behaviour, and information from the media are all reasons for people feeling unsafe or for anxiety for themselves or others regarding hazardous traffic situations (SWOV, 2012b). People are more easily sensitised to risk than safety, because mood states are more influenced by negative expectations. This research only focuses on subjective risk perception, which is much different to objective risk determined by actual crash data.

2.7 Road and roadside environment

Road layout and the roadside environment are among the main factors focused on. Based on the literature, driver speed perception in given road conditions and the risk factors coming from the road environment are reviewed here. These road environment factors are the focus of the experiments.

2.7.1 Drivers' speed perception

Most drivers seem to depend on their subjective perception or 'feeling' of their speed for their speed choice, although a speedometer is ever present (Haglund and Åberg, 2000). Martens et al. (1997), Elliott et al. (2003) and Vanderbilt (2008) show that the illusion cuts both ways, that drivers underestimate their speed when asked to slow down from a high-speed road and overestimate their speed when asked to speed up. There is evidence that drivers overestimate the time-saving from higher speed (Peer and Solomon, 2012) and underestimate or ignore the risk from higher speed (Kanellaidis et al., 2000). Drivers rely on their intuition when estimating travel risks and driving speeds. As a result, individual biases in safety, environment and mobility affect speed perception and compliance with speed limits.

The human perceptual system integrates data from the visual, vestibular and proprioception systems (Kemeny and Panerai, 2003). The visual system provides the most information about the environment, not only distinguishing between speed and contrast information but also using spatial frequency to judge the speed of moving objects (Kemeny and Panerai, 2003; Jamson et al., 2008).

Drivers estimate the motion (speed) of all surface elements in the world by analysing visual input through a process called optic flow (Gibson, 1986). Optic flow and active gaze strategies have both been shown to supply data for self-motion assessment (Kemeny and Panerai, 2003), which plays an important role in the detection and estimation of scene-relative object movement during self-movement. Changes in the optical flow directly specify interactions between the individual and the environment. The optic flow allows the driver of a vehicle move accurately on the road (Giachetti et al., 1998), and to guide locomotion toward a target of interest. For example, lane width perception has been found to alter vehicle speed effectively. Fildes and Lee (1993) show that road width and the number of lanes affect speed choice because the change in visual cues causes a reduction in the driver's sense of speed and a wider road decreases the amount of stimulation in the driver's peripheral vision (Denton, 1980). It seems that psychologically narrowing the perceptual lane width using road centre markings is as effective at reducing travel speeds as physically narrowing the lane width.

2.7.2 Road environment risk factors

Elvik et al. (2009) use a major road in Sweden to summarise the attributable risk problem, which includes bad system design (risk factors related to the design of roads and the traffic environment), environment risk (the effect on accidents of daylight and weather), vulnerability of road users (the enhanced risk run by pedestrians, cyclists and inexperienced drivers), unsafe road user behaviour and insufficient rescue services. Previous research identifies various features related to road accident risk, discussed below.

Number of traffic lanes (cross-section)

Increasing the number of traffic lanes does not, as a rule, appear to improve road safety. A possible explanation for this is that more traffic lanes lead to higher speeds and changing lanes represents a new hazard. Wide straight roads also tend to encourage higher speeds, and thereby increase the likelihood and severity of collisions. Increased speed occurs particularly when the capacity of a road that was previously too small, becomes adequate when the number of traffic lanes is increased (Elvik et al., 2009).

Road lane width

The influence of road lane width on accidents is investigated by Taylor et al. (2000), who show that increased road width is associated with fewer accidents on rural single carriageway roads. The results show that 3.7m lanes are safer than 2.7m or 3m lanes on two-lane roads. Narrow roads lead to the lower speeds, and drivers keep away from the road edge. Drivers rate narrow roads as riskier and they produce more accidents (Lewis-Evans and Charlton, 2006). Narrow roads allow drivers less room to manoeuvre their vehicles resulting in smaller margins to accommodate errors than wide roads. When braking, encountering other vehicles, turning onto or off the road or overtaking, the amount of road area available influences people's driving and the chances of avoiding an accident.

Road hard shoulders

The effects of hard shoulders beyond the edge of traffic lanes have been evaluated in Denmark and the USA (Elvik et al. (2009). Rural roads with hard shoulders have an accident rate around 5-10% lower than rural roads without hard shoulders. However, a narrow shoulder leads drivers to travel closer to the centre line, which constitutes an increased danger on undivided highways of possible encroachment into adjacent lanes. Very narrow road shoulders (less than 1.8m wide) are associated with higher accident rates (Zegeer et al., 1980).

Road curves

Horizontal and vertical curves are common in rural areas. Accidents tend to cluster on bends and accidents increase in frequency with the degree of horizontal curvature. Accidents tend to occur at the crests and near the bottom of downgrades. Curvature is clearly perceived by drivers as an important risk element. Horizontal curves, particularly on two-lane rural roads, are recognised as a significant safety issue, with crash rates 1.5 to 4 times higher on horizontal curves than straight road sections. 25-30% of all fatal accidents occur on curves (SafetyNet, 2009). Curve perception research into visual illusion shows that curvature is underestimated for smaller curve lengths, which explains why sharp curves are more dangerous. Milošević and Milić (1990) indicate that drivers underestimate their speed after a sharp left curve. Warning signs and special pavement markings are used to reduce speed on curves, but make little difference to speed. Safe driving speed on curved roads needs to be investigated further to reduce risk.

Improper road design

In rural areas, it is rare for roads to have consistent road and roadside characteristics (Kloeden et al., 2001). Most single-carriageway rural roads have frequently changing alignments, narrow lanes, limited shoulders, sharp curves, exposed hazards, pavement drop-offs, steep slopes and limited clear zones along roadsides, often with individual hazards (difficult junctions, sharp bends, crests, etc) joined by safer road sections.

Roads of lower quality, such as narrow or winding country lanes, are likely to have lower speed than roads of higher quality, but higher accident rates (Taylor et al., 2002). Weller et al. (2008) show that the "share of fatalities on rural roads is usually approximately 60% compared to 10% for motorways and 30% for inner-urban roads", because of the inherent properties of rural roads, for example, "the unforgiving roadsides (trees, ditches etc.)" (Antonson et al., 2009; Weller et al., 2008). The subjective risk perception is assumed to be higher on these roads which accentuates the underlying attitude reflected in driving behaviour.

In real traffic situations on rural A roads, one reason for speeding is directly related to the design and layout of the road, which does not give many clues about the local speed limit (De Waard et al., 1995). If the road has an inadequate or improper design, neither drivers nor pedestrians may know what the appropriate speed is. Road user limitations, road users' expectations and their interactions with the road's physical characteristics are important for safety. A number of design countermeasures are available to change road configurations and driving behaviour.

According to previous accident research findings, there are three main crash types on two-lane rural single carriageways, head-on collisions, run-out of road single vehicle accidents and collisions with vulnerable road users. It is to be expected that proper road design, applying design principles, could considerably reduce the number of accidents. The concept of the forgiving road layout and roadside environment, including moving badly positioned signage and vegetation, could minimise the risk of injury when vehicles leave the road. How forgiving a road is depends on how the roadside is designed and equipped. For example, paved shoulders are important for the safety of pedestrians and cyclists. Roadside protection can reduce potential conflicts with vulnerable road users and is a countermeasure applied to the most improved roads. Roadside protection may also be less threatening to drivers but, therefore, may have a negative effect on other road users. This needs to be investigated in further research.

Mixed road users

Driving behaviour is more complex on urban roads than other types of roads, because of the mixture of usage, which means various types of vehicle use the same road. This may lead to high potential risks, especially for non-motorised road users. Dedicated areas for specific road-user types substantially improve safety (Shefer and Rietveld, 1997). For example, raised pedestrian crossings lead to a reduction in the number of accidents for both pedestrians and vehicles. The reduction of accidents involving pedestrians on raised pedestrian crossings may be due to more vehicles giving way to people than on a normal pedestrian crossing. The degree to which people feel safe is related to the separation of traffic types and the amount of heavy traffic (SWOV, 2012b). For safer speeds on urban roads, there is a need to balance all road users' speed expectations.

Vehicle type mass and protection

The mass of a vehicle combined with its speed produces its kinetic energy, which is converted into other forms of energy and/or bodily damage during a crash (Wegman et al., 2008). For the occupants of vehicles with high mass, injury risk is much lower than for occupants of lighter vehicles. Users of motorised two-wheelers have the highest fatality rates and risk of injury in road traffic, explained by a combination of high speed with the relatively low mass of the vehicle compared to other motorised traffic, plus the poor crash protection (Elvik et al., 2009).

Traffic volume

Research shows that traffic volume has a major impact on accidents (Elvik et al., 2009). The lower speeds caused by congestion lead to lower numbers of fatal accidents. During peak hours the fatality rate is lower than at other times of the day. When the speed-flow density is zero, traffic flows freely and the road is uncongested. When traffic flow reaches a certain threshold, the speed is reduced to its lowest value. A parabolic relationship has been established between density and fatal accidents on highways (Shefer and Rietveld, 1997). Similar result are found when the traffic flow is light during the early morning, when there are a high number of fatal and serious injury accidents (Turner and Thomas, 1986). When the traffic flow is light in the night time, crashes are much worse in terms of severity. Hence light traffic is a safety problem both in terms of crash rate and crash severity (Martin, 2002).

The relationship between traffic flow and accident risk is shown by the following results. The accident data from central Florida over a period of 3 years shows that heavy traffic increases the likelihood of accidents, in accordance with the negative binomial model (Abdel-Aty and Radwan, 2000). Rear-end accident data from 10 highway routes in Washington State from 2002 to 2006 show that the percentage of trucks and grades have a parabolic impact, increasing crash risk initially but decreasing it after a certain threshold (Lao et al., 2014). Research into 2000km of French interurban motorways over 2 years (Martin, 2002), shows that crashes on 2-lane motorways generally occur at traffic flows of under 1,000 vehicles per hour, with a distinctly skewed distribution, whereas crashes on 3-lane motorways occur at traffic flow rates with a flatter distribution and a mean of 1,500 vehicles per hour. Figure 2-15 shows the crashes against hourly traffic for 2 and 3 lanes.

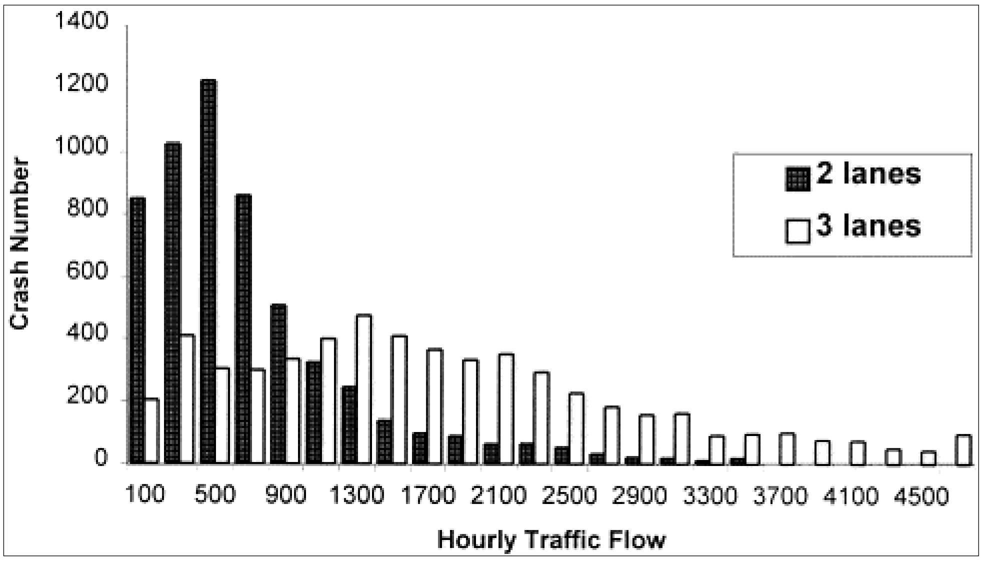


Figure 2-15: Number of crashes per number of lanes versus hourly traffic flow Source: Martin (2002)

Speed variation

Rural single carriageways have the most diverse speed choice patterns and frequently score highest for accident rates (MASTER, 1998). Measurement of free flow conditions on rural single carriageways demonstrates the large variation in speed, with most drivers in the UK driving within the 40-54mph range (Figure 2-16). Variation in vehicle speed in traffic flow is an important risk-inducing factor.

Overtaking behaviour is an additional risk factor which results from speed variations (OECD, 2006). Great variance in speed between vehicles increases the possibility of rear-end accidents, and increases the number of potentially dangerous overtaking manoeuvres, thereby increasing the chance of head-on collisions (Hale et al., 1990).

This might be because of the presence of slow traffic, uncertainty about the speed limit, the potential risk of oncoming vehicles, the presence of curves or the lack of physical barriers. This uncertainty is reflected in the higher differences between drivers' speeds, which is a risk factor. Therefore, there is a need to set credible speed limits that match each road layout clearly, different from that of other categories. The credible speed limit is proposed as an effective way to reduce speed variation and increase safety.

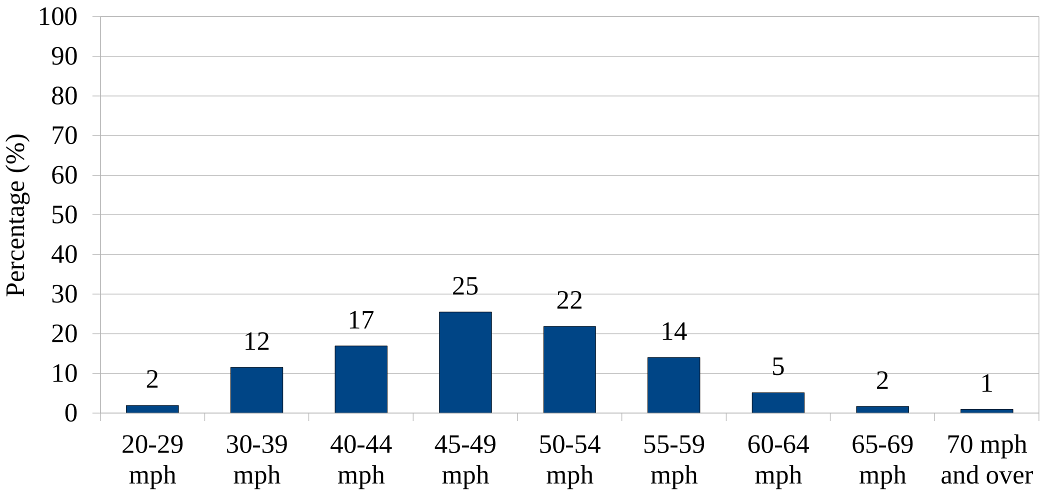


Figure 2-16: Car free flow speed distribution on single carriageway in Great Britain 2015 (Department for Transport, 2016)

2.7.3 Forgiving road environment

A forgiving road reduces human error, and the protection features of the road make drivers feel safer than on unprotected roads. Protection features accommodate driver error and prevent head-on collisions, out of road collisions and conflict between road users. Firstly, to prevent head-on collisions, physical dividers along centre lines need to be implemented. Various designs of divider can be considered as possible solutions. Physical barriers at the centre, central hatching, coloured central surface and wide lanes can all tackle head-on collisions. Secondly, to prevent vehicle loss of control and running off the road, forgiving road features include hard shoulders, an important roadside safety feature which increases the recovery zone in which drivers can adjust their vehicle's trajectory to avoid running off the road. Shoulders vary from 0.5m to 2m on rural roads (Torre, 2012). In addition, paving shoulders can lead to a 5% reduction in accidents on highway roads (Zegeer et al., 1992). Hallmark et al. (2009) come to the same conclusion, that paved shoulders are more effective than non-paved shoulders. However, it should be taken into account that shoulders create the impression of a fast road. Wide paved shoulders can lead to bad driving behaviours, such as speeding, by giving the impression of reduced risk and the use of the shoulders as travel or passing lanes. Safety barriers are also forgiving roadside treatments designed to shield hazardous obstacles and/or to prevent vehicles from running off the road. However, the barrier terminals need to be designed as suitably energy-absorbing to prevent head-on collisions (Torre, 2012). Thirdly, to prevent conflicts between vehicles and cyclists, separate cycle lanes need to be provided. Forgiving road layouts and roadside environments can be used for credible speed limit setting.

2.8 Conclusion

The literature review indicates a few important things. Firstly, the evidence showing the relationship between speed and road safety shows that exceeding the speed limit is one of the most common risk factors on the road. Thus, increasing the credibility of speed limits under the Safe System can benefit road safety. Speed limits set for reasons of safety include 30km/h in pedestrian areas, 50km/h in general urban areas, 70km/h for roads with possible frontal conflicts between cars, and 100km/h for roads with no possible frontal or transverse conflicts between road users. The lower speed limits that are prevalent on UK roads should thus be adopted for safety reasons. Secondly, setting credible speed limits is an important element of achieving self-explaining roads and forgiving roads, with safety features incorporated into road design. Thirdly, based on the research model (Figure 1-3), road layout and the roadside environment, credibility, risk perception and compliance are the four main research focuses. These four factors are reviewed in the previous literature, illustrating the gaps which need to be addressed in this study. Fourthly, several engineering factors, such as road curves, lane widths, hard shoulders and cycle tracks are assumed to affect speed limit credibility, risk perception and speed choice. Both road environment factors and risk factors are assumed to affect speed limit credibility and choice of speed.

The relationship between speed limit credibility and compliance with speed limits needs further research. Although compliance with speed limits is increased by enforcement and penalties for speeding, there is little evidence to show how speed limit compliance is associated with credibility. Drivers perceive roads intuitively based on road layout and the roadside environment. How road layout and the roadside environment affect intrinsic perception of the speed limit, and how speed limit credibility affects compliance with speed limits, need to be measured by quantitative studies. Road conditions are used to determine which characteristics of the road environment most influence speed limit credibility. This relationship is tested in Experiment 1.

The influence of road layout and roadside environment on speed limit credibility, and how driver risk perception affects speed limit credibility also need to be investigated. Risk perception is assumed to be associated with speed limit credibility. Risk perception for individual road users should be evaluated in given road environments and be related to specific traffic situations. Hence, risk perception must be considered along with speed limit credibility. This research investigates how risk perception affects speed limit credibility. With road layout and roadside environment and risk perception factors affecting speed limit credibility, the term credibility needs to be defined by the study. This knowledge gap is addressed by Experiment 2.

Investigating the relationship between driver risk perception and compliance with speed limits also needs specific research methods. An approach is developed to address how drivers' risk feelings affect their behaviour. This research investigates how risk perception affects speed limit compliance on given road layouts and roadside environments. This relationship is tested in Experiment 2.

This leaves the question of how to use intervention to make drivers more compliant with speed limits when a credible speed limit is in place. Setting credible speed limits can stimulate decision makers' consciousness, bringing them to safer speeds in a more natural way than avoiding speeding punishments. Road design is an effective way to affect speed limit credibility. What characteristics of the road and the roadside environment make speed limits more or less credible for specific types of road? There is a potential need to develop different types of interventions, such as warning or information signs, for different road layouts and roadside environments to make speed limits more credible. This intervention effect is tested in Experiment 3.

2.9 Aim and objectives

The study aims to set more credible speed limits by manipulating road layouts and roadside environments to improve drivers' compliance with speed limits.

The main objectives are:

- To investigate how road layout and roadside environment affect speed limit credibility
- To investigate various measurements of credible speed limits based on experimental evidence
- To investigate the relationship between speed limit credibility, risk perception and compliance with the speed limit on rural single carriageways
- To build a list of intervention measurements to improve driver compliance with speed limits.

2.10 Research questions

- How do road layout and roadside environment factors affect speed limit credibility and compliance with the speed limit on current UK roads? (Experiment 1)

  Which characteristics of road layouts and roadside environments make speed limits on current UK roads more or less credible? (Experiment 1)

  What are the relationships between speed limit credibility and compliance with speed limits on current UK roads? (Experiment 1)

- How do road layout and roadside environment factors affect speed limit credibility, risk perception and compliance with the speed limit on UK rural single carriageways? (Experiment 2)

  What are the relationships between speed limit credibility, risk perception and compliance with the speed limit on UK rural single carriageways? (Experiment 2)

  How can credible speed limits be measured in the light of the fact that speed limits can be perceived as too high or too low? (Experiment 2)

- How can a more credible speed limit be set to improve driver compliance with the speed limit on UK rural single carriageways? (Experiment 3)

Chapter 3 Experiment 1: Investigating the relationship between speed limit credibility and speed limit compliance

3.1 Study rationale

Previous literature shows which features influence the credibility of the 80km/h speed limit on rural roads in the Netherlands. These features can be summarised as follows: the road width, the presence or absence of a bend, the view ahead, the view to the right, the clarity of the situation, the presence or absence of buildings, and the presence or absence of trees on the right hand side (Goldenbeld and van Schagen, 2007). Higher speeds are chosen on roads which are wide, have an emergency lane, few bends, a smooth surface, clear road markings, few buildings or little vegetation, all of which facilitate following the road's course (Elliott et al., 2003; Goldenbeld and van Schagen, 2007; SWOV, 2012a). External circumstances such as road geometry and engineering elements have a key influence on drivers' speed choice. The 'self-explaining' road (SER) provides a safe behaviour guide simply through its road layout and roadside environment design (Theeuwes and Godthelp, 1995). Weller and Dietze (2010) show that, in the SER approach, the road layout and roadside environment (e.g. road markings and road width) play vital roles in influencing driving behaviour. Driver's intrinsic cognition, without speed limit signs, results in an individual's driving speed perception depending only on the road layout and the subjective risk.

So far, no studies have examined the effect of road layout and the roadside environment on speed limit credibility or speed on various UK road types. Few attempts have been made to define or prove what a credible speed limit is. It is possible to improve the credibility of the speed limit by better matching the limit to certain characteristics of the road layout and roadside environment.

3.2 Study aims

The present study aims to define credibility by evaluating road layouts and roadside environments that affect speed limit credibility, focusing on motorways, urban motorways, rural single carriageways and urban roads.

The main objectives are:

- To investigate how road layout and the roadside environment affect the credible speed limit, and speed limit compliance.
- To investigate the difference between speed limit credibility and speed limit compliance.

3.3 Method

3.3.1 Questionnaire design

To answer the question of how road environment affects credible speed limit, compliance with the speed limit, and the relationship between speed limit credibility and compliance, a questionnaire survey is used as they are easy to manipulate, relatively low cost and easy to administer. West et al. (1993) indicate that observed speeds are in accordance with drivers' self-report driving speed, which is validated for this study. In the survey, local drivers judge the perceived speed and safe speed limit in a given road scene photograph (Figure 3-1).

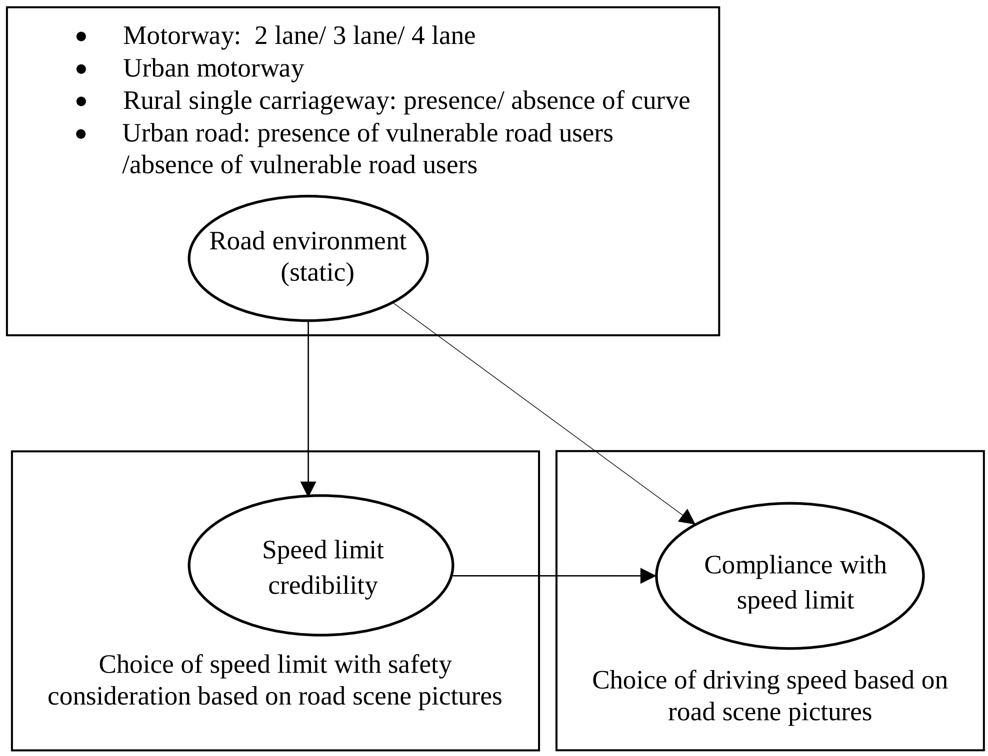


Figure 3-1: Experiment 1 theoretical model

Based on the literature, various road layouts and roadside environmental factors, such as the number of lanes, curved roads and urban roads with the potential for conflict between vehicle drivers and vulnerable road users, are shown to affect speed choice (Goldenbeld and van Schagen, 2007; Elliott et al., 2003; Lee et al., 2017). These factors are adopted for this research on speed limit credibility and speed choice. A questionnaire is used to get drivers' responses to the perception of speed limit credibility and the perception of speed choice. The following road characteristics are included in the analysis: motorways with various numbers of lanes, urban motorways, rural roads with or without curves, urban roads in a residential area with or without vulnerable road users. Other factors, such as road radius, lane width, elevation, sight distance, friction and so on are not taken into consideration. Each factor, for a specific road environment, affects the speed limit credibility on:

- Motorway - 2 lane/3 lane/4 lane
- Urban motorway
- Rural single carriageway - presence of curve /absence of curve
- Urban road - presence of vulnerable road users /absence of vulnerable road users

The respondents are not informed of the posted speed limit for each road scene. The actual speed limits posted on these roads in reality are:

- Motorway: 70mph
- Urban Motorway: 40mph
- Rural single carriageway: 60mph
- Urban road: 30mph


Motorway: 2 lanes


Motorway: 3 lanes


Motorway: 4 lanes


Urban motorway


Rural single carriageway: presence of curve


Rural single carriageway: absence of curve


Urban road: presence of vulnerable road users


Urban road: absence of vulnerable road users

Figure 3-2: Eight road scenes for Experiment 1 questionnaire study

All the pictures are of real roads near Leeds, the A1(M), A64(M), A64, A59 and B6160. All the pictures in the questionnaire are taken from the perspective of a driver's line of sight in low traffic flow conditions. There are no speed limit signs or traffic signs visible, in order to avoid information about the official category to which the road belongs, as this could influence drivers' speed choice and speed limit choice. As the road pictures are static, the drivers are asked at what speed they *would* drive. The pictures are reduced in size to 9.00cm × 6.75cm followed by questions for the respondent to read, which are based on similar credibility research from Goldenbeld and van Schagen (2007). The questions are:

1. **If there was no speed limit, how fast would you drive on the road section shown?**
2. **What speed limit do you think would be safe here?**

The road pictures and questions were colour printed on A4 paper. A face-to-face questionnaire interview was used to get the responses from each participant, which allows for in-depth data collection and comprehensive understanding (Patton, 2005). If a respondent was not clear about the questions, the interviewer can explain directly to help the respondent understand. Taking notes during interviews is often necessary (Sturges and Hanrahan, 2004). Although face-to-face interview are more time-consuming to recruit and conduct, they provide valid responses and are an effective measure.

3.3.2 Participants

Convenience sampling was used to find respondents among local drivers. Convenience sampling (also known as availability sampling) is a specific type of non-probability sampling method that relies on data collection from population members who are conveniently available to participate in the study (Marshall, 1996). Due to the road scene pictures being taken in West Yorkshire, drivers were selected at Woodhouse Lane car park. It was convenient for the researcher to approach individual drivers at the entrance to the car park. For sample size, in order to compare the choice of speed difference between two roads, the paired T-Test was adopted. The calculation process is in Table 3-1 by the sample size calculator (http://www.sample-size.net/sample-size-study-paired-t-test/). The required sample size was 31. The total number of participants in this experiment was 100.

Table 3-1: Sample size calculation for Paired T-Test

α (two-tailed) =	0.050	*Threshold probability for rejecting the null hypothesis. Type I error rate.*
β =	0.200	*Probability of failing to reject the null hypothesis under the alternative hypothesis. Type II error rate.*
E =	0.500	*Effect size*
S(Δ) =	1.000	*Standard Deviation of the CHANGE in the outcome. (If you don't know S(Δ), click here to calculate it.)*

The standard normal deviate for α = Zα = 1.960	The standard normal deviate for β = Zβ = 0.842	A = 1.000	B = (Zα+Zβ)2 = 7.849	C = (E/S(Δ))2 = 0.250	AB/C = 31.4	**Group size N: 31**

The demographic characteristics of the respondents are given in Table 3-2. In order to compare driving speed choice and safe speed limit choice against driving experiences, the respondents were asked how long it had been since they passed their driving test and how many speeding tickets they had received in the past three years. This approach to sampling allows for recruitment of a representative sample of the UK driving population.

Table 3-2: Leeds driving licence holders: distribution by gender and age

Gender	Number	Percentage	Age	Number	Percentage
Male	52	52%	17-20	9	9%
Female	48	48%	21-30	27	27%
			31-40	21	21%
			41-50	19	19%
			51-60	22	22%
			61-70	2	2%

3.3.3 Procedure

The survey was conducted from 6th May to 12th May, 2015 on weekdays. When the sample size reached 100, the surveyor stopped collecting data. A sample size of 100 is large enough for the paired group T-test. Undertaking the questionnaire for the road survey involved presenting the questions on colour printed A4 paper. The questionnaire could be completed within three minutes. For each scenario, the respondents were asked to make an assessment of the speed limit and how they might react faced with the particular driving conditions depicted. It should be noted that these questions rely on the drivers self-reporting speed they would drive at, rather than any objective measurement of speed.

The response to the first question could be any numerical value. The response to the second question could be selected from a scale ranging from 10mph to 80mph in increments of 10mph. The participants were not informed of the actual speed limits. The images show road scenes with very little or no traffic so that drivers could infer what the free flow speed would be. The questionnaires were distributed to drivers randomly. The surveyor stood outside Woodhouse Lane car park, stopped passing by drivers and asked them whether they would like to take part in the questionnaire. The response rate was about 10%, due to most drivers being in a rush or not wanting to be disturbed. After the survey period concluded, the respondents' answers were recorded and saved in the statistical package, SPSS.

3.4 Data Analysis

3.4.1 Variables coding

From the questionnaire, the road layout and the roadside environment and the demographic characteristics are independent variables; the average preferred speed and safe speed limit are both dependent variables. As the speed choice data is a continuous variable, numerical measures of shape skewness can be used to test for normality (Table 3-3). Skewness is a measure of distribution symmetry (Doksum et al., 1977). For a sample of n values (n=100 in this study), an estimator of the population skewness = $\frac{\frac{1}{n}\sum_{i=1}^{n}(xi-\bar{x})}{[\frac{1}{n-1}\sum_{i=1}^{n}(xi-\bar{x})^2]^{\frac{3}{2}}}$ is adapted from Joanes and Gill (1998).

Table 3-3: Choice of speed skewness test

	Skewness statistic
2-lane motorway	0.927
3-lane motorway	0.617
4-lane motorway	0.205
Urban motorway	0.517
Rural single carriageway with curve	0.372

Rural single carriageway without curve	-0.139
Urban road with vulnerable road users (VRU)	-0.311
Urban road with no vulnerable road users (non-VRU)	-0.710

As a general rule of thumb from Bulmer (1979):

- If skewness is less than -1 or greater than 1, the distribution is highly skewed.
- If skewness is between -1 and -0.5 or between 0.5 and 1, the distribution is moderately skewed.
- If skewness is between -0.5 and 0.5, the distribution is approximately symmetric.

The results showed that the data distribution for each road layout was moderately skewed (Table 3-3), which were considered acceptable in order to prove normal univariate distribution (Darren and Mallery, 1999). Larger sample sizes were adopted for such motivations to be valid. Thus, a parametric test was adopted. A parametric test usually has more statistical power than a non-parametric test (Finch, 2005).

The speed limit choice was selected from a set, from 10mph to 80mph with an increment of 10mph. The speed limit choice can be treated as a categorical variable. A non-parametric test was adopted.

3.4.2 Motorway speed and speed limit performance

For each motorway road scene, the perceived safe speed limit and perceived driving speed are analysed as follows.

2-lane motorway

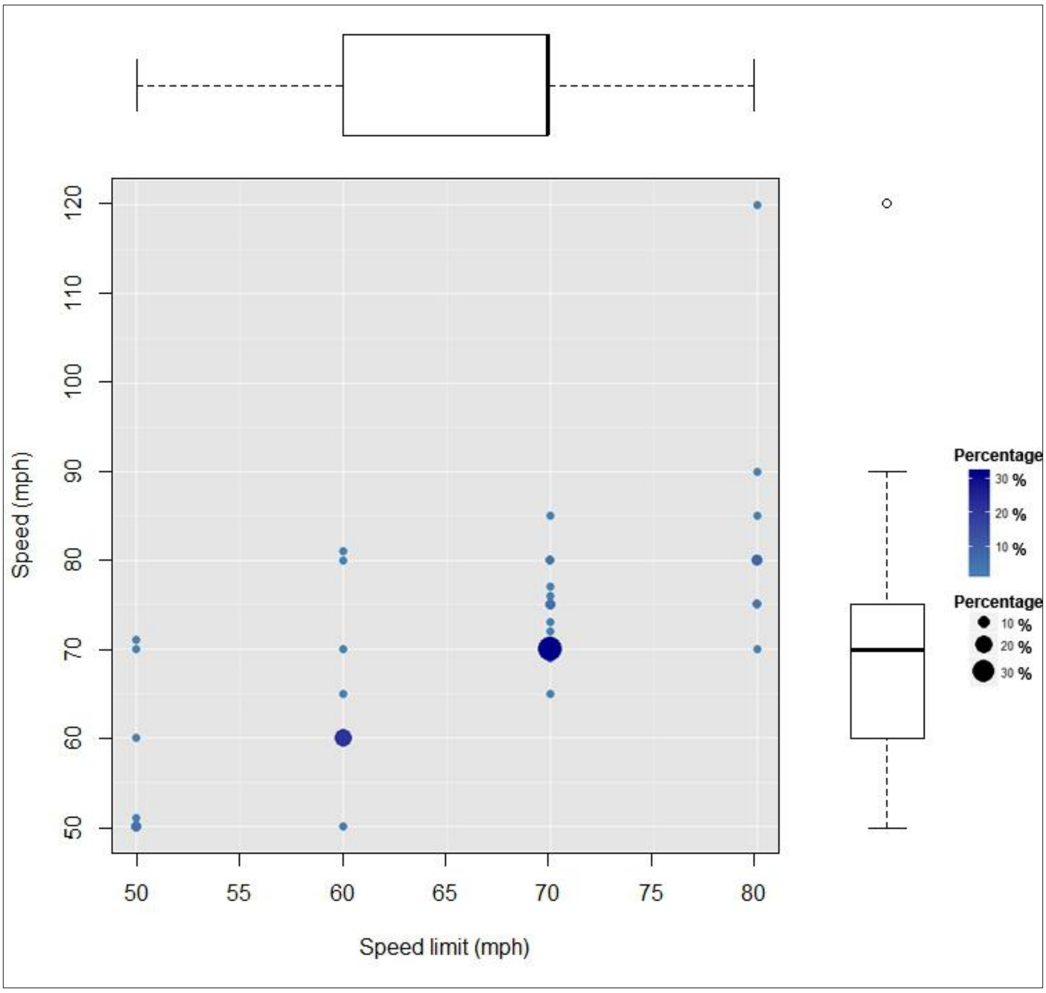


Figure 3-3: 2-lane motorway speed limit and speed choice

Table 3-4: 2-lane motorway mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	50mph	60mph	70mph	80mph	Average
Mean speed (mph)	55.8	61.3	71.9	81.6	69.2
Standard deviation (mph)	8.9	6.6	3.8	11.2	10.3

Table 3-4 shows the speed choice for each speed limit group. For the 2-lane motorway, the mean speed was 69.2mph (±10.3) and the 85th percentile speed was 80mph. The mode speed limit was 70mph (48%). Testing whether the group choosing the 50mph speed limit differed from the group choosing the 60mph speed limit showed that the mean choice of speeds for the chosen speed limit group was significantly different ($p<.05$). The same result is found for the other speed limit groups. Linear regression establishes that the perceived safe speed limit statistically significantly predicts the perceived choice of speed, $F(1, 98) = 132.159$, $p < .01$ and the perceived safe speed limit accounts for 57.4% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive.

Table 3-5: 2-lane motorway speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	50mph	60mph	70mph	80mph	Total
Group 1: Speed <=70mph	8%	25%	34%	1%	68%
Group 2: Speed >70mph	1%	2%	14%	15%	32%
Total	9%	27%	48%	16%	100%

To explain the distribution difference in choice of speed limit between drivers willing to obey the speed limit and drivers who exceed the speed limit, the Chi-square test is adopted for all road types. Table 3-5 shows the speed choice divided into two groups: those who chose speed greater than or less than the national motorway speed limit of 70mph. 68% of the respondents (Group 1) chose to comply with the speed limit (<=70mph); 32% of the respondents (Group 2) chose to exceed the speed limit (>70mph). The null hypothesis is rejected, χ^2 (3, N=100) =37.523, p<.001. There was a significant difference in the speed limit perception of the two speed choice groups. Although the respondents chose the same speed limit, their choice of driving behaviour was different. Conversely, even if respondents chose to comply with the speed limit, their perceptions of the safe speed limit were different.

Table 3-6: Compliance with chosen speed limit level on 2-lane motorway

Speed limit	Statement	Compliance percentage (%)
80mph	Compliance level for drivers choosing 80mph as the credible speed limit	81.2
	Exceeding speed limit level for drivers choosing 80mph as the credible speed limit	18.8
70mph	Compliance level for drivers choosing 70mph as the credible speed limit	70.8
	Exceeding speed limit level for drivers choosing 70mph as the credible speed limit	29.2
60mph	Compliance level for drivers choosing 60mph as the credible speed limit	85.2
	Exceeding speed limit level for drivers choosing 60mph as the credible speed limit	14.8

Table 3-6 classifies compliance level into two groups in terms of drivers' choice of safe speed limit. For each safe speed limit choice, drivers perceived the driving speed to be either above or below the safe speed limit. Drivers presented a higher compliance level for speed limits they perceived as safe. In other words, speeding drivers preferred driving faster on higher speed limit roads, while conservative drivers were willing to drive slowly on lower speed limit roads.

An estimated linear regression line can be fitted to show a positive correlation between choice of speed limit and choice of speed ($F(1, 98) = 132.2$, $p < .001$), and the speed limit accounts for 57% of the explained variability in speed choice. The coefficient p-value is less than 0.05, which means speed limit makes a significant contribution to predicting speed choice. If the choice of speed limit increases by 10mph, the choice of speed increases by 9.2mph. Thus, the higher the speed limit drivers perceive, the faster they drive.

3-lane motorway

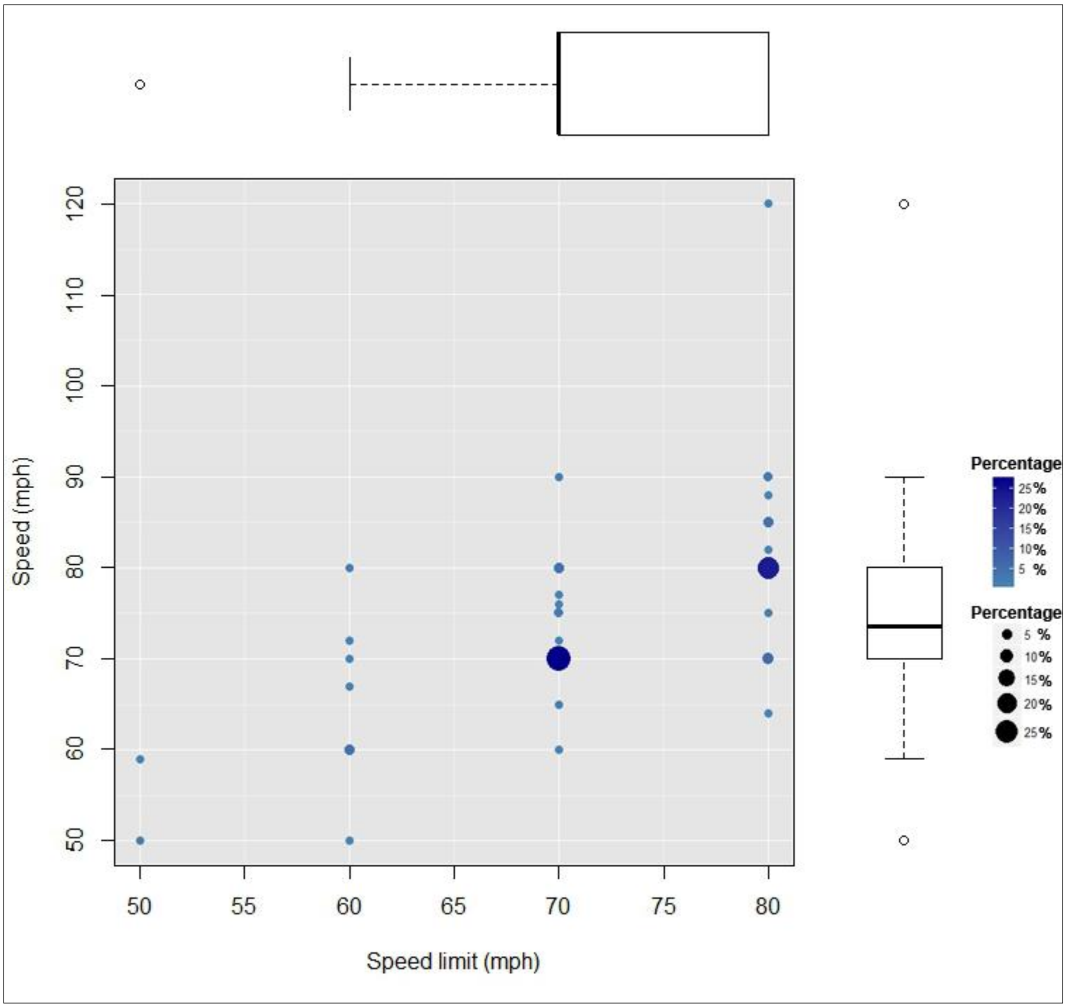


Figure 3-4: 3-lane motorway speed limit and speed choice

Table 3-7: 3-lane motorway mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	50mph	60mph	70mph	80mph	Average
Mean speed (mph)	53.0	65.4	72.3	80.4	74.5
Standard Deviation (mph)	5.2	9.4	5.7	8.4	9.7

Table 3-8: 3-lane motorway speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	50mph	60mph	70mph	80mph	Total
Group 1: Speed <=70mph	3%	8%	30%	7%	48%
Group 2: Speed >70mph	0%	3%	13%	36%	52%
Total	3%	11%	43%	43%	100%

On the 3-lane motorway, the mean speed was 74.5mph (±9.7) and the 85th percentile speed was 80mph. The mode speed limit was 70mph (43%). Table 3-7 shows the speed choice for each speed limit group. A linear regression establishes that perceived safe speed limit can statistically significantly predict the perceived choice of speed, $F(1, 98) = 73.031$, $p < .01$ and the perceived safe speed limit accounts for 42.7% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive.

Table 3-8 shows how drivers judged whether the speed limit was credible in that particular environment, distinguishing the difference between two comparison groups. The test is to explain the difference in choice of speed limit between drivers who obey the speed limit and drivers who exceed the speed limit. The null hypothesis is rejected. There is evidence of a difference in the perception of the speed limit between the two groups (χ^2 (3, N=100) =31.4, $p<.001$). For each safe speed limit choice, drivers perceived driving speed to be either above or below the speed limit, as shown in Table 3-9. Drivers showed a higher compliance level for speed limits they perceived as safe.

Table 3-9: Compliance with chosen speed limit on 3-lane motorway

Speed limit	Statement	Compliance percentage (%)
80mph	Compliance level for drivers choosing 80mph as the credible speed limit	74.4
	Exceeding speed limit level for drivers choosing 80mph as the credible speed limit	25.6
70mph	Compliance level for drivers choosing 70mph as the credible speed limit	69.8
	Exceeding speed limit level for drivers choosing 70mph as the credible speed limit	30.2
60mph	Compliance level for drivers choosing 60mph as the credible speed limit	54.5
	Exceeding speed limit level for drivers choosing 60mph as the credible speed limit	45.5

4-lane motorway

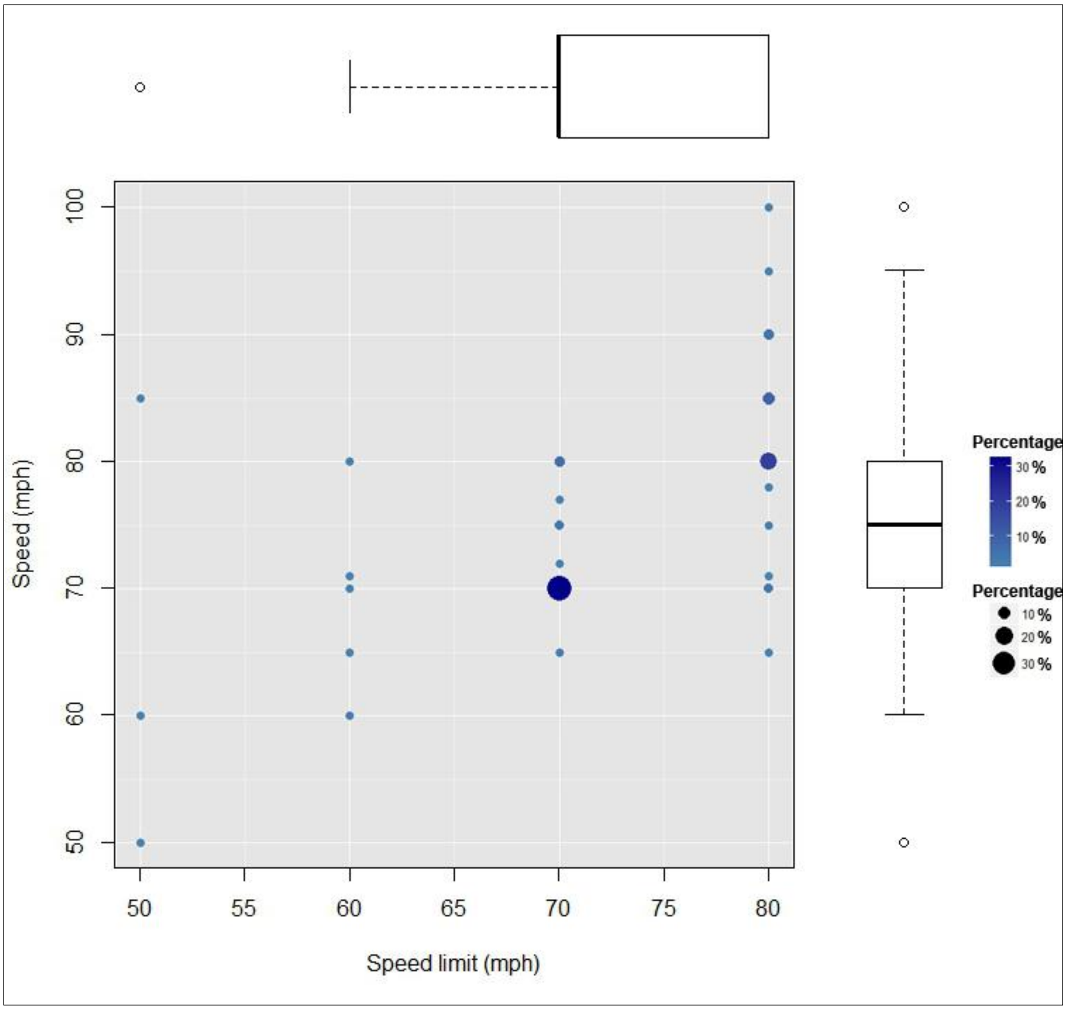


Figure 3-5: 4-lane motorway speed limit and speed choice

Table 3-10: 4-lane motorway mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	50mph	60mph	70mph	80mph	Average
Mean speed (mph)	65.0	67.7	71.7	81.2	75.4
Standard deviation (mph)	18.0	7.7	3.8	6.9	8.1

Table 3-11: 4-lane motorway speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	50mph	60mph	70mph	80mph	Total
Group 1: Speed <=70mph	2%	4%	35%	5%	46%
Group 2: Speed >70mph	1%	2%	12%	39%	54%
Total	3%	6%	47%	44%	100%

On the 4-lane motorway, the mean speed was 75.4mph (±8.1) and the 85th percentile speed was 85mph. The mode speed limit was 70mph (47%) (
Table 3-10). A linear regression establishes that perceived safe speed limit can statistically significantly predict perceived choice of speed, $F(1, 98) = 63.87$, $p < .01$ and perceived safe speed limit accounted for 42.7% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive.

For the speed choice for each speed limit group, the test is to explain the difference in choice of speed limit between drivers who obey the speed limit and drivers who exceed the speed limit (Table 3-11). The null hypothesis is rejected, χ^2 (3, N=100) =38.1, $p<.001$. The distributions for the two groups' chosen speed limits are significantly different. More than half the respondents were willing to drive above the speed limit. Drivers who obey the speed limit tended to have more speed limit choice, equal to or less than 70mph, compared to their counterparts. For each safe speed limit choice, drivers perceived the driving speed to be either above or below the speed limit (Table 3-12). Thus, road environment factors can affect drivers' choice of speed limit and choice of driving speed.

Table 3-12: Compliance with chosen speed limit on 4-lane motorway

Speed Limit	Statement	Compliant Percentage (%)
80mph	Compliance level for drivers choosing 80mph as the credible speed limit	63.6
	Exceeding speed limit level for drivers choosing 80mph as the credible speed limit	36.4
70mph	Compliance level for drivers choosing 70mph as the credible speed limit	74.5
	Exceeding speed limit level for drivers choosing 70mph as the credible speed limit	25.5
60mph	Compliance level for drivers choosing 60mph as the credible speed limit	33.3
	Exceeding speed limit level for drivers choosing 60mph as the credible speed limit	66.7

Motorway group comparison

The average preferred speed and safe speed limit for all motorway scenes are presented in Figure 3-6 and Table 3-13**.** The large standard deviation for both preferred speed and safe speed limit illustrates the large differences between respondents. The 85th percentile speed is also presented. The theory behind the 85th percentile rule is that limits must be practical and enforced by engineering experts (AASHTO, 2001). The mode safe speed limit shows the speed limit chosen by most respondents, used to evaluate how credible the real speed limits are. The group comparison shows that there exists inconsistency between drivers' preferred safe speed limit and the choice of speed, which is also different from the national speed limit.

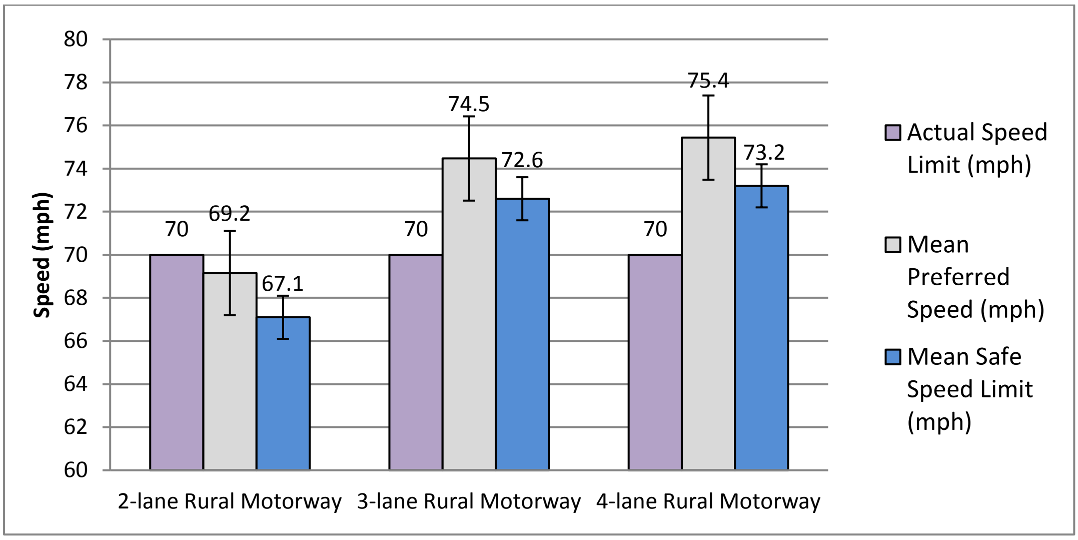


Figure 3-6: Comparison of motorway speed limit choice and speed choice

Table 3-13: Comparison of mean and standard deviation of preferred speed and speed limit by road scene

Road scene	**Preferred choice of speed**				**Choice of safe speed limit**		**Actual speed limit (mph)**
	Mean (S.D) (mph)	50th percentile of speed –median (mph)	85th percentile of speed (mph)	Number of drivers exceeding speed limit (percentage)	Mode (%) (mph)	Number of drivers choosing speed limit greater than actual speed limit (percentage)	
2-lane motorway	69.2 (10.3)	70	80	32 (32%)	70 (48%)	16 (16%)	**70**
3-lane motorway	74.5 (9.7)	73.5	80	52 (52%)	70(43%) 80(43%)	43 (43%)	**70**
4-lane motorway	75.4 (8.1)	75	85	54 (54%)	70(47%)	44 (44%)	**70**

Comparing the results for the three types of motorway shown in Figure 3-7 shows that the number of respondents choosing the 70mph speed limit as credible was 48% for the 2-lane motorway, 43% for the 3-lane, and 47% for the 4-lane. Almost half the respondents chose other speed limits (e.g. 50mph, 60mph or 80mph) which indicates that drivers did not have a common choice. Only 48% of respondents perceived 70mph to be credible on a 2-lane motorway, and 70mph on a 2-lane motorway was perceived as more credible than on other types of motorway. Thus, the mean speed on a 2-lane motorway was close to 70mph and more respondents were willing to comply with the speed limit. Fewer drivers exceeding the speed limit and putting the mode speed limit as 70mph means the road can be considered self-explaining in that condition.

From the speed choice result, the proportion of respondents' speed choice below a 70mph speed limit was 68% for the 2-lane motorway, 48% for the 3-lane, and 46% for the 4-lane. The 2-lane motorway had the highest degree of respondent compliance with the speed limit, but not all chose 70mph as the credible speed limit. For the 3-lane and 4-lane motorways, the driving speeds did not match the speed limit for the road layout and roadside environment. The problem of drivers not complying with the speed limit may be due to the speed limit's lack of credibility for a group of road users. Both speed limit perception and speed choice are affected by road layout and roadside environment.

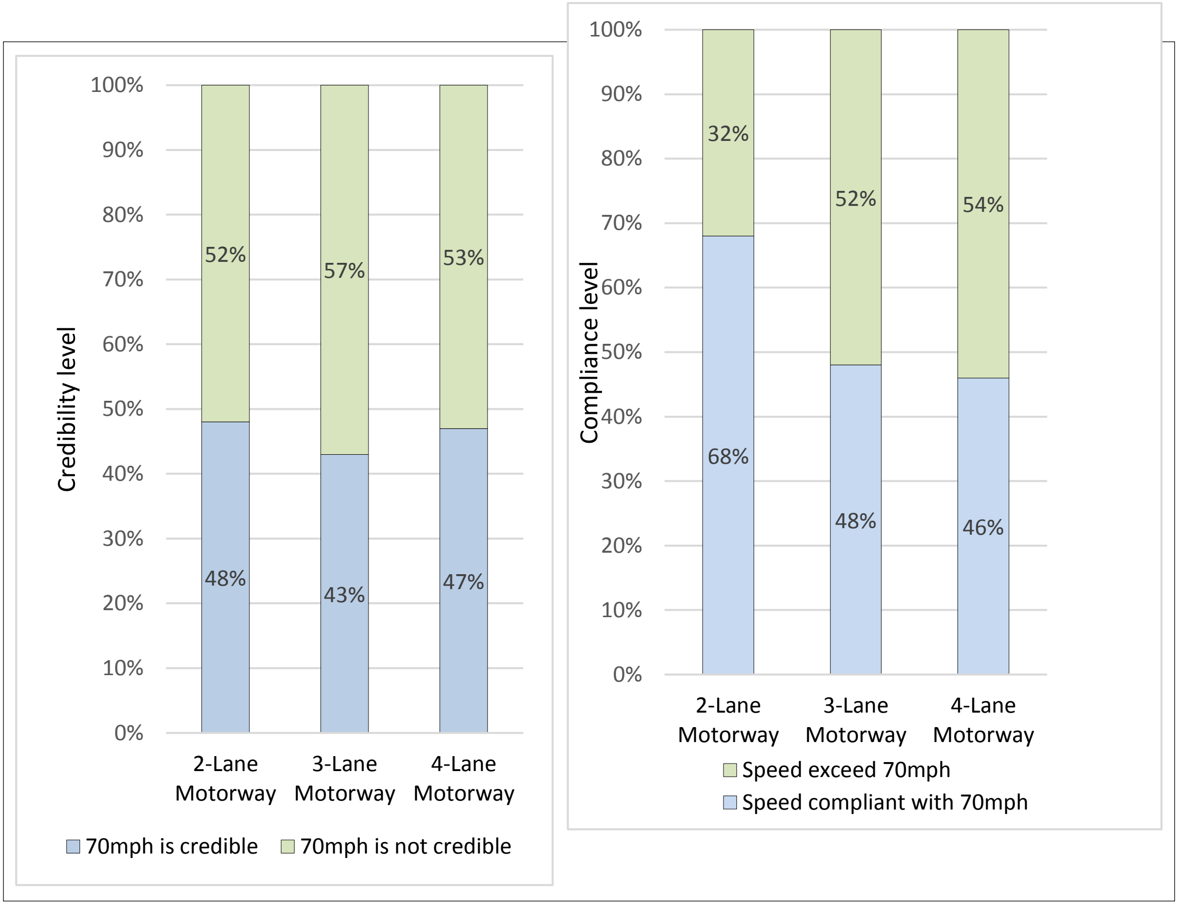


Figure 3-7: Credibility level on 70mph motorway (left)
Compliance level on 70mph motorway (right)

A logistic regression is performed to ascertain the effects of the number of lanes on the likelihood that participants perceived a 70mph speed limit as credible. The binary dependent variable, choice of safe speed limit, needs to appear as two variables, 70mph/not 70mph, with 1= 70mph and 0= not 70mph. The number of lanes is set as a categorical independent variable. As the outcome of logistic regression is binary, Y needs to be transformed so that the regression process can be used. The logit transformation is used in Equation 3-1:

$$\text{logit}(\mathrm{Y}) = \ln\left(\frac{\mathrm{x}}{1-\mathrm{x}}\right) = \alpha + \beta X \tag{3-1}$$

x= probability of event occurring, odds ratio $= \frac{\mathrm{x}}{1-\mathrm{x}}$

The logistic regression result shows that the model correctly classified approximately 53% of cases. On a 2-lane motorway it is 1.2 times more likely for drivers to perceive 70mph as credible than on a 3-lane motorway, and 1.04 times more likely than on a 4-lane motorway. Although the odds ratio result is not statistically significant at 0.05, combined with the descriptive statistics, a 70mph speed limit is more credible on a 2-lane motorway.

To be specific, of the respondents who chose 70mph as a credible speed limit on three different types of motorway, about 70% were willing to drive below the speed limit (Figure 3-8). The compliant/non-compliant ratio was approximately 2.42 on the 2-lane motorway, 2.31 on the 3-lane and 2.92 on the 4-lane. Although almost half of the total respondents chose 70mph as a credible speed limit on motorways, two-thirds chose a driving speed within 70mph, and roughly one-third exceeded the 70mph speed limit. Perceiving 70mph as credible did not necessarily mean compliance with the speed limit.

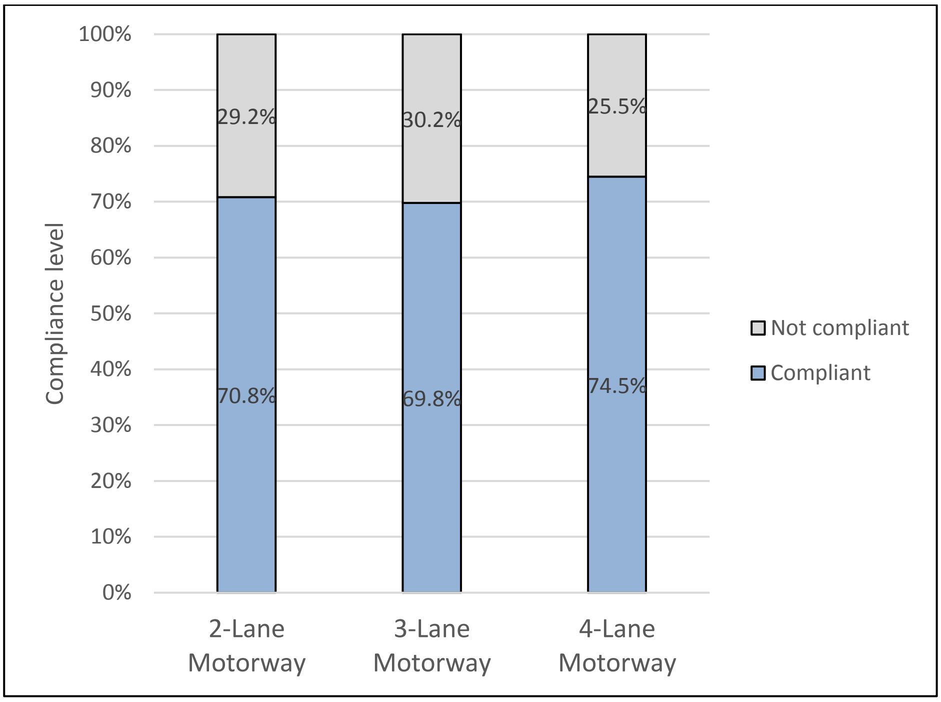


Figure 3-8: Compliance with 70mph speed limit level for those who choose 70mph as credible speed limit on Motorway

A logistic regression is performed to ascertain the effects of the number of lanes on the likelihood that participants' driving speed exceeded the 70mph speed limit. The model correctly classifies approximately 60% of the cases. On the 3-lane motorway, drivers were 2.3 times more likely to exceed the speed limit than on the 2-lane motorway. Drivers on the 4-lane motorway were 1.67 times more likely to exceed the speed limit than on the 2-lane motorway. Although the odds ratio result is not statistically significant at 0.05, combined with the descriptive results, an increasing number of lanes is associated with an increased likelihood of exceeding the 70mph speed limit.

Thus, although a 70mph speed limit on a 2-lane motorway has a relatively high credibility level, not all the respondents who chose 70mph chose a driving speed less than 70mph. On the 4-lane motorway, for those who perceived 70mph as a credible speed limit, the compliance level was slightly higher. Credibility differed from compliance, as 48% of all drivers perceived 70mph to be credible and 68% were willing to drive below 70mph. It can be assumed that the more credible the speed limit is, the more compliant drivers are.

Conversely, drivers' compliance with the 70mph speed limit does not mean they perceive the speed limit as credible. Those who exceed the speed limit did not perceive the road to be dangerous or the need to take care about speed as the roads had rather good conditions. In terms of speed enforcement, speed cameras may work well on motorways for a short stretch of compliance, but this does not mean the speed limit is credible.

3.4.3 Urban motorway speed and speed limit performance

For the urban motorway road scene, the perceived safe speed limit and perceived driving speed are analysed as follows.

2-lane urban motorway

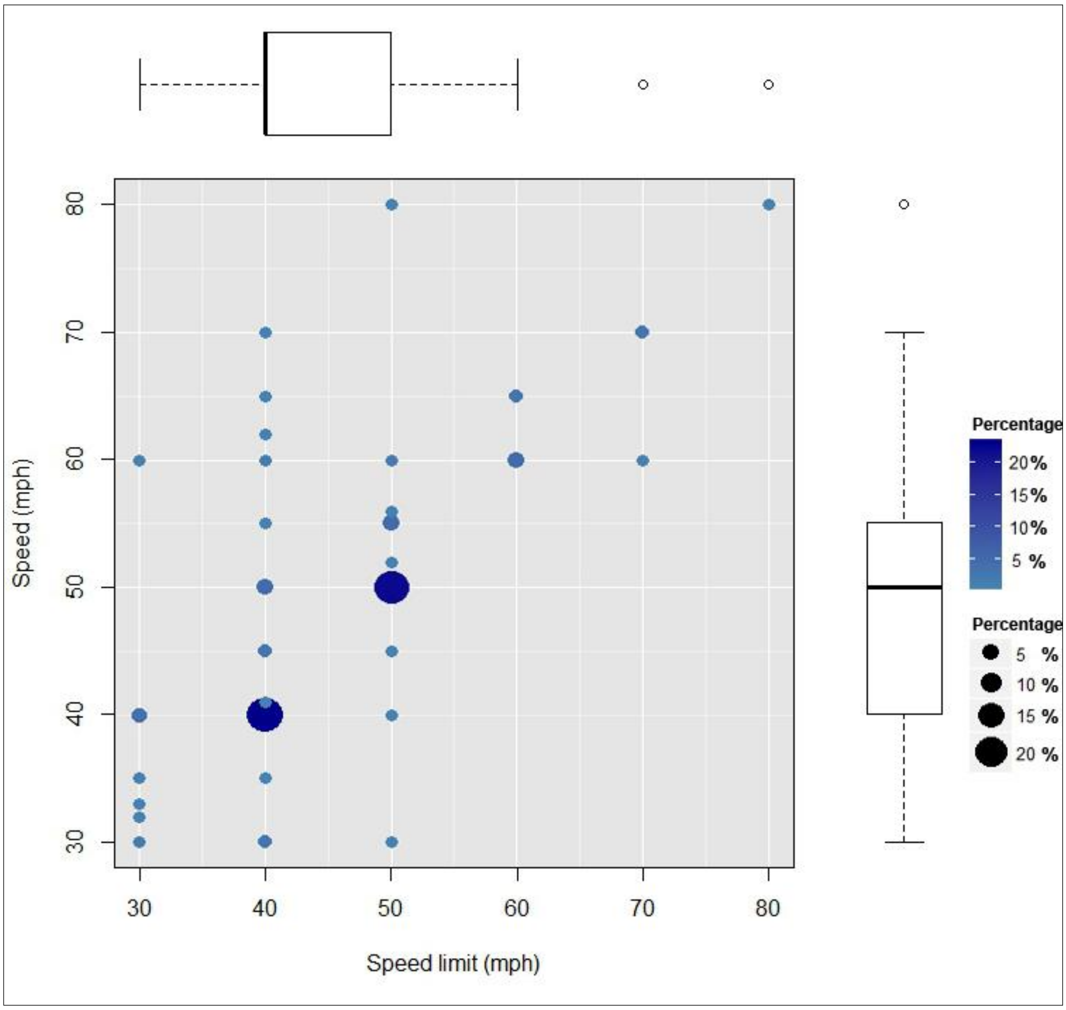


Figure 3-9: 2-lane urban motorway speed limit and speed choice

Table 3-14: 2-lane urban motorway mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	30mph	40mph	50mph	60mph	70mph	80mph	Average
Mean speed (mph)	38.0	43.9	51.4	61.9	67.5	80.0	48.7
Standard deviation (mph)	8.8	9.0	7.1	2.6	5.0	None	11.0

Table 3-15: 2-lane urban motorway speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	30mph	40mph	50mph	60mph	70mph	80mph	Total
Group 1: Speed <=40mph	9%	27%	2%	0	0	0	38%
Group 2: Speed >40mph	1%	15%	33%	8%	4%	1%	62%
Total	10%	42%	35%	8%	4%	1%	100%

On the 2-lane urban motorway, the mean speed was 48.7mph (±11.0) and the 85th percentile speed was 60mph. The mode speed limit was 40mph (42%). The mean speed was significantly higher (8.7mph) than the speed limit ($t(99) = 7.866$, $p < .001$) and 90% exceeded the speed limit.

Table 3-14 shows the speed choice for each speed limit group. A linear regression establishes that perceived safe speed limit can statistically significantly predict perceived choice of speed, $F(1, 98) = 99.808$, $p < .01$ and perceived safe speed limit accounts for 50.5% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive. The test is to explain the difference in choice of speed limit between drivers who obey the speed limit and drivers who exceed the speed limit. In the Chi-square test shown in Table 3-15, seven cells have an expected count of less than 5. A valid result cannot be concluded.

Table 3-16: Mean and standard deviation of preferred speed and speed limit by road scene

Road scene	Preferred Speed				Safe speed limit		Actual speed limit (mph)
	Mean (S.D) (mph)	50th percentile of speed – median (mph)	85th percentile of speed (mph)	Number of drivers exceeding speed limit (percentage)	Mode (%) (mph)	Number of drivers choosing a speed limit greater than the actual speed limit (percentage)	
Urban motorway	48.7 (11.0)	50	60	62 (62%)	40(42%)	48(48%)	**40**

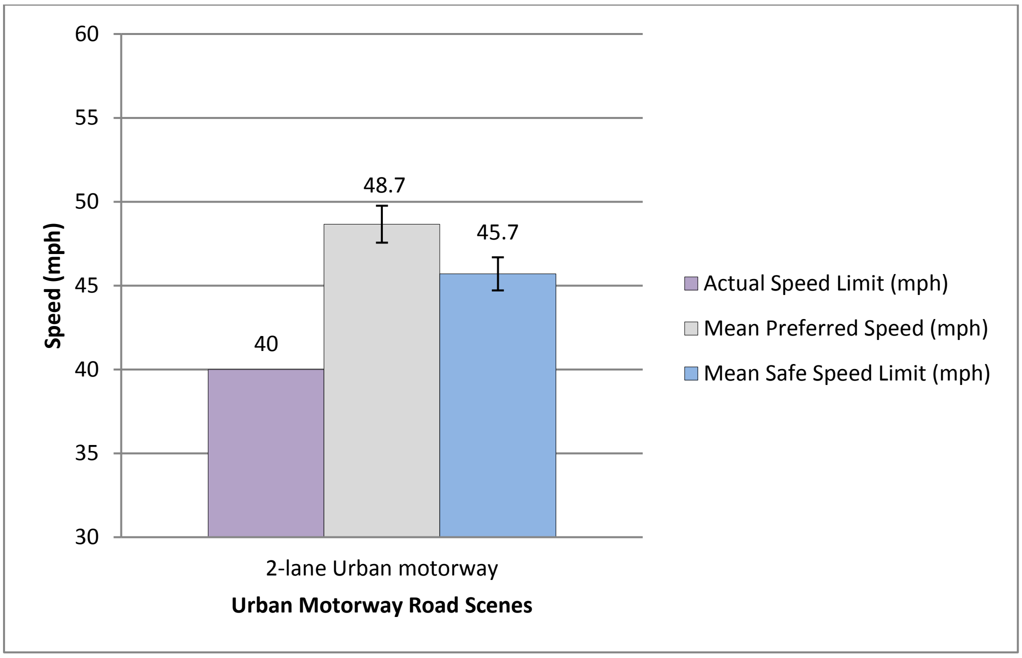


Figure 3-10: Comparison of urban motorway speed limit and speed choice

As shown in Table 3-14 and Figure 3-10, both speed limit and speed choice were higher than the legal speed limit. Although 40mph was the mode speed limit that 42% of the respondents considered credible, more than half the drivers (62%) exceeded the 40mph speed limit, which indicates that drivers did not perceive 40mph as appropriate for the road layout and roadside environment. Urban motorways usually have no hard shoulder, narrower lanes, walls alongside instead of vegetation, and buildings outside the road. As such, 40mph was regarded as too slow for the situation, as using a motorway is mainly a mobility function. The urban motorway was not self-explaining. Therefore, with a lower speed limit credibility on the urban motorway, drivers' compliance with the speed limit was quite low as well, as shown in Figure 3-11. Since 40mph was not credible on the 2-lane urban motorway, it remains unknown what type of road layout and roadside environment would make 40mph speed limits credible on urban motorways. With the speed limit presenting lower credibility, drivers' compliance with the speed limit was quite low too. For each safe speed limit choice, drivers perceived a driving speed either above or below the speed limit as shown in Table 3-17.

Table 3-17: Compliance with chosen speed limit level on urban motorway

Speed limit	Statement	Compliance percentage (%)
40mph	Compliance level for drivers choosing 40mph as the credible speed limit	64.3
	Exceeding speed limit level for drivers choosing the 40mph as the credible speed limit	35.7

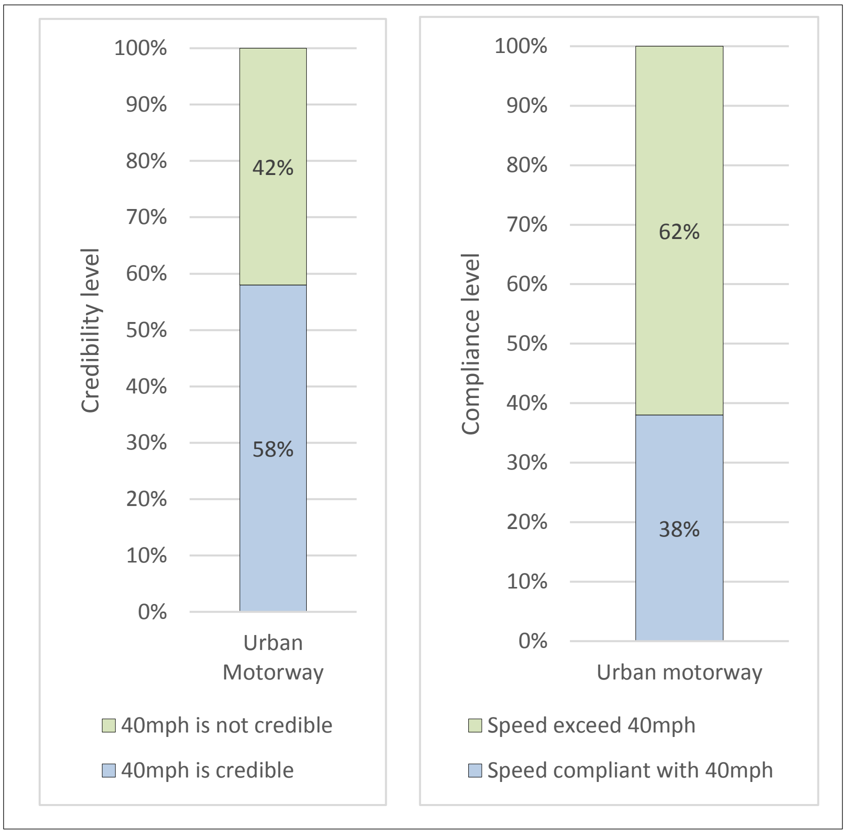


Figure 3-11: Credibility level on 40mph urban motorway (left) Compliance level on 40mph urban motorway (right)

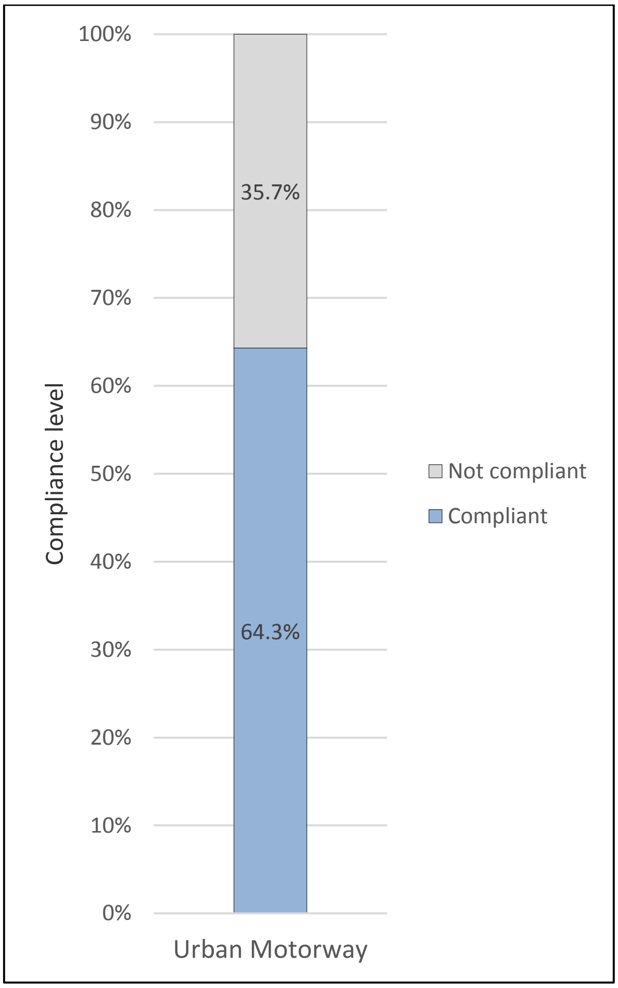


Figure 3-12: Compliance with 40mph speed limit level for those who chose 40mph as the credible speed limit on motorways

As shown in Figure 3-12, the ratio of drivers' compliant/non-compliant with the 40mph speed limit was approximately 1.8. For the respondents who chose 40mph as the credible speed limit, the compliance level was 64.3%, 1.8 times higher than for respondents exceeding the 40mph speed limit.

3.4.4 Rural single carriageway speed and speed limit performance

On a UK single carriageway, the national speed limit is 60mph (96km/h) for cars and other vehicles. The Department for Transport 2010 Speed Survey shows the particular speeding behaviour on 60 mph roads: with 8% of drivers speeding, but only 1% going over 70 mph. The 10-minute average journey speeds observed on single carriageways vary from 30km/h to 95km/h. For 60mph speed limit single carriageways, the Leeds road accident data in 2013 shows that most accidents happened at T or staggered junction and road link. For slight accidents, road links were four times more often the location than T or staggered junctions. Roundabouts were represented twice as often as crossroads in the slight accidents. Serious accidents happened four times more often at road links than T or staggered junctions. Roundabouts, private drives or entrances and crossroads all had approximately the same accident numbers. In this study, road link pictures of straight and curved roads were provided. The perception of the safe speed limit and speed choice were investigated.

Rural single carriageway curve

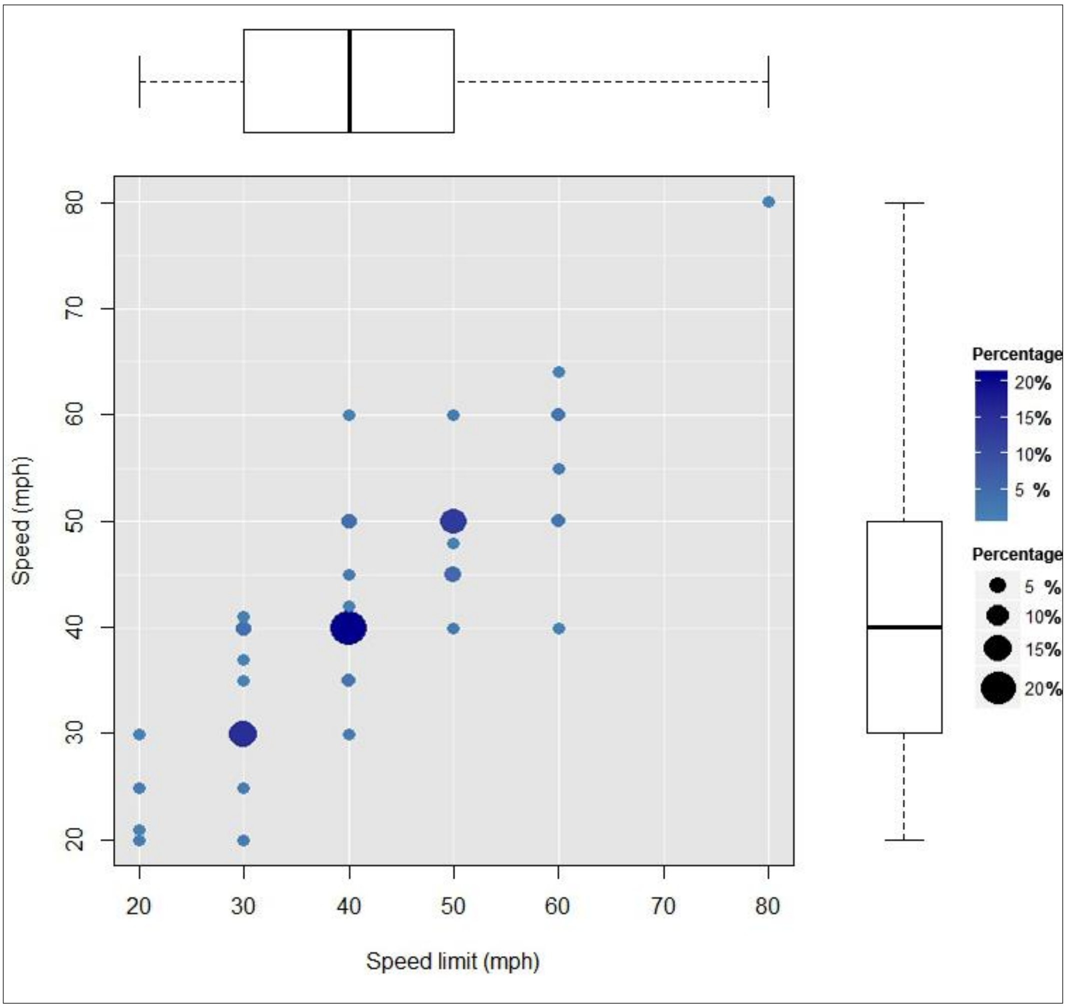


Figure 3-13: Rural single carriageway with curve speed limit and speed choice

Table 3-18: Rural single carriageway with curve mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	20mph	30mph	40mph	50mph	60mph	70mph	80mph	Average
Mean speed (mph)	23.5	31.3	41.1	48.8	54.4	0	80.0	41.0
Standard deviation (mph)	3.9	5.7	5.7	4.8	7.1	0	None	11.0

Table 3-19: Rural single carriageway with curve speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	20mph	30mph	40mph	50mph	60mph	70mph	80mph	Total
Group 1: Speed <=60mph	6%	26%	34%	23%	9%	0	0	98%
Group 2: Speed >60mph	0	0	0	0	1%	0	1%	2%
Total	6%	26%	34%	23%	10%	0	1%	100%

On the rural single carriageway with a curved road, the mean speed was 41.0 mph (±10.9) and the 85th percentile speed was 50mph with 98% of chosen speed <=60mph. The mode speed limit selected was 40mph (34%). A linear regression establishes that perceived safe speed limit can statistically significantly predict perceived choice of speed, $F(1, 98) = 380.697$, $p < .01$ and perceived safe speed limit accounts for 78.9% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive.

Table 3-18 and Table 3-19 show the speed choice for each speed limit group. The test is to explain the difference in choice of speed limit between drivers who obey the speed limit and drivers who exceed the speed limit. 98% of respondents chose a speed less than 60mph, which indicates that the drivers did not perceive 60mph to be appropriate for the road layout and the roadside environment, because 60mph was too high for the conditions. They may have perceived a lower speed limit as more reasonable and safe. Seven cells in Table 3-19 have expected counts of less than 5. Valid results cannot be concluded from the table. From the road users' perspective, the curve on the single carriageway should imply a lower speed limit. The curve led to more fluctuation in the speed limit and speed choice than other road types due to the sharp curve presenting more potential risk for drivers and a need to adjust their speed to the situation. Respondents' perceptions of speed limit and speed were quite different from one another. For each safe speed limit choice, drivers perceived driving speed either above or below the speed limit, as shown in Table 3-20.

Table 3-20: Compliance with chosen speed limit level on rural single carriageway with curve

Speed limit	Statement	Compliance percentage (%)
60mph	Compliance level for drivers choosing 60mph as the credible speed limit	90.0
	Exceeding speed limit level for drivers choosing 60mph as the credible speed limit	10.0
50mph	Compliance level for drivers choosing 50mph as the credible speed limit	91.3
	Exceeding speed limit level for drivers choosing 50mph as the credible speed limit	8.7
40mph	Compliance level for drivers choosing 40mph as the credible speed limit	76.5
	Exceeding speed limit level for drivers choosing 40mph as the credible speed limit	23.5
30mph	Compliance level for drivers choosing 30mph as the credible speed limit	73.1
	Exceeding speed limit level for drivers choosing 30mph as the credible speed limit	26.9

Rural single carriageway straight

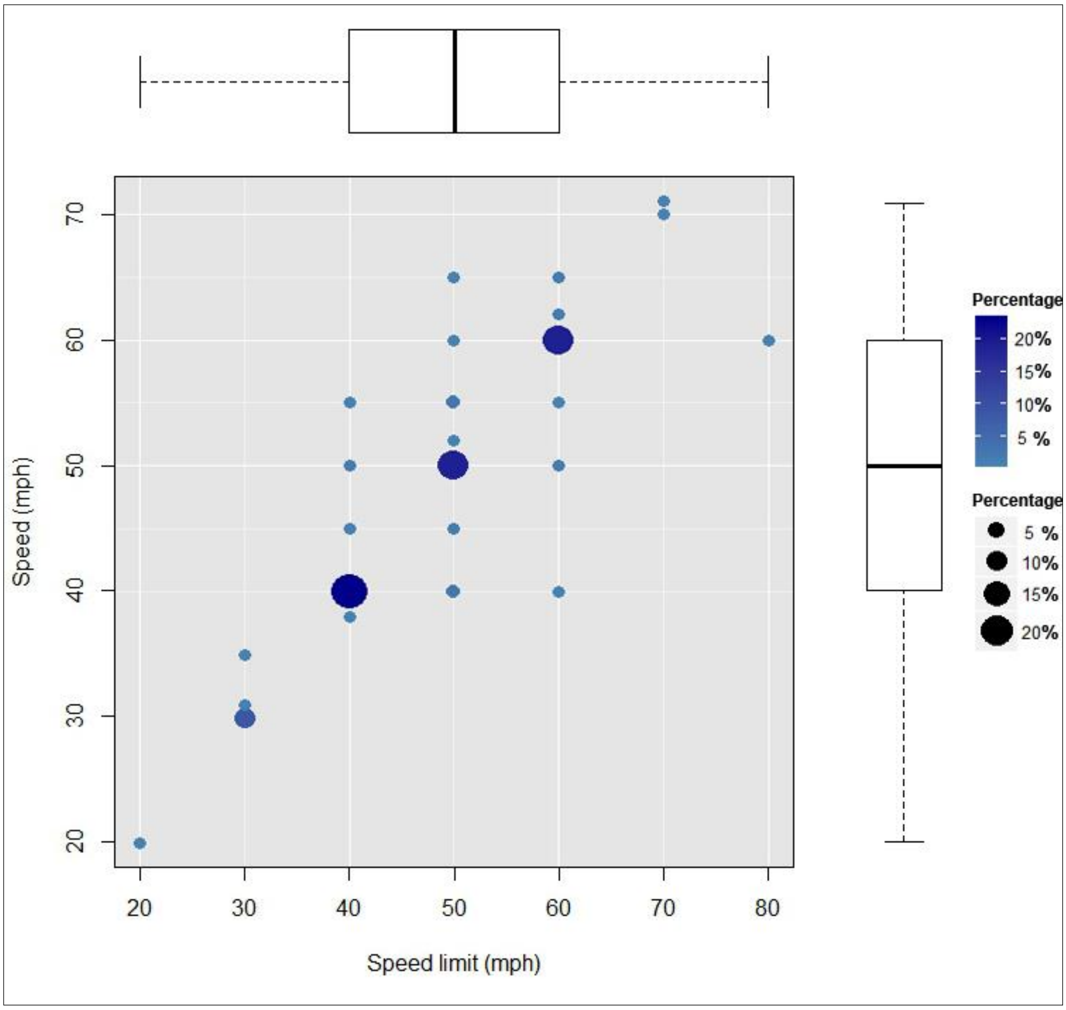


Figure 3-14: Rural single carriageway without curve speed limit and speed choice

Table 3-21: Rural single carriageway without curve mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	20mph	30mph	40mph	50mph	60mph	70mph	80mph	Average
Mean speed (mph)	20	30.5	41.4	50.1	58.9	70.5	60	48.1
Standard deviation (mph)	None	1.5	3.9	5.1	5.0	0.7	None	10.9

Table 3-22: Rural single carriageway without curve speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	20mph	30mph	40mph	50mph	60mph	70mph	80mph	Total
Group 1: Speed <=60mph	1%	11%	24%	29%	23%	0	1%	89%
Group 2: Speed >60mph	0	0%	4%	1%	4%	2%	0	11%
Total	1%	11%	28%	30%	27%	2%	1%	100%

On the rural single carriageway without a curved road, the mean speed was 48.1mph (±10.9) and the 85th percentile speed was 60mph. 89% of respondents chose a speed limit equal to or below 60mph. The mode speed limit was 50mph (30%). Table 3-21 shows the speed choice for each speed limit choice group. A linear regression establishes that perceived safe speed limit can statistically significantly predict perceived choice of speed, $F(1, 98) = 431.846$, $p < .01$ and perceived safe speed limit accounts for 81.5% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive.

In Table 3-20, the test is to explain the difference in choice of speed limit between drivers who obey the speed limit and drivers who exceed the speed limit. Valid results could not be concluded from the table due to 10 cells having an expected count of less than 5. This indicates that most of the drivers did not perceive 60mph to be appropriate for the road layout and roadside environment, and 60mph was too high for the conditions. For each safe speed limit choice, drivers perceived the driving speed as either above or below the speed limit, as shown in Table 3-21.

For the respondents who chose 50mph as the credible speed limit on the rural single carriageway, the compliant/non-compliant ratio was 10.49 on the curved road and 4 on the straight road. If 50mph were the advisory speed limit, there would be a higher level of compliance. Driving speed on the curved road showed a higher level of compliance than on the straight road, although 23% of the respondents saw 50mph as credible on the curved road and 30% of the respondents saw 50mph as credible on the straight road. For compliance with 50mph speed limit level, a higher percentage of compliance with a 50mph speed limit was seen on the curved rural single carriageway.

For the respondents who chose 40mph as the credible speed limit on the rural single carriageway, the compliant/non-compliant ratio was 3.25 and 6 on the curved and straight road, respectively. Although 40mph was more credible on the curved rural road, not all respondents had a driving speed of less than 40mph. The driving speed on the straight rural road showed higher compliance for a 40mph speed limit. Although 34% of the total respondents perceived 40mph as credible on the curved road and 28% of the total respondents perceived 40mph as credible on the straight road, a higher level of compliance with the 40mph speed limit level can be seen on the straight rural single carriageway.

Table 3-23: Compliance with chosen speed limit level on rural single carriageway

Speed limit	Statement	Compliance percentage (%)
60mph	Compliance level for drivers choosing 60mph as the credible speed limit	85.2
	Exceeding speed limit level for drivers choosing 60mph as the credible speed limit	14.8
50mph	Compliance level for drivers choosing 50mph as the credible speed limit	80.0
	Exceeding speed limit level for drivers choosing 50mph as the credible speed limit	20.0
40mph	Compliance level for drivers choosing 40mph as the credible speed limit	85.7
	Exceeding speed limit level for drivers choosing 40mph as the credible speed limit	14.3
30mph	Compliance level for drivers choosing 30mph as the credible speed limit	81.8
	Exceeding speed limit level for drivers choosing 30mph as the credible speed limit	18.2

Rural single carriageway group comparison

Table 3-24 and Figure 3-15 show the speed and speed limit choice for the curved and straight rural road groups. On the rural single carriageway, the mean speed was 41.0 mph (±10.9) and the 85th percentile speed was 50mph. The mode speed limit was 40mph (34%). The curve rural road mean speed was 7.1 mph lower than the straight rural road. Most respondents perceived 40mph to be the appropriate speed limit on the curve rural road. Almost all the respondents intended to drive below the 60mph speed limit.

Table 3-24: Comparison of mean and standard deviation of preferred speed and speed limit by road scene

Road scene	**Preferred choice of speed**				**Choice of safe speed limit**		**Actual speed limit (mph)**
	Mean (S.D) (mph)	50th percentile of speed –median (mph)	85th percentile of speed (mph)	Number of drivers exceeding speed limit (percentage)	Mode (%) (mph)	Number of drivers choosing speed limit greater than actual speed limit (percentage)	
Rural road, presence of curve	41.0 (10.9)	40	50	2(2%)	40(34%)	1(1%)	**60**
Rural road, absence of curve	48.1 (10.8)	50	60	7(7%)	50(30%)	3(3%)	**60**

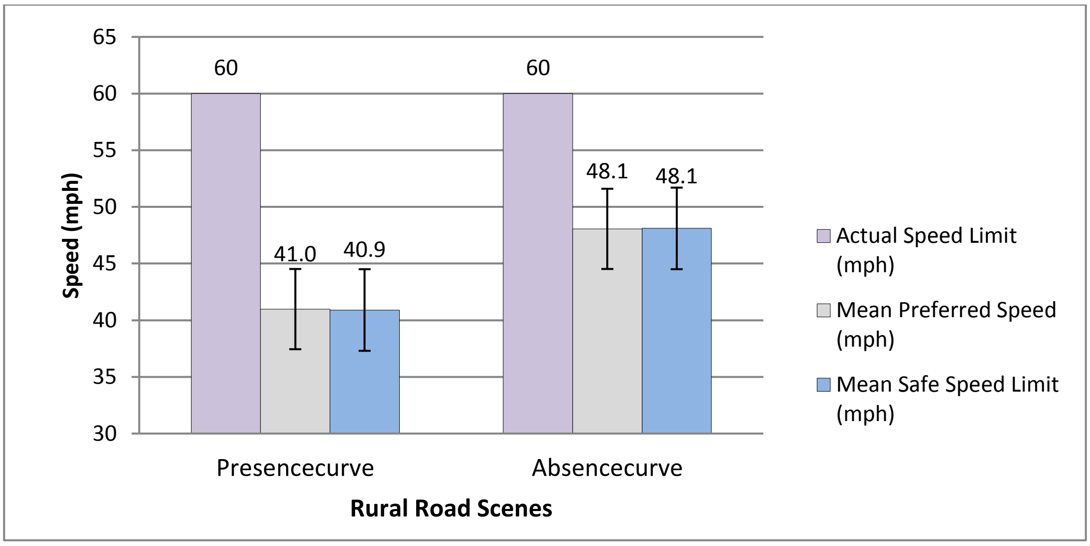


Figure 3-15: Comparison of rural single carriageway speed limit, mean preferred speed and mean safe speed limit

Rural single carriageway road scenes were evaluated for one road with a sharp curve and one straight road. Both scenes had vegetation at the roadside, with a speed limit of 60mph. Curve presence and curve absence showed the speed and speed limit not to be in accordance with the actual speed limit, as follows.

Speed limit

Comparing the two scenes in Figure 3-16 and Figure 3-17, both speed limit choices varied from 20mph to 80mph. The number of respondents who chose the actual 60mph speed limit in the presence and absence of the curve was 10% and 27%, respectively. On the curved road, 34% of the respondents affirmed that 40mph was an appropriate safe speed limit and 6% of the respondent chose 20mph as the speed limit, which showed that they perceived the rural road to have a higher risk situation. On the straight road, more respondents perceived 60mph as appropriate than on the curved road. The presence or absence of the curve was the main factor affecting speed limit credibility.

Speed

For the speed choice result, the proportion of respondents' driving speed below the 60mph speed limit in the presence and absence of the curve was 98% and 89%, respectively. The main difference was that drivers perceived driving an average 19mph below the speed limit on the curved road and drivers tended to drive an average 12mph below the speed limit on the straight road. The presence or absence of the curve was the main factor affecting driving speed. Although there was high compliance with the speed limit, 60mph was apparently too high on the rural single carriageway. Respondents preferred a lower speed limit on rural single carriageways. The lower speed limit set needs to be explored further.

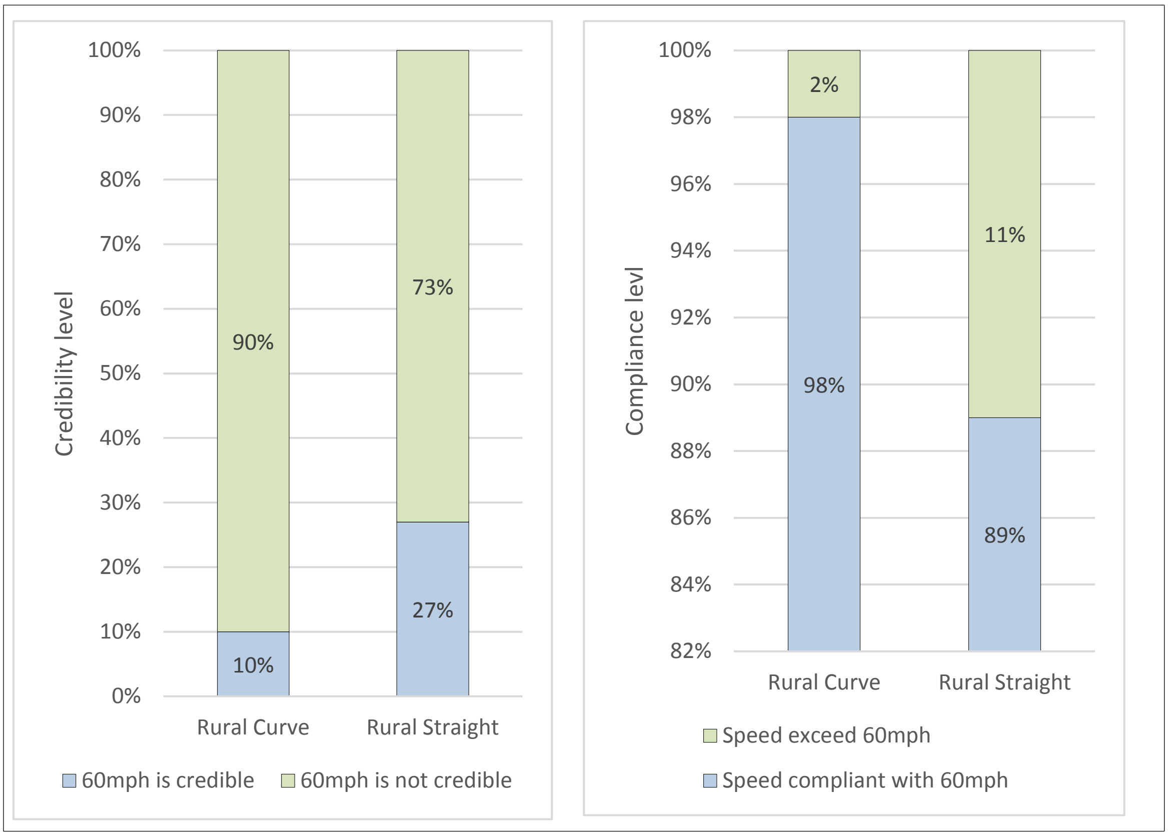


Figure 3-16: Credibility level of 60mph on rural single carriageway (left) Compliance level of 60mph on rural single carriageway (right)

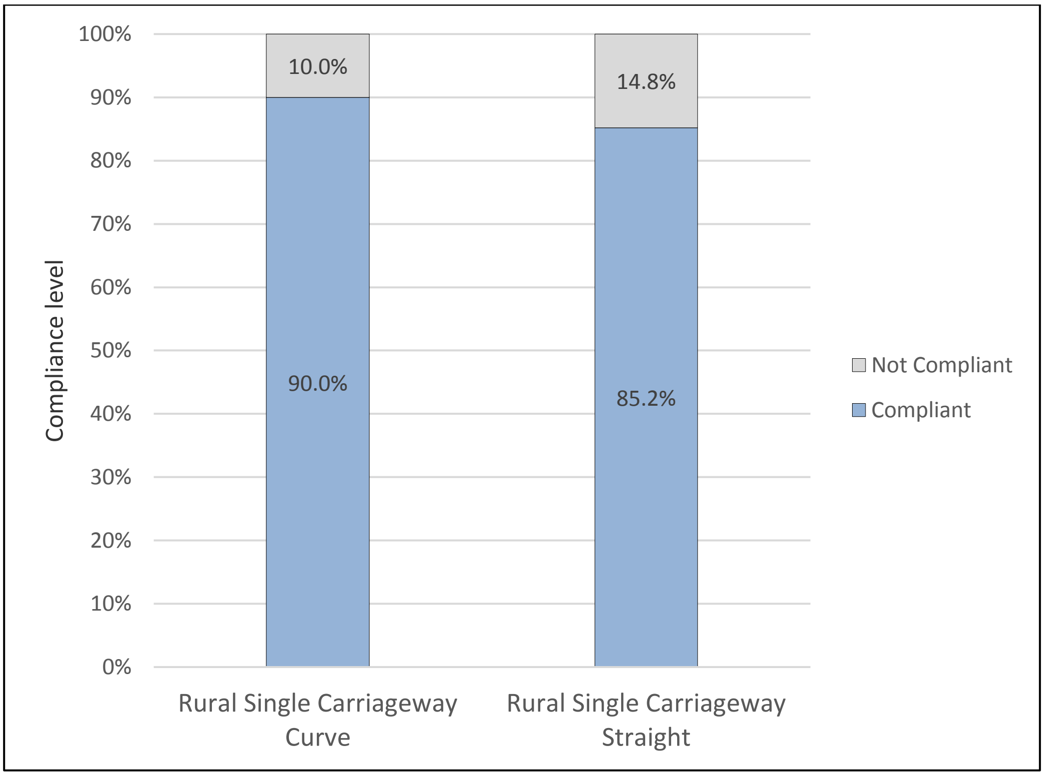


Figure 3-17: Compliance with 60mph speed limit by those who choose 60mph as the credible speed limit on the rural single carriageway

3.4.5 Urban road speed and speed limit performance

For the urban road scenes, the perceived safe speed limit and perceived driving speed are analysed as follows.

Urban road with vulnerable road users (VRU)

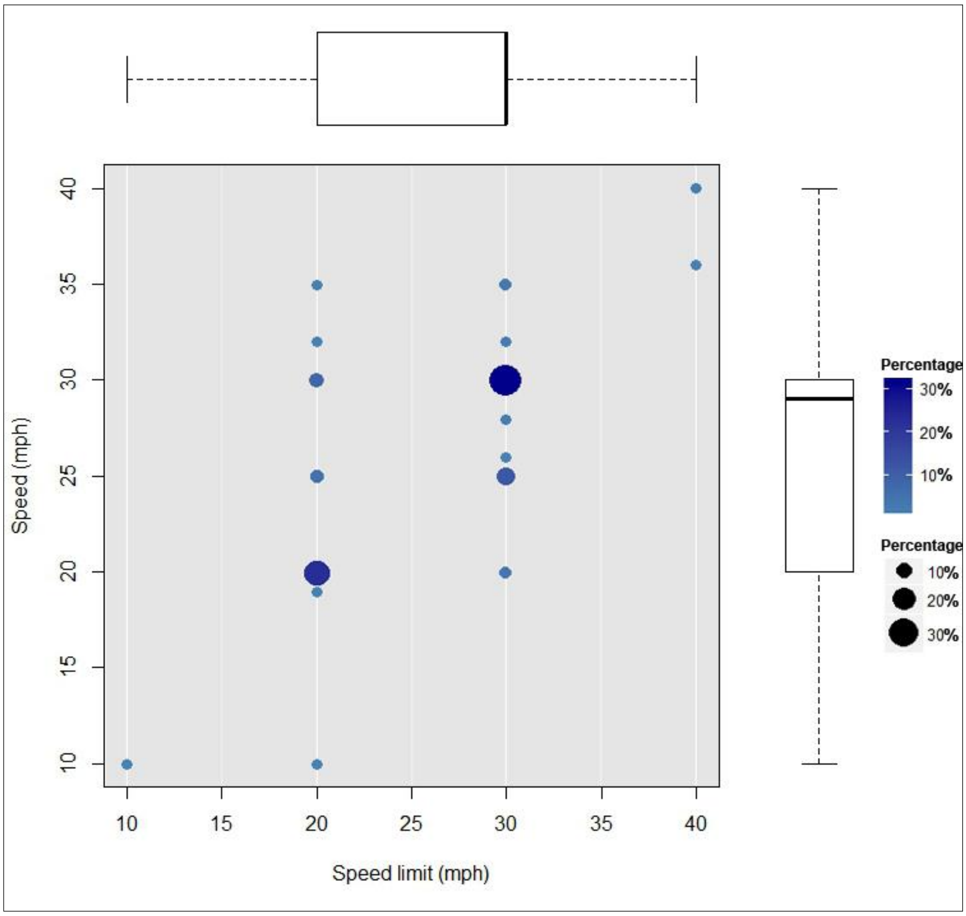


Figure 3-18: Urban road with VRU speed limit and speed choice

Table 3-25: Urban road with VRU mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	10mph	20mph	30mph	40mph	Average
Mean speed (mph)	10.0	23.0	28.4	38.7	26.4
Standard deviation (mph)	None	5.1	3.5	2.3	5.6

Table 3-26: Urban road with VRU speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	10mph	20mph	30mph	40mph	Total
Group 1: Speed <=30mph	1%	38%	51%	0	90%

Group 2: Speed >30mph	0	2%	5%	3%	10%
Total	1%	40%	56%	3%	100%

The mean speed on the urban road with VRU present was 26.4mph (±5.6) and the 85th percentile speed was 30mph. 90% of the respondents chose a speed <=30mph. A linear regression establishes that perceived safe speed limit can statistically significantly predict perceived choice of speed, $F(1, 98) = 71.116$, $p < .01$ and perceived safe speed limit accounts for 42.1% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive.

Table 3-25 shows the speed choice for each speed limit group. The test is to explain the difference in choice of speed limit between drivers who obeyed the speed limit and drivers who exceed the speed limit. In the Chi-square test shown in Table 3-26, five cells have expected counts of less than 5. Valid results cannot be concluded from the table. Considering the mode speed limit choice, 56% of the respondents chose 30mph as the appropriate speed limit. 51% of the respondents chose <=30mph and perceived 30mph to an appropriate speed limit. Therefore, 30mph can be seen to be the credible speed limit for 51% of respondents. The respondents whose driving speeds were greater than the speed limit indicate that 30mph was not a credible speed limit. In addition, a considerable 25% of respondents chose a speed equal to or less than 20mph and perceived a 20mph speed limit to be appropriate for the environment, due to the VRU present on the road. For each safe speed limit choice, drivers perceived driving speeds either above or below the speed limit, as shown in Table 3-27.

Table 3-27: Compliance with chosen speed limit on urban road with VRU

Speed limit	**Statement**	**Compliance percentage (%)**
30mph	Compliance level for drivers choosing 30mph as the credible speed limit	91.1
	Exceeding speed limit level for drivers choosing 30mph as the credible speed limit	8.9
20mph	Compliance level for drivers choosing 20mph as the credible speed limit	62.5
	Exceeding speed limit level for drivers choosing 20mph as the credible speed limit	37.5

Urban road with no vulnerable road users (non-VRU)

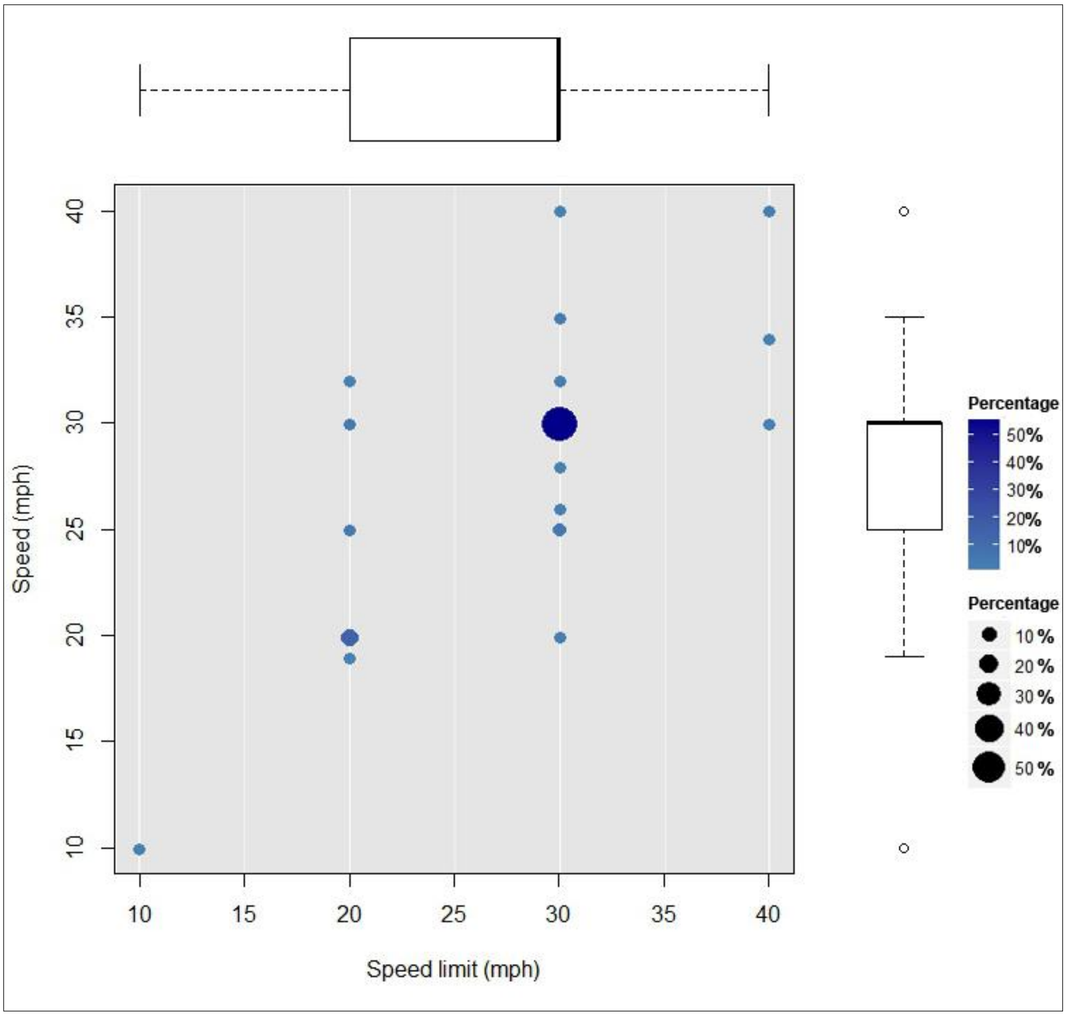


Figure 3-19: Urban road without VRU speed limit and speed choice

Table 3-28: Urban road without VRU mean choice of speed for each chosen speed limit group

Choice of speed limit / Choice of speed	10mph	20mph	30mph	40mph	Average
Mean speed (mph)	10	22.84	29.69	36	28.0
Standard deviation (mph)	None	4.29	2.75	4.89	5.0

Table 3-29: Urban road without VRU speed limit and speed choice contingency table

Choice of speed limit / Choice of speed	10mph	20mph	30mph	40mph	Total
Group 1: Speed <=30mph	1%	24%	64%	1%	90%
Group 2: Speed >30mph	0	1%	6%	3%	10%
Total	1%	25%	70%	4%	100%

The mean speeds for each speed limit choice group are summarised in Table 3-28. The mean speed on the urban road with VRU absent was 28.0mph (±5.0) and the85th percentile speed was 30mph. A linear regression establishes that perceived safe speed limit can statistically significantly predict perceived choice of speed, $F(1, 98) = 129.109$, $p < .01$ and perceived safe speed limit accounts for 56.8% of the explained variability in choice of speed. The higher the speed limit drivers perceived, the higher speed they tended to drive. 90% of the respondents chose speed <=30mph. The mode speed limit was 30mph (70%). The test is to explain the difference in choice of speed limit between drivers who obey the speed limit and drivers who exceed the speed limit. In the Chi-square test shown in Table 3-29, five cells have expected counts less than 5. Valid results cannot be concluded from the table. Drivers whose speed obeyed the speed limit (less than 30mph) tended to have a greater speed limit choice equal to or less than 30mph, compared to their counterparts. For each safe speed limit choice, drivers perceived driving speed either above or below the speed limit as shown in Table 3-30.

Table 3-30: Compliance with chosen speed limit level on urban road without VRU

Speed limit	Statement	Compliant Percentage (%)
30mph	Compliance level for drivers choosing 30mph as the credible speed limit	91.4
	Exceeding speed limit level for drivers choosing 30mph as the credible speed limit	8.6
20mph	Compliance level for drivers choosing 20mph as the credible speed limit	64.0
	Exceeding speed limit level for drivers choosing 20mph as the credible speed limit	36.0

Urban road group comparison

Table 3-31: Mean and standard deviation of preferred speed and speed limit by road scene

Road scene	Preferred choice of speed				Choice of safe speed limit		Actual speed limit (mph)
	Mean (S.D) (mph)	50th percentile of speed – median (mph)	85th percentile of speed (mph)	Number of drivers exceeding speed limit (percentage)	Mode (%) (mph)	Number of drivers choosing speed limit greater than the actual speed limit (percentage)	
Urban road, presence of VRU	26.4 (5.6)	29	30	10 (10%)	30(56%)	3(3%)	**30**
Urban road, absence ofVRU	28.0 (5.0)	30	30	10 (10%)	30(70%)	4(4%)	**30**

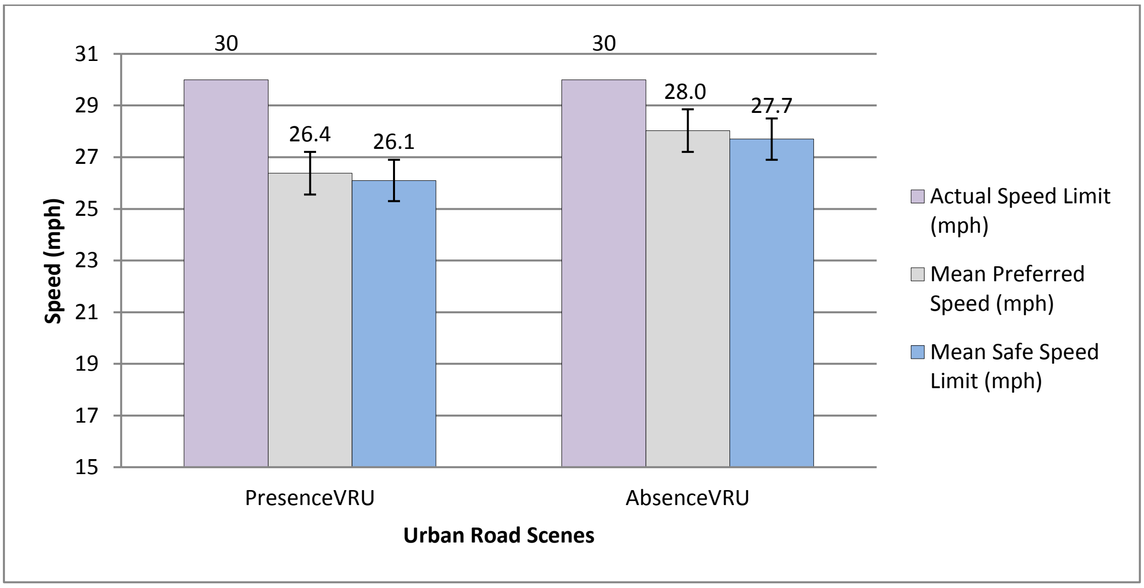


Figure 3-20: Comparison of urban road without VRU speed limit and speed choice

Speed limit

Comparing Table 3-31 and Figure 3-20, the number of respondents choosing the actual speed limit of 30mph as their speed limit choice for VRU present and VRU absent was 56% and 70%, respectively. For the urban road without VRU, more than 70% of respondents chose that speed and speed limit range. 64% of respondents chose a speed <=30mph and perceived 30mph as the safe speed limit. Therefore, 30mph was a credible speed limit for 64% of respondents. The respondents whose driving speeds were greater than the speed limit indicated that 30mph was not a credible speed limit. If more types of road users were present on the road, the interaction between motorists and VRU would be complicated and the number of potential conflicts would be greater. Therefore, 30mph was more credible without VRU than with VRU.

Speed

For the speed choice result, the mean speed for both urban roads was lower than 30mph. The proportion of respondents' compliant with the 30mph speed limit with VRU present and VRU absent was 90% and 90%, respectively. For the VRU present urban road scenario, although 40% of the respondents perceived 20mph to be a safe speed limit for drivers, cyclists and pedestrians, not all were willing to drive within the 20mph limit. Although the speed limit was highly credible on the VRU absent road, compliance was lower. Risk perception with VRU involved on the road was the main reason for speed limit perception and driving speed behaviour being different with and without VRU. If more types of road users were present on the road, the interaction between the motorists and the VRU would be complicated and the number of potential conflicts would be greater.

In urban areas, various types of vehicle use the same roads. This leads to high potential risks, especially for non-motorised or vulnerable road users. Separation of road-user types is one way to substantially improve safety (Shefer and Rietveld, 1997). Another way is 20mph zones which significantly decreased the risk of being injured in a collision. Their greater use would reduce the number of traffic injuries in the UK. Research also shows that, according to a survey, the overwhelming majority of the public want to see a 20mph speed limit introduced in built-up areas, including around schools and town centres (ITV, 2014). The Go 20 campaign proposes changing the default speed limit across areas to make the most cost-effective strides towards 20mph limits in villages, towns and cities (Living Street, 2014). In addition, vehicles' situations differ from each other, especially on urban roads. Driving behaviour, such as accelerating, decelerating, car following, overtaking, turning and slow driving can all be observed on urban roads. Due to driving behaviours being more complex on urban roads than other types of roads, more types of crashes occur. The degree to which people feel safe is related to the separation of types of traffic and the share of heavy traffic (SWOV, 2012b).

For the respondents who chose 30mph as the credible speed limit on urban roads, the compliance with the speed limit is shown in Figure 3-21 and Figure 3-22. The compliant/ non-compliant ratio was approximately 10.2 and 10.7 on the urban road with VRU and the urban road without VRU, respectively. Driving speed on the urban road without VRU had almost the same compliance levels as with VRU. For the respondents who chose 20mph as the credible speed limit on urban roads, the compliant/non-compliant ratio was approximately 1.7 and 1.8 on the urban road with VRU and the urban road without VRU, respectively.

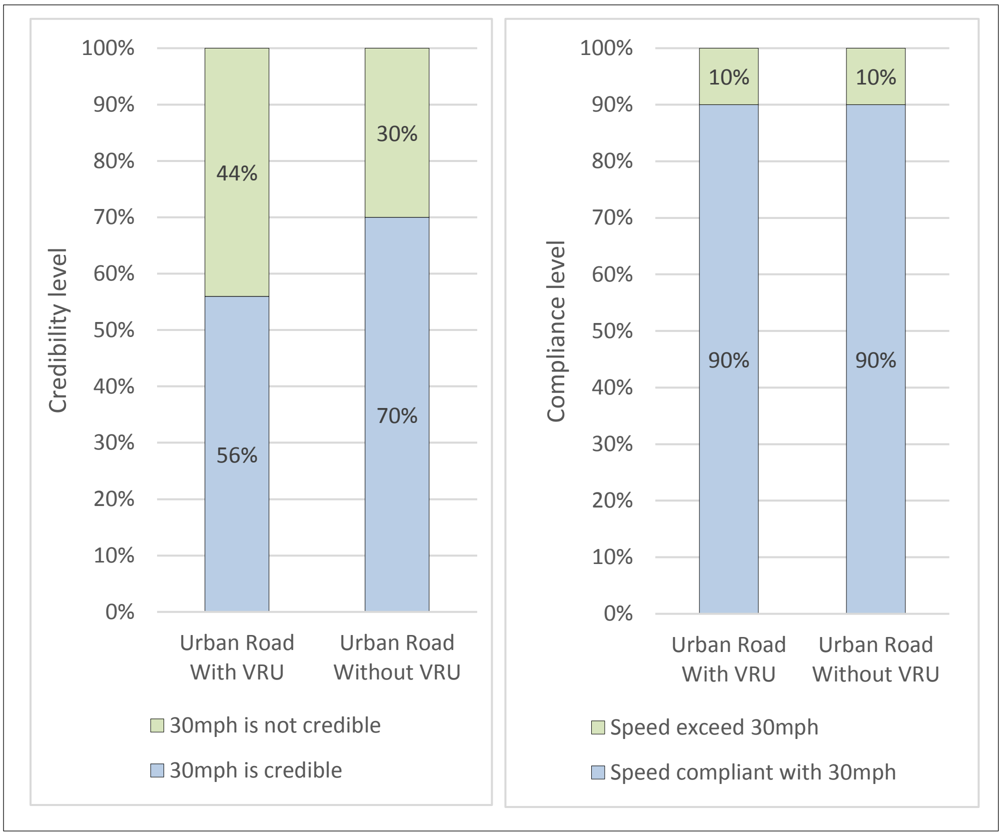


Figure 3-21: Credibility level on 30mph urban road (left) Compliance level on 30mph urban road (right)

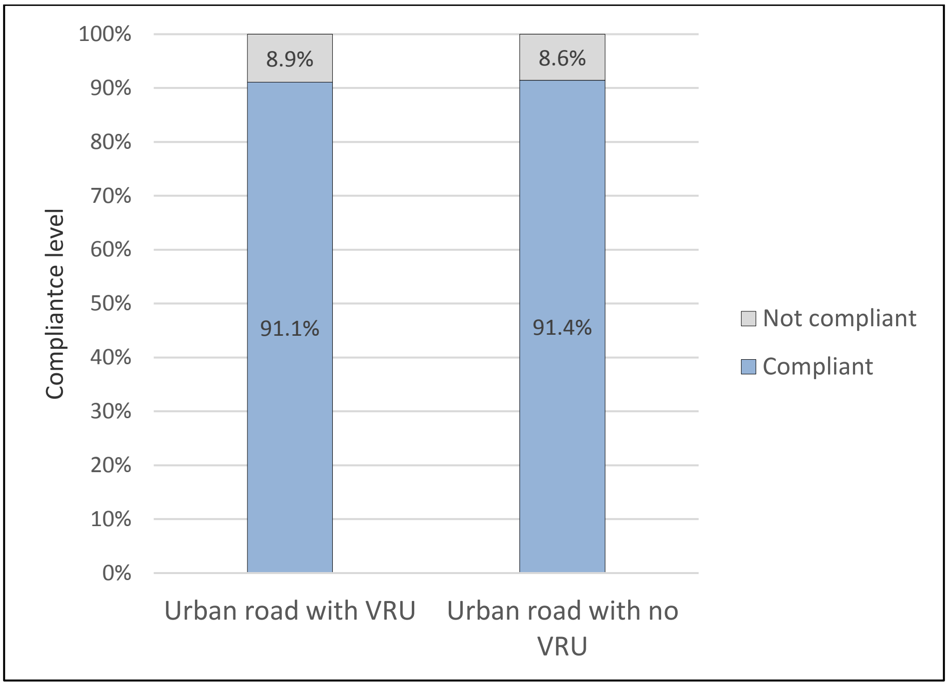


Figure 3-22: Compliance with 30mph speed limit levels for those who choose 30mph as credible speed limit on Urban Road

3.4.6 The effect of personal characteristics on speed limit credibility and speed choice

A conclusion needs to be drawn regarding the effects of age, gender and driving experience on drivers' speed/speed limit perception. The Department for Transport (2012) show that 22% of personal injury road accidents involve at least one young car driver aged 17 to 24. Rolls and Ingham (1992) indicate a number of factors which might explain the differences in driver behaviour and performance in younger male groups (17-25 years old). To be specific, previous literature (Oltedal and Rundmo, 2006; Jonah, 1997; Jonah et al., 2001) shows that young male drivers and high sensation seekers prefer higher speed than their counterparts. Young drivers are less competent at scanning the details of the driving environment for road safety than older drivers' defined as from 56 to 71 years (McPhee et al., 2004). In the current study, the age groups used for the analysis are 17-25 for young drivers, 26-55 for middle-aged drivers and 56+ for older drivers. Young drivers with only a few years of driving experience have a higher tendency for accidents. 20% of drivers aged 17-20 have an 'own fault' accident per year, while for drivers aged 31-40 the figure is 4.5% (Rolls and Ingham, 1992). Those with driving experience of less than three years are defined as novice drivers while those with driving experience greater than three years are defined as well-experienced drivers. Well-experienced drivers are more aware of potential risk and more able to adapt their speed to the environment to avoid danger. For receiving speeding tickets, drivers are divided into two groups, those with no speeding tickets and those with speeding tickets.

Safe Speed limit

Table 3-32 presents the mode safe speed limit choice by gender, age, driving experience and speeding tickets. The numbers in red represent choices of safe speed limit which are different from national speed limits.

On the 2-lane motorway, a 70mph speed limit was credible for all subgroups. On the 3-lane motorway, a 70mph speed limit was not credible for males, aged 26-55 with driving experience >3 years and having speeding tickets, who presented a higher speed limit. On the 4-lane motorway, a 70mph speed limit was not credible for males, aged 26-55 and having speeding tickets, who preferred a higher speed limit.

On the urban motorway and urban roads, all the subgroups had a common choice of speed limit which was in accordance with the urban motorway speed limit of 40mph.

On the rural single carriageway with a curve, the speed limit 60mph was not credible for all sub-groups of respondents. All the subgroups preferred 40mph, except those aged 26-55 and with speeding tickets, who preferred 30mph. Apparently, the rural single carriageway with a curve needs a more credible speed limit. A 60mph speed limit on the straight rural single carriageway was not credible for the following groups: females, drivers aged<=25 or 56+, those with driving experience <=3 years and those without speeding tickets, who perceived that a lower speed limits would be credible.

Table 3-32: Mode safe speed limit for subgroups of respondents

	Gender		Age			Driving experience		Speeding tickets		National Speed limit
Road scenes	Male (N=52)	Female (N=48)	<=25 (N=28)	26-55 (N=57)	56+ (N=15)	<=3 (N=20)	>3 (N=80)	None (N=86)	Have (N=14)	
2-lane motorway	70	70	70	70	70	70	70	70	70	70
3-lane motorway	80	70	70	80	70	70	80	70	80	70
4-lane motorway	80	70	70	80	70	70	70	70	80	70
Urban motorway	40	40	40	40	40	40	40	40	40	40
Rural single carriageway curve	40	40	40	30	40	40	40	40	30	60
Rural single carriageway straight	60	40	50	60	40	50	60	50	60	60
Urban road with VRU	30	30	30	30	30	30	30	30	30	30
Urban road without VRU	30	30	30	30	30	30	30	30	30	30

Preferred driving speed

Table 3-33 presents the results of the one sample T-Test, showing the average scores for preferred driving speed by gender, age, driving experience and speeding tickets (the symbol* represents significant result, $p<.05$).

On the motorway, the preferred speeds of male drivers were significantly higher than those of female drivers for all numbers of lanes. The female group had a more conservative preferred speed on the motorway. These results are in accordance with previous studies. Drivers with speeding tickets wanted to drive faster, reflected in their preferred speed. At the same time, the preferred speeds of the middle aged (26-55) group were significantly higher than the young and old groups on motorways.

Although well-experienced drivers may be more aware of potential risks and adapt their speed to the environment to avoid danger, the well-experienced driver group drives faster than the novice driver group on motorways. Drivers who had previously received speeding tickets chose a higher speed on all motorways. According to the independent T-test and one-way ANOVA results, for comparison of group differences, the two gender groups showed a different perception of speed on the 2-lane motorway ($t(98)=2.569$, $p=.012$). The two speeding ticket groups showed a different perception of speed on the 2-lane motorway ($t(98)=-2.908$, $p=.004$). The other groups did not show any significant differences.

On the urban motorway, the well-experienced driver group gave speeds significantly lower than those of novice drivers. There exists no significant difference for preferred speed across gender groups or age groups.

On the rural single carriageway, in order to find any significant difference regarding speed limits within each demographic group, the T-test showed a significant effect of two gender groups on the straight rural single carriageway (t(98)=2.188, p=.031).

The well-experienced driver group preferred to drive faster than the novice driver group on motorways, whereas, on the urban motorway, rural single carriageway with curve and urban road, their speeds were significantly lower than novice drivers. Drivers who had previously received speeding tickets, gave a higher speed in all motorway, rural road and urban road situations, except urban road without VRU. Three age groups showed a different perception of speed in the presence of VRU (F (2, 97) =3.201, p=.045) and absence of VRU (F (2, 97) =3.176, p=.046).

Table 3-33: Mean (S D) and T-test result for subgroups of respondents' preferred speed

	Gender		Age			Driving experience		Speeding tickets		National Speed limit
Road scene	Male (N=52)	Female (N=48)	<=25 (N=28)	26-55 (N=57)	56+ (N=15)	<=3 (N=20)	>3 (N=80)	None (N=86)	Have (N=14)	
2-lane motorway	71.4 (11.3)	66.4* (8.8)	69.1 (8.8)	69.6 (11.2)	67.5 (9.5)	67.0 (9.2)	69.6 (10.4)	67.9* (8.4)	76.3 (16.5)	70
3-lane motorway	76.2* (10.1)	72.6 (9.3)	73.7* (9.3)	75.7* (9.9)	71.1 (9.1)	73.1 (10.0)	74.8* (9.6)	73.8* (8.6)	78.6* (14.2)	70
4-lane motorway	76.7* (7.9)	73.8* (8.1)	75.3* (9.2)	75.9* (7.9)	73.9* (6.9)	73.9 (8.6)	75.8* (7.9)	74.9* (8.0)	78.2* (8.2)	70
Urban motorway	48.4* (11.7)	48.8* (10.7)	52.4* (12.1)	47.2* (10.7)	47.0* (8.4)	51.7* (12.7)	47.9* (10.4)	47.9* (10.0)	52.8* (15.5)	40
Rural single carriageway curve	41.6* (10.8)	40.3* (11.6)	43.8* (12.5)	40.3* (10.7)	38.1* (8.0)	43.3* (14.7)	40.4* (9.8)	40.7* (10.9)	42.5* (11.7)	60
Rural single carriageway straight	50.6* (10.4)	45.6* (11.0)	46.4* (12.6)	49.5* (10.1)	45.4* (9.4)	46.2* (13.3)	48.5* (10.2)	47.3* (10.9)	52.5* (9.3)	60
Urban road with VRU	26.2* (5.9)	26.4* (5.3)	28.0 (5.2)	25.2* (5.5)	27.9 (5.8)	26.6* (5.6)	26.3* (5.6)	26.3* (5.7)	26.4* (4.5)	30
Urban road without VRU	27.7* (5.4)	28.3* (4.5)	29.9 (4.1)	27.1* (5.0)	28.2 (5.7)	29.4 (4.2)	27.6* (5.1)	28.1* (5.1)	27.8 (4.7)	30

*(p<0.05) significant difference from legal speed limit

3.4.7 The effects of road and roadside characteristics

Table 3-34 shows the results for the effects of road characteristics present/absent separately. The results for preferred speeds for the same road type with one factor present and absent reveal differences. To know precisely how large the effects of one factor's being present or absent are in the data, Cohen's *d* effect size is adopted where *d*=0.2 represents a 'small' effect, 0.5 represents a 'medium' effect and 0.8 a 'large' effect. This means that if there is a *d* of 1, the two groups' means are different by one standard deviation. For example, an effect size of 0.8 means that the score of the average person in the experimental group is 0.8 standard deviations above the average person in the control group, and hence exceeds the scores of 79% of the control group. The 2-lane and 4-lane motorways had the strongest effect sizes and rural single carriageway curve presence/absence presented the second strongest effect. The 4-lane motorway had a 6mph higher preferred driving speed than the 2-lane motorway (*d*=.68). Likewise, the rural curved road had a 8mph lower preferred driving speed than the rural straight road (*d*=-.65). However, for the urban road VRU presence/absence, the difference within the group was small. Therefore, motorway, rural single carriageway and urban road were all affected by the road characteristics in terms of preferred speed and safe speed limit.

Table 3-34: ANOVA results with road characteristics as an independent variable and preferred speed and safe speed limit as dependent variables

Road characteristics	Mean preferred speed (mph)	Preferred speed				Mean safe speed limit (mph)	Perceived safe speed limit			
		d.f.	*F*	*p*	*Cohen's d*		d.f.	*F*	*p*	*Cohen's d*
Motorway	4-lane 75.44 2-lane 69.15	1,198	23.15	.000	0.68	4-lane 73.20 2-lane 67.10	1,198	30.11	.000	0.77
Rural single carriageway	Curve 40.98 Straight 48.06	1,198	21.02	.000	-0.65	Curve 40.9 Straight 48.10	1,198	20.56	.000	-0.64
Urban road	Presence VRU 26.38 Absence VRU 28.03	1,198	4.82	.029	-0.31	Presence VRU 26.10 Absence VRU 27.70	1,198	4.26	.040	-0.29

3.5 Discussion

3.5.1 Picture questionnaire validity

Clearly, the photographs provided sufficient visual information about the road and environmental features to enable drivers to make appropriate speed judgements that systematically varied with actual speed limits. The environmental features' were used by the participants as a basis for their judgements of speed and speed limits. The results suggest that drivers are affected by the comparative characteristics of the road, such as the number of road lanes, the presence of curves and the presence of VRU. Traffic on the same and opposite carriageway did not affect the drivers' judgements about the speed choice or speed limit choice. Drivers may have considered the traffic situation as temporary or not relevant to general judgements about speed and speed limits.

3.5.2 The relationship between speed limit perception and speed perception

There was a positive correlation between the perceived safe speed limit and the perceived speed when judged by drivers in a given road situation. The relationship shows that the judged driving speed tended to be higher than the perceived speed limit of the road. This result is consistent with previous research which suggests people prefer speeds faster than the actual speed limits of roads when in ignorance of the actual speed limits (Fleiter and Watson, 2006; Goldenbeld and van Schagen, 2007). Thus, choosing the appropriate speed limit guides drivers in choosing the appropriate speed.

3.5.3 Motorway

A speed limit survey by the Automobile Association (2013) shows that 8% of drivers, which is equivalent to more than 2.8 million drivers, gave incorrect speed limits; with 7% thinking 80mph was the correct speed limit on motorways, and 1% thinking 60mph was correct. The number of males was twice the number of females who thought 80mph was correct for UK motorways.

The results of Experiment 1 show that motorway was the most self- explaining road based on a significantly more uniform driving speed than other road types. This result is in accordance with the result that motorways were an excellent example of SER, which did not need any further explanation or learning process to know what it means and what to expect (Walker et al., 2013; Stelling-Konczak et al., 2011).

For the motorway, with a speed limit of 70mph, the number of lanes was an important factor affecting speed limit credibility and speed choice. The result is in accordance with Fildes and Lee (1993) that the number of lanes affects speed choice. For the 2-lane motorway, driving speed was closer to the national speed limit, while for the 3-lane and 4-lane motorways, drivers preferred to drive 4-5mph faster than the speed limit. Motorists who exceeded the speed limit may have considered themselves to be safe on a 3-lane or 4-lane motorway and assessed their driving skills favourably compared to other drivers. This might be because drivers tend to accept more risk in familiar situations (Slovic, 1987; Goldenbeld and van Schagen, 2007). As the pictures all showed roads in good weather conditions with low traffic flow, this may have led respondents to report relatively higher speed preferences. Reasons the drivers complied with speed limits include, they may feel the subjective risk is higher than others or they may not be willing to break the law so keep within a margin above the speed limit (Corbett, 2001; Goldenbeld and van Schagen, 2007). The 2-lane motorway had more common choices of speed and speed limit, meaning the 70mph speed limit on the 2-lane motorway was more credible than on other types of motorway.

3.5.4 Urban motorway

The urban motorway, with a 40mph speed limit, showed a difference in road layout from the motorways. The results show 40mph to be too slow on the urban motorway for the situation, as motorways undertake the mobility function the most. This type of urban motorway is not with credible speed limits. Since there is no protection infrastructure protecting drivers if a vehicle loses control, the risk perceptions for urban motorways might be higher.

3.5.5 Rural single carriageway

For the rural single carriageway with a 60mph speed limit, curve presence or absence is a factor affecting speed limit credibility and compliance. The preferred speed in the presence and absence of a curve was much less than 60mph. For the rural road, the perceived safe speed limit ranged from 20mph to 80mph, which causes more overtaking behaviour in a real traffic situation. The more homogeneous the speed on rural single carriageways, the safer drivers are. The reason for the speed limit not being credible might be because the lane width is relatively narrow and other vehicles are present ahead. The respondents were aware of the risk posed by the presence of the curve in the rural road, as the chosen speed and speed limit were lower on the rural road. Thus, 60mph is not credible on either the straight road or the curved road, which justifies personal risk being higher on a narrow road and a sharp curve.

3.5.6 Urban road

On the urban road, the presence of vulnerable road users (VRU) was a key issue that affected speed limit credibility and compliance, with 30mph in the absence of VRU being more credible than in the presence of VRU. On the urban road, the speed limits are more in harmony since the general speed limit is 30 mph, with a few exceptions of 20mph in speed calming areas. Vulnerable road users present on the road need to be taken into consideration and have an impact on drivers' awareness. Therefore, the results show that when drivers consider these issues, their average driving speed and speed limit are lower than the actual speed limit. In residential zones and school zones a more credible speed limit integrated with traffic calming would be necessary.

3.6 Conclusion

This questionnaire study shows that the credibility of a speed limit is highly influenced by specific, identifiable and comparable characteristics of the road layout and roadside environment, including the number of lanes, urban motorway, no physical barriers, presence of curve and presence of VRU. The questionnaire results show which speed limits are credible and which are not by group comparison. If most drivers have a common speed limit and the choice of speed is less than or equal to that limit, it can be assumed that the speed limit is credible for the road environment.

It can be concluded that speed limit perception affects speed choice. The difference between preferred speed choice and safe speed limit shows how compliant motorists are with the speed limit. This was tested for motorways, a rural single carriageway and an urban road around Leeds by identifying roads and roadside features. Risk factors include the number of lanes, being an urban motorway, the absence of physical road barriers, the presence of a sharp curve and the presence of VRU, on various types of road, which are the same factors as for credibility. Speed choice is informed jointly by speed limit credibility (cognition) and risk factors, which could be a topic for further study.

A large difference is shown between demographic groups with regards to preferred speed. The differences appear to be related to gender, age, driving experience and having speeding tickets on specific roads. For example, males and females differ in their judgement of driving speed. This finding is consistent with McKenna et al. (1998) that males drive faster than females, although gender differences in preferred speed may have decreased over time (Stradling et al., 2003). With regards to the speed limit, although there are differences within groups for specific road scenes, there are some preferred speeds in common. Drivers' personality traits, such as risk-taking attitude, are related to risky driving behaviour, especially among young drivers (Turner and McClure, 2003; Iversen, 2004). Dangerous driving incidents are characterised by reckless intent, driving late at night, riding with peers especially involving alcohol and drugs, reporting impaired driving, and distractions in the car (Farrow, 1987). Thus, drivers' personality traits are not taken into consideration in this experiment which focuses on the perception of the speed limit and speed for a given road layout. The findings are intended to address all drivers.

Risk factors are generated by the road layout and the roadside environment. Speed limit credibility is assumed to be associated with risk perception. Based on credibility research, higher speeds occur on roads which are wide, with no curves, smooth surfaces, clear road markings and relatively low accident rates (Taylor et al., 2002), due to the potential subjective risks on such roads being quite low. Under such circumstances, even if the speed limit is credible for that road, drivers do not comply with speed limits, due to the subjective risk possibly being lower. In contrast, when considering roads with vulnerable road users, T-junctions, sharp curves or walls along the roadside, the risk perception for individual drivers, being different, influences their perception of speed limit credibility. Thus, low-risk perception with high or low speed limit credibility may give a different result for compliance with the speed limit. High-risk perception with high or low-speed limit credibility may give a different result for compliance with speed limit too. In addition, individual motorists do not have the same perception of the hazards of speed in a given traffic situation, due to their differing personality traits and driving experience.

To sum up, speed limit credibility is different from compliance with speed limit. Satisfaction with the speed limit does not mean that one obeys it. Respondents may perceive a lower speed limit as credible, but still choose a higher speed. The compliance level pattern for different types of roads is different. Some drivers may not know the actual speed limit on a given road and may be influenced by the speed limit to a limited extent. Drivers' lack of compliance with the speed limit might be due to the speed limit not being credible. It can be assumed that motorists' perceptions of speed limit credibility affect their compliance with the speed limit; the more credible the speed limit, the more compliant they are. However, even if the speed limit is credible, drivers' compliance level is highly uncertain due to the traffic situation, personal traits, road environment, vehicle dynamics etc.

3.7 Study Limitations

The first limitation of this study is that the answers are only valid for the road scenes used, based on fixed pictures. Although the photographs were of real road scenes, real driving tasks are far more complex with constantly changing views, own and other vehicle dynamics, and the speed behaviour of other vehicles. Static photographs restrict the relevant information. Specifically, the presence or absence of other vehicles has an effect on the preferred speed, and the safe speed limit needs to be validated and evaluated for credibility. Perception of risk needs to be considered in speed limit credibility on roads with heavy goods vehicles or vulnerable road users. The way these factors influence compliance with speed limits merits further research.

The second issue is the limitations of the road scenes for each road type. Two pictures of a rural single carriageway cannot represent all rural single carriageway conditions. The research does not consider how combined road layouts or roadside environmental factors influence speed and speed limit perception. Each pair of road scene comparisons needs to be considered precisely to prevent comparison bias, which can be traced back to the experimental design process. Further experiment could evaluate the condition of each rural single carriageway in detail.

The third limitation is that self-report speed is used rather than real driving speed. Further study could consider a more realistic in-car driving environment from which to collect driving behaviour data.

3.8 Reveal the gap and reasons to carry out experiment two

Speed limit credibility information can be used to create safe road infrastructure in the future. Setting credible speed limits is a new way to design road infrastructure for better compliance. There is a need to determine limits that are more credible for the majority of drivers. Experiment 1 only addresses road environment factors affecting speed limit credibility, for example how the number of lanes affects motorway speed limit credibility, how road curves affect rural single carriageway speed limit credibility, and how vulnerable road users affect urban road speed limit credibility. However, from this questionnaire, the extent to which risk perception affects speed limit credibility and driving behaviour cannot be known.

Thus, the relationship between risk perception and speed limit credibility needs further research to build this knowledge. Perception of risk in various road situations has not been investigated thus far. In addition, other environmental factors besides road curves affect speed limit credibility on rural single carriageways. The rural curve speed limit could be lowered or rural single carriageway road layouts could be changed. Therefore, it should be possible for most motorists to have the same level of perceived credible speed limit, resulting in greater compliance with that limit. The relationship between risk perception and compliance also needs to be investigated. The interactions between speed limit, risk perception and compliance need to be adequately researched in the future. The results of Experiment 1 provide a fundamental definition of speed limit credibility that can be used in the next stage of the study.

According to MASTER (1998) research results, the selection of the prevailing values of speed limits is usually vague. There is little evidence showing speed limits to be optimal from the viewpoint of society, the road transport system, or the individual road user. A speed limit is credible when the limit in force conforms to what the road user considers to be reasonable for that particular section of road. A large number of respondents agree with a range of statements about the advantages of lower speeds when considering road safety. Pedestrians and cyclists are more in favour of speed reduction measures than car drivers, especially at sites where they have to interact with car drivers. Therefore, determination of the desired speed limit should be based on explicit criteria and the impact of speed on different road types, for different road users. Experiment 1 emphasises the crucial aspects of the non-credible speed limits which exist on UK roads, and leads to a second study, the development of a credible speed limit that is acceptable to the majority of drivers for a given road environment.

Chapter 4 Experiment 2 - Investigating how to set a more credible speed limit

4.1 Study Rationale

The theoretical model adopted for Experiment 2 links road environment, speed limit credibility, risk perception and speed limit compliance (Figure 4-1). It provides various measurements of credible speed limits and how to set a credible speed limit that improves driver compliance. A picture questionnaire, a driving simulator in an automated condition and manual driving in a simulator are used for the measurements. The experiment consists of: Task 1: questionnaire about speed limit credibility; Task 2: speed feeling and risk feeling in an automated driving condition; and Task 3: manual driving.

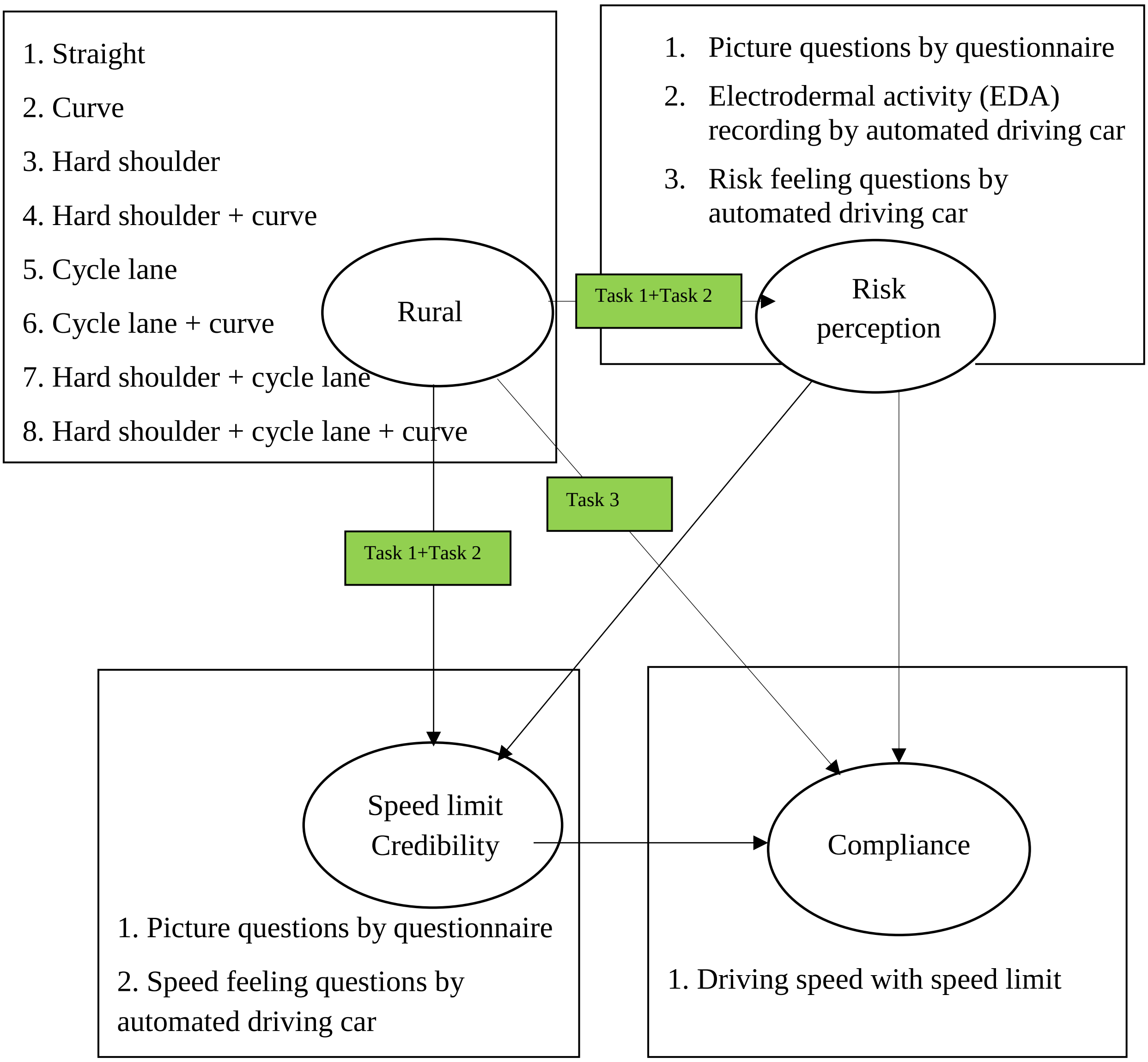


Figure 4-1 Experiment 2 theoretical model

Experiment 1 builds the relationship between speed limit credibility and compliance with the speed limit, finding that credibility and compliance are not identical. A further component of risk perception is now added to the model to make the theoretical framework more complete. Figure 4-1 shows a schematic representation of the speed limit credibility theoretical model. Credibility reflects an individual's recognition, determined by two predictors, road environment and risk perception. The first component is the environment, which is static. The second determinant of credibility is subjective risk perception, which is a person's own perception of the hazard level, coming from both the static road environment and driving speed. Both speed limit credibility and risk perception affect compliance with the speed limit. It is assumed that the most immediate determinant of compliance behaviour is an individual's perception of speed limit credibility and risk perception of performing the behaviour.

Road layout and roadside environment are determined by road geometry, road surfacing, weather conditions and the traffic situation. Providing a hard shoulder is an effective way to direct drivers towards the centre of the lane, and accident rates decrease with increased shoulder widths (Rosey et al., 2008; Rosey et al., 2009).

Providing a cycle lane is a positive variable for cyclists and non-cyclists determining route choices (Caulfield et al., 2012). Roundabouts with cycle tracks lead to the greatest reduction in injuries to cyclists and moped drivers, according to a study in the Netherlands (Schoon and van Minnen, 1994).

The presence of a curve is a common road layout on rural roads. Curve radius and steering competence both affect steering errors during curve driving, resulting in compensatory speed reduction (van Winsum and Godthelp, 1996). Horizontal curves on rural single carriageways are recognised as a significant safety issue. Crash rates are 1.5 to 4 times higher on horizontal curves than straight road sections, and 25-30% of all fatal accidents occur on curves (SafetyNet, 2009). Accident rates decrease as the radius increases (Wegman and Slop, 1998). Hard shoulders, cycle lanes and curved roads are basic road geometry design considered in the context of road safety. This experimental design considers these three factors in combination in a rural road environment. It needs to be ensured that each factor combination is understandable from a driver's perspective.

In order to build the relationships between the three main components, credibility, risk perception and compliance, the same road environment is adopted for each test. The three main components can be measured directly. Credibility is assessed using picture questions and speed sensation questions in an automated car. Risk perception is assessed by EDA recording and speed sensation risk perception questions in an automated car. Compliance is assessed by manual driving. The measurement justification for each component is explained in Section 4.3.

4.2 Study aims

The study aims to set a credible speed limit for a given road layout and roadside environment, and improve driver compliance with the credible speed limit.

The main objectives are:

- To investigate how road layout and roadside environment affect credible speed limit, risk perception, and compliance with the speed limit
- To investigate various measurements of credible speed limit based on the experimental evidence
- To investigate the relationship between risk perception, speed limit credibility, and compliance with speed limit.

4.3 Measurements justification

4.3.1 Measurements of speed limit credibility

a) Credibility as a slide scale level from very non-credible to very credible

SWOV (2012d) suggests that the credibility of a speed limit is not an absolute value. Credibility is a sliding scale that varies from 'very credible' to 'very non-credible'. A speed limit can be non-credible either because the limit is judged as too high or too low. However, this evaluation has not been justified by previous research. To evaluate the credibility level of each road and compare the difference between two road scenarios, continuous data measurement is used, which can take any value within a range. Credibility is a sliding scale of judgement of whether a speed limit is credible or not for a given road layout. Thus, the visual analogue scale is adopted (Vagias, 2006; Ohnhaus and Adler, 1975). The visual analogue scale is a 100mm bipolar sliding scale on which the subject can mark a point. Individuals compare the given speed limit with their safety speed limit to indicate whether the given limit is credible or non-credible. In addition, based on Goldenbeld and van Schagen (2007) research, the respondents are asked about the perceived safe speed limit, from a list of choices between 10mph and 90mph with intervals of 10mph.

b) Credibility as a speed judgement from too slow to too fast

The second credibility measurement is assessed by speed sensation. Speed limit credibility represents the level of speed appropriateness when driving on the road compared with the safety speed limit, which should be within an individual's safety margin. It is the subject's feeling that the driving speed matches the given road layout, neither too slow nor too fast. Speeding can increase the risk of being involved in a crash and also increase the severity of the crash. Many countermeasures have been put in place to deal with drivers who have speeding behaviour. One factor in speeding behaviour may the speed limit having low credibility on that road. This measurement is used in Task 2 for each road scene at a given speed. If the vehicle's driving speed is greater than the perception of the limit that matches the road, it means either the speed is too fast for the road conditions or the speed limit is not credible. If the speed limit is credible, the driving speed should be equal to or less than the speed limit. This task is achieved using an automated car.

Road users often have spontaneous and unconscious perceptions of information from their surroundings. Road users rely on visual information. The visual design of road layouts and roadside environments is very important (Herrstedt, 2006). To explore how drivers' assessments of road layouts and conditions might work in relation to speed limit credibility, the respondents are shown photographs depicting various road layouts and asked questions about the level of credibility.

In an earlier study, Colbourn (1978) uses colour photographs of actual road scenes to obtain direct measures of the perceived driving risk under differing motivational conditions. Kaptein (1998) uses a picture sorting task and a driving simulator task to investigate the effects of road design characteristics on cognitive road classification and driving behaviour. The stimuli used are computer-generated images from a simulator database from the driver's point of view. The study shows that using a 10 × 15cm picture is feasible for current road and SER road classification research. Homogeneous driving speeds may be achieved by consistent road design within categories. SWOV (2012d) concludes that photographs and animations can be used to determine which characteristics of roads and environments most influence credibility.

4.3.2 Measurements of risk perception

Road and road environment design consistency evaluations and safety inspections are two safety issues to be addressed. An important human factor to consider in the evaluation of road users' behaviour is their risk perception of the road's safety. According to Sjoberg (1998), the perceived consequences of a negative event should be applied as a measure of risk perception. An alternative assessment of risk perception could give a better estimate of the influence of perceived risk on risky driving behaviour, as an emotional response can be measured in at least three ways, affective reports, physiological reactivity and overt behavioural acts (Lang, 1969, cited in Bradley and Lang, 1994). In this research, the risk perception information is acquired by two methods:

1) Subjective self-assessment — the individual participant reports the level of risk experienced, implemented by self-assessment questionnaire.

2) Objective electrodermal activity measurement — an entity (human or machine) observes the monitored individual and maintains a journal of the individual's actions (Ayzenberg and Picard, 2014).

a) Subjective risk perception - Self-assessment questionnaire

In this study, it is useful to construct a composite 'risk index' or 'safety index' to evaluate subject risk perception in a static road environment. There are three components of risk, the exposure of road users to road hazards, the probability of a vehicle being involved in an accident, and the consequences should an accident occur (Cafiso et al., 2007). Assessment of the probabilities and consequences of adverse events can be described as risk assessment (Slovic and Weber, 2002). This is the subjective judgement an individual makes about risk characteristics and the severity of outcomes. Therefore, a self-assessment report obtained by questioning is an effective way to encourage subjects to state the status and strength of the emotions they feel during the applied induction protocol (Kim et al., 2004).

It can be inferred that subjective risk perception comes from the road environment (road layout and design), driving speed, oncoming vehicles, conflict between vehicles and cyclists, risk of running off the road etc. The subjective risk perception is, therefore, the individual's assessment of the risk of the situation, based on their knowledge about the objective risk. To understand how drivers' subjective risk perception in road situations is related to their perception of the credible speed limit, measures of cognitive-based risk perception and emotion-based risk perception have been developed. These can be adopted from the relevant constructs identified by Rundmo and Iversen (2004) to create a scale to measure drivers' perceptions of risk or hazard to themselves on the road. Cognition-based risk perception is the belief-based component of risk perception that evaluates the probability of an accident. Emotion-based risk perception occurs when thinking of, or being, exposed to the risk source or risky activity, i.e. the extent to which the respondent feels safe or unsafe. The higher the negative risk perception, the greater the likelihood of changing behaviour.

- **Risk as a perceivable outcome**

Generally, the objective risk of driving, such as the chance of having an accident on any particular journey, is very low. Risk is an inherently subjective measurement (Slovic, 1990). Levels of subjectively of perceived risk are much different from the objective risk in the situation as determined by actual crash data. This research only focuses on subjective risk perception.

The the feeling of risk or subjective risk is described by Summala (1988) in the zero-risk model as "the fear resulting from the perception or expectation of a loss of control of one's car, or of being on a collision course."

In terms of respondents' verbal ratings, previous studies use different numbers of scale points and point definitions (Heino et al., 1996). Heino *et al.* (1990) use a seven-point rating scale, from 0, meaning no risk perceived, to 6, indicating a traffic situation in which an accident could be avoided only with the greatest effort. In the current study, the risk perception is assessed using a questionnaire to estimate the risk of crashing for each road scenario, compared to the base scenario risk outcome on a sliding scale with 0 indicating 'extremely low risk' and 100 indicating 'extremely high risk'.

Considering how road layout affects risk perception, the presence of a hard shoulder leaves enough of a safety margin in a loss of control situation to avoid a severe accident. The presence of a hard shoulder provides separate space for cyclists to avoid potential conflicts with drivers. The risk perception of roads with safety margins is assumed to be different from roads without safety margins. Exploring peoples' perceptions of risk and their attitudes towards speed limit credibility together may assist in identifying safer roads, but cannot imply that perceptions of risk actually encourage safe driving.

- **Risk as unsafe feeling**

Research into drivers' perceptions of risk shows that drivers do form judgements about the risk of the road and traffic situations they encounter. Risk is a dominant factor in accounting for attitude (Sjöberg et al., 2004). People are more easily sensitised to risk than to safety due to mood states being more influenced by negative expectations than positive ones. Drivers' steering and speed are perceptually adjusted to keep the car headed into the field of safe travel. It is expected that subjects would report lower levels of risk and lower driving speeds towards safer road environments

Pelz and Krupat (1974) showed 60 undergraduate males a 5-minute wide-angle film of highway driving as seen from the driver's seat and recorded moment-to-moment judgements of danger by means of an "apprehension meter" (Pelz and Krupat, 1974), a lever with a scale marked 'very safe' at one end and 'very unsafe' at the other. This research adopts the above researchers' questions about subjective feeling of risk. For subjective measurement, self-report risk rating measures are tested during exposure to risk in an automated driving environment. The process of feeling and judging tests their alertness scenario by scenario. Each subject's meter is constructed in order to evaluate the level of risk perception. For objective measurement, the study takes the self-report measures in conjunction with physiological measures.

b) Objective risk perception-Psychophysiological measures

- **Risk as an arousal of fear**

Objective measurement of risk perception needs to be adopted in the experiment, because risky activities are assumed to be involved in driving behaviour. Risky activities or hazards may be associated with fear, insecurity, worry and anxiety. To be specific, fear arises from the appraisal of profound uncertainty, a sense that even such basic needs as safety are uncertain, as well as the appraisal of situational control, a sense that factors beyond one's control shape the outcomes (Smith and Ellsworth, 1985). In this study, risk feelings are generated when the passive driving speed on the road is too fast compared with the respondents' autonomic appropriate driving speed. The dynamic visual stimuli and motion stimuli consist of road environments and automated speed. During the event, the feeling of risk is triggered by the brain's appraisal of the stimulus with respect to the subject's goal of survival. Is is important that the speed induces a very specific type of emotion, so that the maximum possible arousal is achieved for all subjects. The aim of using high speed in a given road environment is to induce a state of general psychophysiological activation.

Taylor (1964) carried out research on drivers' galvanic skin response (GSR), changes in the electrical properties of the skin, and the risk of accidents. Based on the findings, it can be predicted that the physiological arousal of the subjects viewing the affective stimuli would be lower in less risky situations, and higher in high risk situations. GSR can be maintained at a constant level by adjusting the driving speed. Skin conductance (as with GSR) is a particularly appropriate measurement for testing arousal, as unpleasant risk stimuli elicit greater skin conductance activity than neutral stimuli. Therefore, the second risk perception measurement is physiological electrodermal activity (EDA) (the same as GSR), identified by skin conductance response (SCR) in each scenario. Individuals with higher risk perception should show especially strong skin conductance reactivity to emotional (especially aversive) stimuli (Norris et al., 2007).

That is also the basis of the zero-risk model of Näätänen and Summala (1974). Heino et al. (1996) suggest that a forced increase in risk at the behavioural level is reflected in an increase in risk at both the cognitive and physiological levels. Wilde (1998) shows that driver assessment of subjective risk reflects objective risk in road segments, determining their fear response (i.e. GSR) and behaviour adjustment. Although Wilde admits that GSR is a general measure of arousal rather than risk perception and Heino states that electrodermal activity is not very sensitive to changes in perceived level of risk (Fuller, 2005), GSR can reflect the subjective response in terms of a fear state and be used to estimate the probability of collision in a driving situation, with high confidence.

EDA is a way to assess affective physiological arousal and a sensitive psychophysiological index of changes in autonomic sympathetic arousal integrated with emotional and cognitive states (Critchley, 2002; Dawson et al., 2000). EDA can quickly and accurately assess a participant's emotional reaction to an event and track the participant's feeling of risk when processing stimuli, as EDA parameters are related to the intensity of negative and fear-related arousal that accompany anxiety levels in subjective risk perception (Weller, 2010). Thus, EDA is better for understanding driving behaviour and reveals important mechanisms that explain the potential risk of accidents. Since the aim of the study is to compare EDA in various road scenarios, speeds of 60mph, 50mph and 40mph are used on a rural single carriageway. This research focuses on skin conductance response (SCR) which is derived from the phasic part of EDA (Boucsein, 2012). SCR is elicited for a specific road scenario stimulus, a given speed on a stretch of road which continues for 15 seconds. The amplitude parameter (the height of the SCR in a given time window) is analysed, as shown in Figure 4-2.

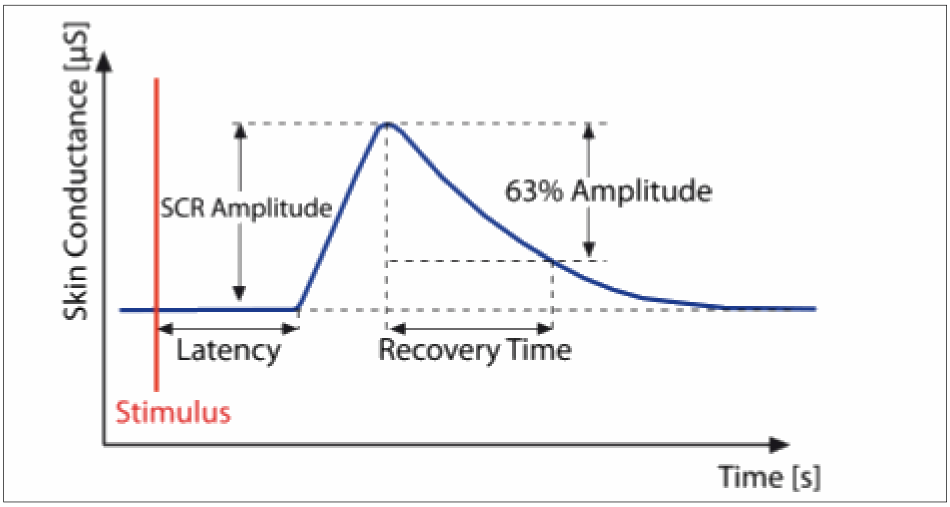


Figure 4-2: Ideal Skin Conductance Response (SCR) with typically computed features

- **EDA Feature calculation**

EDA, as an index of sympathetic activity, increases during the cognitive and emotional stressors as well as decreases during the recovery phase (Visnovcova et al., 2013). The skin conductance response is elicited by almost any novel, unexpected stimuli. EDA levels also have to be obtained during the whole Task 2 (a speed feeling and risk feeling in an automated driving condition task) period including baseline, each road scenarios and resting conditions. For EDA record, real-time data will be recorded as a waveform in BIOPAC 4.0 software. The following terminology was involved for data collection and data analysis.

EDA (Electrodermal Activity)-The general area of the skin conductance signals. Sometimes referred to by the older term "galvanic skin response."

Skin Conductance Response (SCR) -Phasic change in electrical conductivity of skin. An individual localized change in the tonic EDA signal. An SCR may occur in response to a stimulus or may occur spontaneously. In general, there are multiple SCRs present in a tonic EDA signal and they can be detected as deflections from the localized baseline.

Tonic EDA--- Tonic skin conductance is generally considered to be the level of electrical skin conductance in the absence of any particular discrete environmental event or external stimuli (Dawson et al., 2000). This slow-changing level is generally referred to as Skin Conductance Level (SCL). Tonic SCL can vary over time depending on individual's psychological state, hydration, skin dryness, and autonomic regulation which changes occur in a period of from tens of seconds to minutes (Empatica Support, 2016).

Phasic EDA--- Phasic EDA is measured as skin conductance response (SCR) associated with short-term events occurred in the presence of discrete environmental stimuli.

SCR amplitudes --- Reflect the amount of affective or emotional arousal elicited by a stimulus or situation. Phasic changes usually show up as abrupt increases in the skin conductance, or "peaks" in the skin conductance. These peaks are generally referred to as Skin Conductance Responses (SCRs) (Empatica Support, 2016).

SCR analysis determines how responsive a subject is and measures the size and amplitude of each response. Table 4-1 lists the five types of commonly-used measurements to measure EDA objective risk perception levels. Although Skin Conductance mean value, SCR Rise Time, Event Amplitude, SCR Slope of Amplitude can be used to represent risk arousal, SCR Amplitude is the most widely used measurement to evaluate each specific scenario.

Table 4-1: Objective risk perception Measurement 1 – EDA recording in automated driving (from signal to risk level)

List of Variables	Function name	Description	Value (Unit)	Variables related to arousal (risk)
Mean	Mean	Mean computes the mean amplitude value of the data samples between the endpoints of the selected area.	X (µmho)	greater X means the greater arousal (risk feeling)
SCR Rise Time	Delta T	Temporal interval between SCR initiation and SCR peak (1-3s) [*tmax* - *tonset*]	X (s)	shorter X means the greater arousal (risk feeling)
SCR Amplitude	Delta	Height of the corresponding SCR as determined by the change in the tonic EDA amplitude from the time of SCR onset to the maximum tonic EDA amplitude achieved during the SCR: [EDA(*tmax*) – EDA(*tonset*)]	X (µmho)	greater X means the greater arousal (risk feeling)
Event Amplitude	Max	Maximum tonic EDA amplitude achieved during the SCR, also equal to Absolute SCR Size. Formula: EDA [*tmax*]	X (µmho)	greater X means the greater arousal (risk feeling)
SCR Slope of Amplitude	Slope	The slope measurement the endpoint of the selected area to determine the difference in magnitude divided by the time interval. This value is normally expressed in unit change per second since high sample rates can artificially deflate the value of the slope. SCR Slope of Amplitude (0.01~0.5µS per level)	X	greater X means the greater arousal (risk feeling)

(Boucsein and Backs, 2000; Dawson et al., 2000; Biopac, 2008)

Generally, individuals' electrodermal activity differs (Boucsein, 2012). To draw a valid conclusion from individual EDAs, the within-subject approach is used in order to distinguish the risk perception generated by speed and road environment from underlying changes in SCL and SCR in a manner that is unbiased, using the between-subject difference in overall EDA or task performance. For within-subject scenarios, the raw individual SCR data is transformed into a value on a scale of 0 to 1.

- Electoral-dermal Activity Data manipulation

Setup and Calibration

Calibration needs to be done before acquiring the first segment of data. Double point calibration is performed on the channel by recording two independent voltages in a consequence of two dialogue steps and records the first in the input volts for Cal1 and the second for the input volts in Cal2. At the beginning of the test, when the EDA signal was tested, participants are required to take a deep breath as the startle stimulus and to hold it for a second. This process will result in a response from most subjects. The oscillogram will present a function of latency + rise time + recovery time. It was suggested no less than 8-10 seconds.

Acquisition rate

The acquisition sample rate was set at 1000 Hz to ensure trigger event was accurately represented in the measurements.

Channel sample rate

EDA was a relatively slow signal so the data were downsampled to 200 Hz, which is a minimum to ensure enough samples for accurate separation of a phasic waveform from tonic signals. In addition, reduce the sample rate can lessen the computational load for the analysis.

Filtering signal

Low pass Finite Impulse Response (FIR) digital filter is adopted to filter the signal. A low pass filter will allow low-frequency signals to pass but eliminate high-frequency signals. Due to EDA responses are quite low, so a cut-off frequency of $fc = 1Hz$ fixed low-pass filter will not eliminate anything of interest but will remove higher frequency signals components.

Baseline estimation:

The estimate of the baseline is generated using median value smoothing. This is more computationally intensive than high pass filtering. Increasing the window will increase sensitivity and return more responses (AcqKnowledge 4 Software Guide). As the data was continuous recorded, there was no need to differentiate the questionnaire operation-induced SCL from raw data within a fixed specific period (30 seconds). For practical applications, such phases of an invalid signal were excluded from the analysis, then median smoothing function was used as follows.

Smoothing baseline removal

Smoothing baseline removal constructs phasic EDA by subtracting an estimate of the baseline conductance from the tonic EDA (AcqKnowledge 4 Software Guide).

As the skin conductivity consists of two components: a tonic component, which represents a low-frequency baseline and a phasic component superposed on the tonic part. The smoothing function is a transformation that computes the moving average of a series of data points and replaces each value with the mean value of the moving "window." Smoothing baseline removal was used as a method to obtain the phasic EDA signal, which represents changes in EDA. This transformation decomposed the signal into coefficient at 5 multiplied by sample rate (100 per second). 5 means baseline window set to 5 seconds. In order to subtract the background SCL from the tonic signal to establish a truer representation of the amplitudes of SCR. This subtraction results in a signal which showed a virtually zero baseline and positive deflection (Benedek and Kaernbach, 2010). Then the threshold level and differentiate need to be adopted as follows.

Threshold level

This level should be varied according to the change in EDA characteristics, dependent on the subjects and the electrodes employed. The number of detected peaks depends on the choice of the threshold: The lower the threshold, the more peaks are detected. Historically the most common threshold is set at 0.05μS. Deflections in the signal that do not satisfy the threshold criteria are not concluded as SCR or non-SCR.

Define Event-related SCR

An SCR shows a steep incline to the peak and a slow decline to the baseline. Thus, SCR amplitude is measured by subtracting the onset value from the peak value to provide the amplitude value. The size of the response is relative to the SCL at the point the response started. It is important that an SCR reaches the peak over 1-3 seconds while 50% decay may take anywhere from 2-10 seconds.

Cycle detector

The Biopac Student Lab cycle detector can take measurements around specific stimulus event including waveform onset, waveform end, and skin conductance response. Since the function can identify specific and nonspecific skin conductance response. The nonspecific skin conductance response needs to be removed manually. Each SCR is marked as a blue water droplet (a sign) as peak SCR response, each SCR has an open bracket before it as SCR onset and closed bracket after it as the end of SCR.

4.3.3 Measurements of compliance with speed limit

Kaptein (1998) explicitly addresses the relationship between cognitive road classification and actual driving behaviour. Repetition in a driving simulator experiment is used to provide subjects with a clear impression of the available set of road environments, so they can determine their driving speed on the basis of this set of environments. Whether drivers can drive uniformly within each road category can be tested. Thus, road characteristics are an important determinant of driving speed homogeneity. Hauer et al. (1982) and Aljanahi et al. (1999) adopt mean speed, standard deviation and percentiles of speed distribution as indicators to measure drivers' speed choice compared to the speed limit. Numerous sources show that the 85th percentile speed should be considered when establishing a speed limit (Fitzpatrick et al., 1995). Jamson (2006) shows that there is an effect of the amount of time drivers spend over the speed limit, with thresholds of 10% over the speed limit and 20% over the speed limit. The Department for Transport (2006b) uses the percentage of cars exceeding the speed limit by 5mph to evaluate the limit compliance on urban roads. Speed at the point and percentage of speed change are used to evaluate the speed profile in various treatments (Jamson et al., 2008).

Interactive driving simulator experiments under lab-controlled conditions are used to conduct scientific research into driver behaviour characteristics, vehicle dynamics and transportation facility evaluation. Simulator study allows controllability of design elements so that they can be kept as constant as possible. This allows for systematic manipulation and testing of variables in the experimental design to find the 'pure' effect of the variables through controlled study (Houtenbos et al., 2011). The use of a driving simulator is validated for specific aspects of driving behaviour, such as speed, trajectory, braking etc. Two driving simulator validation studies on rural roads reveal that speeds are about the same in simulated and real cases (Alm, 1996; Harms, 1996). Longitudinal speed can be estimated correctly from visual information provided in driving simulators which have a large field of view, at least 120° (Kemeny and Panerai, 2003).

To validate the most frequent driving behaviours, speed is used as a driving performance indicator to describe and analyse the behaviour of a driver (Gatti et al., 2007). To explain driver behaviour compliance level, choice of speed is the main measurement. The difference between the driving speed and the speed limit gives speed compliance, and indicates whether the actual speed limit is credible. If a driver chooses a driving speed equal to or less than the speed limit, it is considered an indicator of credibility. Each subject uses the manual drive to drive through all the roads. Balanced design is more likely to identify true differences in the effects of different conditions.

For each road section, the other driving behaviour measurements are:

- Point Speed before speed limit sign and after speed limit sign; specifically, measurement of curve speed 100m before the curve, 50m before the curve, 50m after the curve, 100m after the curve, along with the curve entry, apex and exit speeds
- Lateral position
- The proportion of time drivers exceed the actual speed limit.

4.3.4 Automation condition in a driving simulator

As this experiment adopts automated driving conditions for speed perception and risk perception, the methodology justification needs to be emphasised. The usefulness of driving simulators in the road-design process has been confirmed by a study (Keith *et al.*, 2005), which recommends the use of driving simulators by the road-design community. They can ensure that the curiosity of drivers and their attention is continuously aroused (Herrstedt, 2006). The road sections do not involve any dynamic factors such as traffic situations or weather. Mental workload comes only from the road environment and driving speed. Thus, using a driving simulator is effective in eliciting predicted responses in pre-set driving situations.

The methodological strengths of driving simulators include modern driving simulators being advanced laboratories with real car bodies in which various movements can be simulated. Although the landscapes being projected on the large screens are computer animated, they look relatively real. Secondly, the simulator offers a realistic driving experience very close to the real thing, and can repeatedly offer exactly the same conditions for each subject, which real driving situations cannot. Therefore, in the controlled road environment, driving behaviour data can be collected using an experimental design with a repeatable and systematic process.

Road scene pictures limit the relevant information to static information. Visual stimulation using still road scene images is not sufficient for effective emotion induction. Some claim the landscape experience while driving resembles watching a movie based on continuously changing views. Both are travels through time and space, offering quick changes of scenery, and making the subject curious about what comes next (Antonson et al., 2009). Horswill and McKenna (1999); Fuller et al. (2008); Lewis-Evans and Rothengatter (2009) demonstrate the reliability (and, incidentally, the internal and ecological validity) of video simulation of driving tasks. The University of Leeds driving simulator is used in this research. The vehicle is in motion at the onset of a trial, without requiring acceleration from a stationary start. By using automated driving at a given driving speed, road scenarios can be compared to evaluate subjective risk rating estimates and physiological responses. Drivers are able to experience identical sections of road at systematically different speeds in different road environments, holding everything else constant.

An automated condition in a driving simulator can be used to evaluate subjective comfort levels as well as physiological responses. There are various reasons for this. The visual perceptual mechanism is combined with an ambient mode (spatial orientation and locomotion) and focal mode (object recognition and identification) for drivers' decision-making and reduced reaction time (Castro, ed. 2008), with one system control positive and the other informing of potential environmental hazards. In terms of an individual's estimation of driver performance, the ambient visual system is concerned with the concept of vehicle guidance, using information gained from optic flow to inform driver estimation of vehicle positioning. Meanwhile, the focal system concentrates on the detection and identification of objects of importance in the environment, such as other vehicles or road threats. For the dynamic driving process, drivers must take both absolute and relative estimates, including the driver's own field of travel, the possibility of intruding objectives and the road surface (Castro, ed. 2008). Estimation is based on the individual's surrounding environment, combined single stimulus channel or property, and the comparative evaluation of multiple stimuli together (e.g. whether the car is moving at a safe speed compared to other traffic). The visual perception of the road layout and roadside environment is a very strong factor. Speed is a relevant issue in safety discussions regarding attention and perception. Speed is perceived as higher in relation to closer objects. The higher the speed, the faster the optical expansion process, and the higher the visual load. The optical focus initially stands still, then, as the car moves forward, the optical expansion, depending on all the objects in the field of view, visually increases (Herrstedt, 2006). Thus, an automated condition in a driving simulator can be used for the experiment.

4.4 Method

4.4.1 Experimental design

As stated in SWOV (2012d), if a speed limit is not credible, there are two ways to do something about it, either change the limit or change the layout of the road or environment. The experimental design consists of 3-way within-subject factors, assuming each subject goes through all types of road scenarios (repeated measures). The experiment has three factors and each factor has two levels, a 2 × 2 × 2 factorial design. Eight road scenarios were modelled in the simulated scene, each according to the Design Manual for Roads and Bridges (Volumes 6 and 8) (DMRB, 2002), with road markings, widths and signage conforming to current UK legislation. Table 4-2 shows the experimental conditions.

Table 4-2: Experimental design for questionnaire

	Factors			
Experimental scenario number	**Road curve**	**Hard shoulder**	**Cycle lane**	**Rural Road scenes**
A	Present	Present	Present	Curve + Shoulder + Cycle lane
B	Present	Present	Absent	Curve + Shoulder
C	Present	Absent	Present	Curve + Cycle lane
D	Present	Absent	Absent	Curve only
E	Absent	Present	Present	Shoulder + Cycle lane
F	Absent	Present	Absent	Shoulder only
G	Absent	Absent	Present	Cycle lane only
H	Absent	Absent	Absent	Straight only

Concentrating on the basic principles of classification, artificial environments are used as stimuli. Screenshots from the simulated environment are shown in Figure 4-3. Subjects can easily classify the eight road layout scenarios. In the questionnaire task the participants were presented with each road picture and answer the questions.

A__Curve + Shoulder + Cycle Lane

B__Curve + Shoulder

C__Curve + Cycle Lane

D__Curve

E__Straight + Shoulder + Cycle Lane

F__Straight + Shoulder

G__Straight + CycleLane

H__Straight

Figure 4-3: Eight rural single carriageway road scenes

For the automated driving task, three levels of speed (40mph, 50mph and 60mph) are used in the experiment, a $2 \times 2 \times 2 \times 3$ factorial design with 24 totally automated driving scenarios.

For the manual driving test, three speed limit signs (40mph, 50mph and 60mph) are used in the experiment. Each road type is presented with the three speed limit signs, a $2 \times 2 \times 2 \times 3$ factorial design with a total of 24 manual driving scenarios. With balanced design, it is possible to identify the true differences in the effects of different conditions. Counterbalancing the order of treatment is a control for sequential confounding. Each treatment is presented in an unpredictable order to minimise carryover effects (Barlow and Hayes, 1979). The details of each task procedure are given in Section 4.4.5.

4.4.2 Apparatus

Monitor

A widescreen monitor is used to present each road scene. In total, eight screenshot road scenes are presented on the 15” monitor. Each picture matches 8 questions. For each question, the participant places a mark on the sliding scale which describes their reaction to the picture. Participant have to answer the questions in the questionnaire in a given time.

Driving simulator

The study is conducted on a motion-base, high-fidelity driving simulator (University of Leeds Driving Simulator). The simulator vehicle is an adapted vehicle cab of a 2005 Jaguar S-type model, housed in a 4m spherical projection dome with a 300° field of view projection system. The internal controls and dashboard instruments function as they would in a fully-operational vehicle. In automated driving, the driving simulator is controlled automatically and SAE level 2 (hands off, feet off, conditional automation) vehicle automation is used. In manual driving, participants have full control of the vehicle and are encouraged to operate the controls as they would in their own vehicle. The vehicle has automatic transmission so participants are not required to interact with the gear-shift lever. The, driving simulator is in a well-equipped laboratory suited for almost any psychophysiological measurement (Brookhuis and de Waard, 2011).

Biopac MP35

The Biopac Student Lab System is an integrated set of software and hardware for life science data acquisition and analysis. The hardware includes a MP35 Acquisition Unit, electrodes, electrode lead cables, transducers, headphones, connection cables, a wall transformer and other accessories. The physiological information is transferred via a cable to the Biopac Student Lab. The type of signal determines the type of device on the end of the cable. EDA is designated as channel 3. The laboratory set up includes:

- BIOPAC Student Lab System: BSL 4.0 software, MP35 hardware
- Computer system (Windows 7)
- BIOPAC EDA setup.

Disposable setup: EDA lead (SS57L) and EDA gelled electrodes (EL507*2).

Reusable setup: EDA transducer (SS3LA/L) and electrode gel (GEL101).

Paperwork for each participant

The paperwork and facilities chosen guarantee that the experiment is conducted in a controlled and safe fashion. The participants complete a set of forms prior to each experiment, to ensure uniformity and safety in a controlled experiment. The documents and resources used in this experiment include:

- Participant information sheet
- Consent form.
- Safety guidance form
- Paper-based credibility and risk perception questions
- Participants’ signed form for £10 payment.

4.4.3 Simulated road environment

- **Speed limit**

Table 4-3 sets out the recommended speed limits for roads with a predominant motor traffic flow function, defined by the Department for Transport (2013a). The national standard for rural single carriageways is 60mph applied to higher standard roads. If road bends, junctions, cycling, horse riding, or community or environmental factors are present on any road section, consideration should be given to using a lower limit. In this study, 60mph, 50mph and 40mph speed limits are used to test credibility.

Table 4-3: Speed limits for single carriageway roads with a predominant motor traffic flow function

Speed limit (mph)	Where limit should apply:	
60	Recommended for most high-quality strategic A and B roads with few bends, junctions or accesses.	
50	Should be considered for lower quality A and B roads that may have a relatively high number of bends, junctions or accesses. Can also be considered where mean speeds are below 50 mph, so the lower limit does not interfere with traffic flow.	
40	Should be considered where there are many bends, junctions or accesses, substantial development, a strong environmental or landscape reason, or where there are considerable numbers of vulnerable road users.	

Source: Department for Transport (2013a)

The advisory speed is calculated from the median speed and speed limit on the rural road in Experiment 1 (Chapter 3). The median for the preferred safe speed limit is 50mph for the straight road and 40mph for the curved road. For driving speed, the median is 50mph for the straight road (mean speed = 48.1mph) and 40mph for the curved road (mean speed = 41.0mph). The problem is that the actual speed locally is lower than the speed limit. Therefore, 40mph and 50mph are used as advisory testing speeds and speed limits for the rural curved road, while 50mph and 60mph are used for the straight road in Task 2: speed feeling and risk feeling in an automated driving condition. For Task 3: manual driving, on the basis of Swedish Vision Zero, 40mph, 50mph and 60mph speed limits are tested to measure drivers' compliance with speed limits.

- **Curve radius**

Curves with different radii produce different results for speed measurement. Table 4-4 lists the relationships between curve radius and curve speed from previous research. In general, larger curve radius leads to higher average curve speed. Daytime is based on the beginning and ending times of civil twilight specified by the US Naval Observatory. A curve radius of 125m has an average driving speed of approximately 40mph. Based on the relationship between radius and speed, if 40mph is tested for credibility on curved roads, the curve radius selected is 200m. There are no differences between the left curve and right curve for speed measurement (Comte and Jamson, 2000).

Table 4-4: Summary statistics of curve radius and speed from daytime data for passenger cars (Bonneson et al., 2007)

Curve Radius (m)	Regulatory Speed Limit (mph)	Advisory Speed (mph)	Deflection direction	Average Curve speed (mph)	Standard deviation	85^{th} Percentile curve speed (mph)
218	65	45	R	52.4	8.2	60.0
			L	51.5	5.3	57.0
218	60	45	R	50.5	5.0	55.0
			L	48.7	6.1	55.0
175	65	35	R	46.1	9.2	53.0
			L	46.2	6.0	52.0
175	65	35	R	50.9	6.3	56.5
			L	49.6	5.7	55.0
145	60	40	R	42.1	6.1	48.0
			L	42.6	5.5	48.0
134	60	35	R	44.4	6.2	50.0
			L	44.3	4.4	48.0
134	55	35	R	44.2	4.6	49.0
			L	45.3	5.3	50.0
125	55	35	R	41.4	4.6	45.0
			L	40.0	3.5	43.0
97	55	30	R	36.5	4.0	41.0
			L	36.0	3.9	40.0

- **Curve speed**

Concerning the safety at the bends, he advisory speeds for the particular curves are calculated using a standard formula which is adopted by Papacostas (1987).

$$v = \sqrt{g * R * (e + fs)}$$

Where fs = coefficient of side friction
R = curve radius (m)
e = superelevation
g = acceleration due to gravity (m/s^2)

Regarding curves, the main part of road standards is the design speed concept and the rules concerning the values of the characteristics on which design speed depends. Table 4-5 shows wet roadside friction coefficient values, used as an indicator of safe behaviour, derived as a safety margin. The appropriate speed for curves is rounded to 40mph on 200m radius curves and this is used as the advisory speed in this study. No bend signs or chevron boards are used at the curves.

Table 4-5: Appropriate highest speeds for negotiating curves by friction values (superelevation *e* = 0.055)

Road Condition		Curve Radius			
		100 m		200m	
Dry	*f*=0.5	$fs = 0.20$	57km/h	$fs = 0.18$	78 km/h
Wet	*f*=0.4	$fs = 0.17$	53 km/h	$fs = 0.16$	73 km/h
	f=0.3	$fs = 0.13$	48 km/h	$fs = 0.12$	67 km/h
Slippery	*f*=0.2	$fs = 0.09$	43 km/h	$fs = 0.08$	59 km/h
	f=0.1	$fs = 0.05$	36 km/h	$fs = 0.04$	50 km/h

- **Hard shoulder**

Hard shoulders, which often serve as emergency stopping lanes, are reserved lanes at the verge of a road or motorway. On higher speed rural single carriageways, paved shoulders (hard strips), with a width of **1.0m** and a different colour or paving type, stress the special function of these lanes, different from the functions of the main lanes.

- **Cycle lane**

The Handbook for Cycle-friendly Design claims that **2.0m** is the recommended width of a cycle lane, and 1.5m is the minimum, where either cycle or general traffic flows are high or the speed limit is 40mph (Cambridge Cycling Campaign, 2015). Coloured surfaces achieve better results than the non-coloured surfaces (with respect to peripheral hatching), which is perhaps attributable to a higher degree of contrast (Jamson et al., 2008), reinforcing the effect of the hatching treatment.

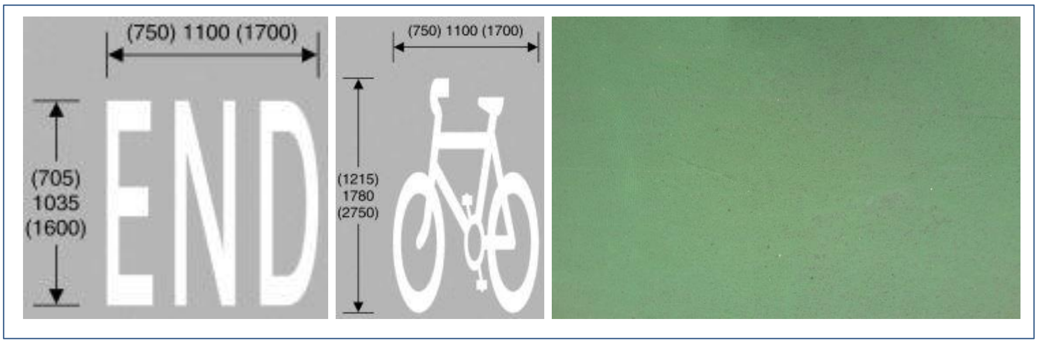


Figure 4-4: Cycle lane infrastructure signs

Considering the feasibility of scenarios running in the simulator (which cannot provide a physical barrier, cyclists or animals), hard shoulders and separated cycle lanes are used in this research. Road infrastructure design should be developed in order to better to support credible speed limits.

- **Lane width**

A lane width of 3.65m is used, taken from DMRB (2002).

- **Landscape**

The landscape of the computer-animated road used in the simulator is characterised as rural single carriageway, with road pavements, trees, grass verges, cars, slopes, unimpeded visibility, meeting smoothly with the road surface, flat and no vertical gradient and no elements such as objects or forests near the road (Antonson et al., 2009). Each object has a number of characteristics that specify form, colour, texture and shading. The road network has a low flow traffic and speed limit signs. Each pair of road scenarios is linked by rural junctions to avoid the treadmill effect.

4.4.4 Participants

Based on the experimental factors and levels, there are a total of eight treatment combinations. Factorial trials are powerful and can detect the main effects of interventions since having adequate power to detect plausible interactions requires greatly increased sample sizes. In the case of two-intervention experiments (Wolbers et al., 2011), a factorial design adequately powered to detect individual treatment effects would require at least 8 times the sample size of the combination trial, which is 8x4 = 32 combination trails. In order to get a reasonable sample size to compare the difference between the road scenarios within-subject, the calculation uses the following factors:

- The level of statistical significance for the experiment, or alpha = 0.05
- Statistical power, or the ability to reject the null, power > 0.8
- The effect size estimate of the variance within an experiment that is explained or accounted for by the experimental model, here a medium effect size of 0.40 is adopted.

This research evaluates speed limit credibility balanced for all types of drivers, therefore, driver factors such as gender and driving experience are taken into consideration. Males have higher rates of crash involvement than females, even when corrected for exposure factors (NHTSA, 2012). The reason for focusing on younger male drivers is that accident statistics and the findings from the survey part of this research suggest that they have a tendency to drive at higher speeds and be involved in riskier driving behaviours than other groups. The research considers young novice drivers and their passengers to be high-risk groups (Karpf and Williams, 1984; Trankle *et al*., 1990). To be specific, the group of young drivers and riders with less experience has the highest number of accidents and causes of death, especially for those between 18 and 25 (Peden et al., 2004). Novice drivers are in the process of acquiring driving skills, have completely different cognitions and emotions, and have been shown to speed more often (Wasielewski, 1984). Therefore, 34 participants are selected for the study, the attributes of which are summarised in Table 4-6.

The participants were required to have a valid driving licence. The participants were 17 males and 17 females, ranging in age from 18 to 62 (M = 31.71, SD = 14.41), with driving experience ranging from 1 year to 45 years (M = 12.10, SD = 13.41).

Table 4-6: Participant Sample combination

Gender	Driving Experience	Number of Participants
Male	≤3 years	9
Male	>3 years	8
Female	≤3 years	6
Female	>3 years	11

4.4.5 Task procedure

Three tasks were undertaken. Task 1 was a paper-based questionnaire. Task 2 was a speed feeling and risk feeling in automated driving condition task. Task 3 was a manual driving task. After arriving at the simulator, the participants were briefed on the requirements of the study, their ethical rights, risks, and safety measures. Then the participants were given instructions about their role in the study, including general information about the questionnaire, electrodermal activity and simulator driving procedures. The subjects were required to sign the consent form and informed that they could withdraw at any time. Before starting, they were asked to drive the simulator for at least 5 minutes to familiarise themselves with the controls of the car. The experimenter indicated which controls were required. If the participants felt sick or uneasy with the simulator at this point they were removed from the experiment.

- **Task 1 Questionnaire**

For Task 1, the participants remained seated in the office room facing a 15” monitor, and filled in a paper-based questionnaire. The experimenter presented the rural road layout combination picture slides, to ensure the questions and pictures were time matched. The participant was told that a series of pictures would be presented and several rating questions asked for each picture on the paper-based questionnaire. Two types of pictures were presented, single screenshot road scenes and compared group screenshot road scenes. The credibility questionnaire survey and risk perception questionnaire survey for Task 1 are shown in Table 4-7 and Table 4-8. The questions include single choice, slide scale and open questions for each road scene. As reduced speed can help avoid accidents, cause less severe accidents, or simply lead to making the right manoeuvre for the current traffic conditions (Castro, ed. 2008), the respondents were asked to provide the lowest credible speed limit. The next question asked the participants to mark the credibility of the speed limits on a sliding scale from very non-credible to very credible, with the middle point meaning neutrality, which was explained to the participants. The following demographic questions asked the participants for standard personal information, including gender, age and driving experience. The 8 screenshot pictures were presented to the 34 participants in a balanced sequence to minimise carryover effects.

Table 4-7: Credibility Questionnaire survey - Task 1

What is the **lowest** speed limit (mph) you think would be credible here?
⑳ ㉚ ㊵ ㊿ 60 70 80
How do you perceive a 70mph speed limit on this type of road? Very non-credible-----------------------------------Very credible
How do you perceive a 60mph speed limit on this type of road? Very non-credible-----------------------------------Very credible
How do you perceive a 50mph speed limit on this type of road? Very non-credible-----------------------------------Very credible
How do you perceive a 40mph speed limit on this type of road? Very non-credible-----------------------------------Very credible
What are the reasons that you feel about the speed limit credible/non-credible?

Table 4-8: Risk perception Questionnaire survey - Task 1

What is the risk of your car running off the road here? Extremely low risk Extremely high risk 0--100
What is the risk of your car hitting the oncoming vehicle here? Extremely low risk Extremely high risk 0--100
What is the risk of your car hitting the cyclist here? Extremely low risk Extremely high risk 0--100
Compared with baseline road situation, you might feel Lower risk Same risk Higher risk 0----------------------------------50---------------------------------100

- **Task 2 Automated driving**

The experiment followed a 2 × 2 × 2 × 3 within-subject design, with road layout (8 levels) and automated driving speed (3 levels) as within-subjects factors. The experiment task was conducted in a driving simulator with the vehicle controlled automatically. The road situation combined road layout and automated driving speed in 24 counterbalanced conditions, as shown in Table 4-9. The speeds were presented in a random order within each trial to avoid order effect.

The driving simulator was precisely controlled in terms of timing. The trial started with a 120s baseline (calm down and relax time). The experiment presented the road scenes at inter-stimulus intervals of 75s. For each road scene presentation, the visual scene faded in with a constant automated driving speed for 15s, followed by a 30s questionnaire and a 30s recovery period. An opposite vehicle passed the own vehicle in the middle of each stimulus, followed by another stimulus until all 24 automated driving stimuli were done.

Table 4-9: Design matrix of experiment for the automated driving task

	Road environment Factor				
Experimental condition number	Road curve	Hard shoulder	Cycle lane	Rural Road scenes	Automation Speed
1	Present	Present	Present	Curve + Shoulder + Cycle lane	40mph
2					50mph
3					60mph
4	Present	Present	Absent	Curve + Shoulder	40mph
5					50mph
6					60mph
7	Present	Absent	Present	Curve + Cycle lane	40mph
8					50mph
9					60mph
10	Present	Absent	Absent	Curve only	40mph
11					50mph
12					60mph
13	Absent	Present	Present	Shoulder + Cycle lane	40mph
14					50mph
15					60mph
16	Absent	Present	Absent	Shoulder only	40mph
17					50mph
18					60mph
19	Absent	Absent	Present	Cycle lane only	40mph
20					50mph
21					60mph
22	Absent	Absent	Absent	Straight only	40mph
23					50mph
24					60mph

For Task 2 the participants were introduced to the driving simulator. They were escorted into the simulator and seated in the vehicle cab with the image generation system showing a 360-degree full white display. The escorting researcher verbally repeated the characteristics of the requisite driving scenario, emphasising the self-driving nature of the task. The automated driving task required the participant to be seated in the driver’s seat and feel the speed of a given road environment. It required the participant to record the speed sensation and risk feeling at automated speed. The experimenter was seated behind the participant to make sure the BIOPAC facility was connected and the questionnaire was present for the participant. The questions in the credibility questionnaire survey for Task 2 and risk perception questionnaire survey for Task 2 are shown in Table 4-10 and Table 4-11.

Table 4-10: Credibility Questionnaire survey _ Task 2

Automation condition in driving simulator	How do you feel about the speed? Too slow ------------------------------------- Too fast

Table 4-11: Risk perception Questionnaire survey _ Task 2

Automation condition in driving simulator	With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very Unsafe-------------------------------------Very Safe

During the task, physiological measurements of EDA were taken using a recording system involving placing electrodes on the fingers. The skin conductive sensors were attached to the second phalanxes of the index and middle fingers of the participant's non-dominant hand, with the sensor on the bottom of the fingertips held by adhesive tape. An isotonic conductive gel (Gel 101) was applied between the skin conductive sensors and the skin to improve sensor-skin contact, as recommended (Fowles et al., 1981). Thus, the skin conductance response was measured by the voltage drop between the two electrodes (priya Muthusamy, 2012). The psychological measurement was performed using BIOPAC MP35 and software for digital data acquisition BIOPAC Student Lab with a sampling rate of 500Hz. A laptop was used for recording the data.

The EDA measurement environment was controlled by temperature, respiration and movement (Boucsein, 2012). The room temperature was held between 20°C and 22°C to ensure data collection accuracy. The optimal recording conditions were based on the maximum signal to noise ratio in the laboratory (Empatica Support, 2016). Participants were asked to be seated and not to move. EDA was recorded from the finger surface of the non-dominant hand based on traditional recording processes (priya Muthusamy, 2012). The participants were asked to wash their hands with warm water before the electrodes were placed, for skin conductance (Branković, 2011). EDA was recorded for the whole process.

As the threat of shock significantly increases tonic skin conductance level, to maintain accurate comparisons between participants, a 2 minute baseline scenario was recorded for each driver prior to the experiment. During this period the subject was asked to sit comfortably and relax. The values were averaged to provide a baseline for basic emotion. Research (Michaels, 1960) indicates that traffic events occur, depending on the street, at a rate of one every 21 to 35 seconds. This study adopts an interval of 15 seconds for subjects in the automated driving task to see the road segments and feel the speed. After each stimulus, questions were presented, one speed sensation question and one risk feeling question, then the experiment moved on to another stimulus until all the animations were done.

- Task 3 Manual driving

The experiment followed a 2 × 2 × 2 × 3 within-subject design with road layout (eight levels) and road speed limit signs presented (three levels). Each subject was asked to drive through all road scenarios, which followed in a balanced sequence. They were told to drive as they usually would along a rural road. It is assumed that the participants would select the driving speeds at which they felt comfortable and optimise their performance. After 2 minutes of training for familiarisation with the driving simulator, the manual driving session involved driving through all the road scenarios. The speed limits were indicated on the roadside by standard speed limit signs (40mph, 50mph and 60mph), which are the commonly used signs on rural single carriageways.

Table 4-12: Participant allocation for manual driving road scenarios order

Participant ID	Scenario sequence							
1, 9, 17, 25, 33	A 60-40-50	B 40-60-50	H 60-40-50	C 50-60-40	G 40-60-50	D 60-40-50	F 50-60-40	E 40-60-50
2, 10, 18, 26, 34	A 60-50-40	B 40-50-60	H 60-50-40	C 50-40-60	G 40-50-60	D 60-50-40	F 50-40-60	E 40-50-60
3, 11, 19, 27, 35	D 50-60-40	E 50-60-40	C 40-60-50	F 60-40-50	B 60-40-50	G 60-40-50	A 40-60-50	H 40-60-50
4, 12, 20, 28, 36	D 50-40-60	E 50-40-60	C 40-50-60	F 60-50-40	B 60-50-40	G 60-50-40	A 40-50-60	H 40-50-60
5, 13, 21, 29	E 60-40-50	F 40-60-50	D 40-60-50	G 50-60-40	C 60-40-50	H 50-60-40	B 50-60-40	A 50-60-40
6, 14, 22, 30	E 60-50-40	F 40-50-60	D 40-50-60	G 50-40-60	C 60-50-40	H 50-40-60	B 50-40-60	A 50-40-60
7, 15, 23, 31	H 60-40-50	A 60-40-50	G 40-60-50	B 40-60-50	F 50-60-40	C 60-40-50	E 40-60-50	D 60-40-50
8, 16, 24, 32	H 60-50-40	A 60-50-40	G 40-50-60	B 40-50-60	F 50-40-60	C 60-50-40	E 40-50-60	D 60-50-40

For the road section combination in Table 4-13,

$$\text{Each Curve Section } = 504 * 4 + 315 * 3 = 2961\text{m}$$

$$\text{Each Straight Section} = 756 * 3 = 2268\text{m}$$

$$\text{Total road length} = \text{Curve Sections} * 4 + \text{Straight Sections} * 4 = 20916\text{m}$$

Table 4-13: Task 3 Road layout

<table>
<tr><th>Scenario number</th><th>Road type</th><th colspan="7">Road segment</th><th>Total</th></tr>
<tr><td>A</td><td>Curve + Shoulder + Cycle lane</td><td rowspan="4">Straight 504m</td><td rowspan="4">Curve 315m</td><td rowspan="4">Straight 504m</td><td rowspan="4">Curve 315m</td><td rowspan="4">Straight 504m</td><td rowspan="4">Curve 315m</td><td rowspan="4">Straight 504m</td><td rowspan="4">2961m</td></tr>
<tr><td>B</td><td>Curve + Shoulder</td></tr>
<tr><td>C</td><td>Curve + Cycle lane</td></tr>
<tr><td>D</td><td>Curve only</td></tr>
<tr><td>E</td><td>Shoulder + Cycle lane</td><td colspan="2" rowspan="4">Straight 756m</td><td colspan="2" rowspan="4">Straight 756m</td><td colspan="3" rowspan="4">Straight 756m</td><td rowspan="4">2268m</td></tr>
<tr><td>F</td><td>Shoulder only</td></tr>
<tr><td>G</td><td>Cycle lane only</td></tr>
<tr><td>H</td><td>Straight only</td></tr>
</table>

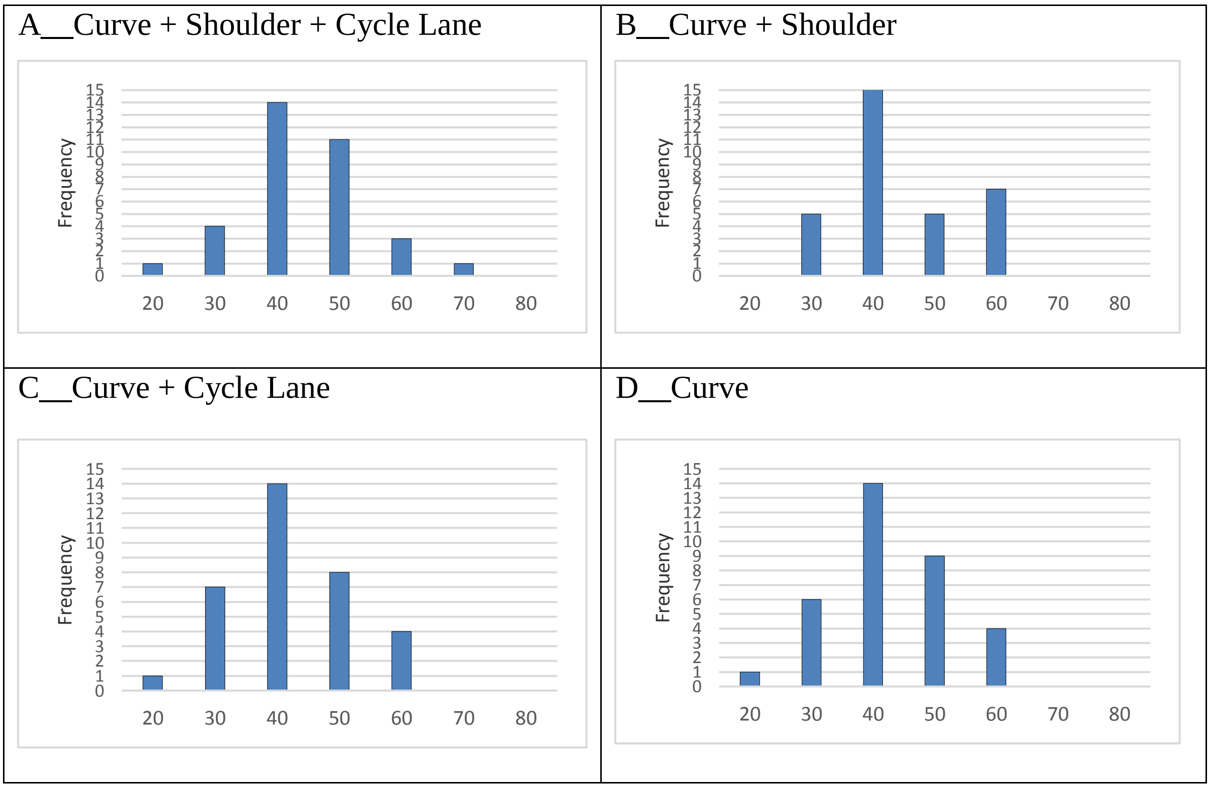
It is not acceptable to have one speed limit along the whole length of a road, but at the same time, it is not reasonable to have too many speed limit changes on the road. Most countries set a minimum distance over which local speed limits are applied – for instance not less than 600m – and encourage reasonable consistency of limits over the length of a route. Adequate, consistent speed limit signage is critically important to maintain awareness of the limits and for public support of its application and enforcement (OECD, 2006). In Task 3, the speed limits were changed every 756m on the straight road, and every 819m on the curved road.

The experiment sequence setup was a questionnaire followed by speed sensation, followed by manual driving. The reasons being: 1) to manage a tight schedule, starting and stopping the simulator was too time-consuming, as speed sensation and manual driving should be tested together; 2) the static road picture questionnaire was put first to avoid revealing the study's aim and so that the subjects would not have the feeling of speed at the beginning; and 3) drivers could determine their driving speed on the basis of recognition knowledge of the set of environments in Task 2 and Task 3. In total the three task took approximately 120 minutes. Between each trial, the participants were allowed a short break. On completion of the three tasks, the participants were debriefed and paid £10.

4.5 Results of credibility

4.5.1 Task 1 Speed limit credibility chosen result

In Task 1, the question was to choose one lowest credible speed limit for a given road picture. Figure 4-5 shows the frequency distribution of the respondents' credibility speed limit choice, with the x-axis representing the speed limit and the y-axis representing the frequency. 40mph was accepted by most respondents on four types of curved roads. For the straight roads, 50mph was more credible on Straight + Shoulder + CycleLane and Straight + CycleLane, while 60mph was more credible on Straight + Shoulder and Straight road. Since the aim is to find the lowest credible speed limit, these result can be referenced as evidence for the final decision.



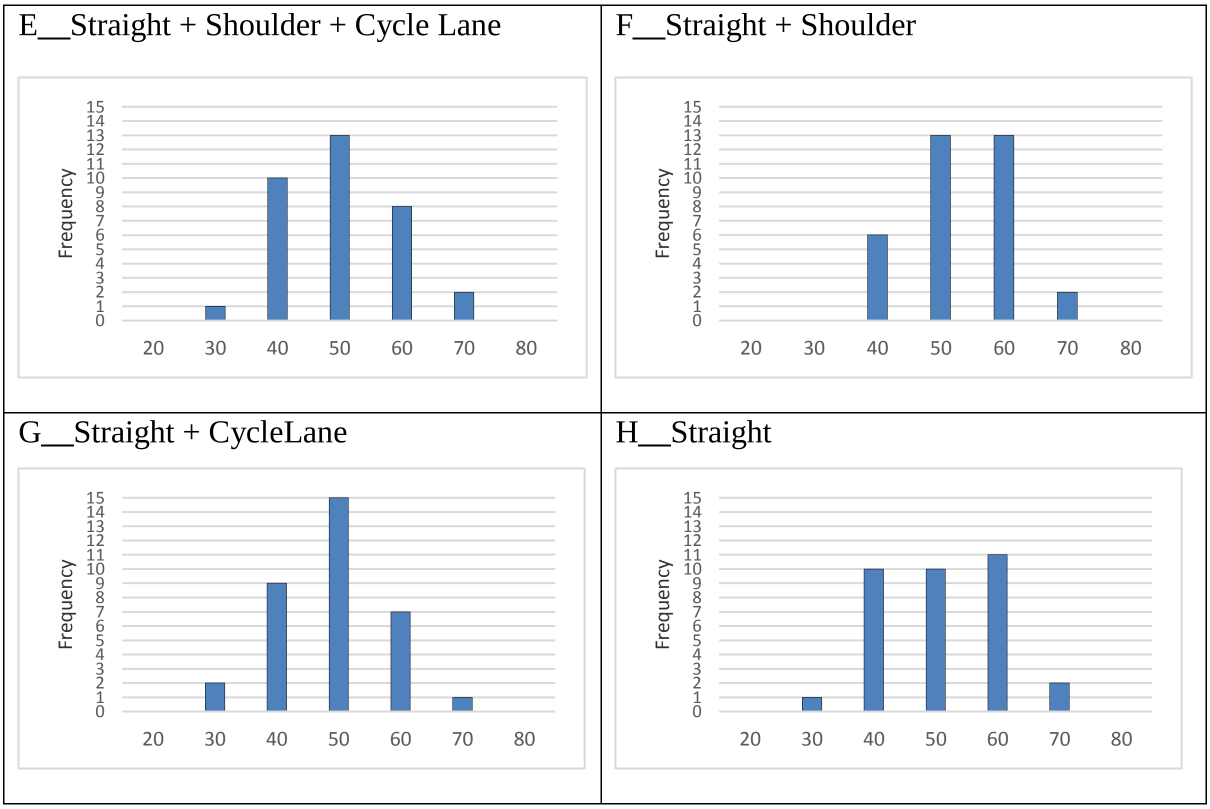


Figure 4-5: Credible Speed limit chosen frequency on eight roads

Table 4-14: Comparison result for the mode and the median value for credible speed limit

	Mode (mph)	**Median (mph)**
A_Curve + Shoulder + Cycle Lane	40	40
B_Curve + Shoulder	40	40
C_Curve + Cycle Lane	40	40
D_Curve	40	40
E_Straight + Shoulder + Cycle Lane	50	50
F_Straight + Shoulder	50/60	50
G_Straight + CycleLane	50	50
H_Straight	60	50

Table 4-14 lists the mode and median values of the credible speed limits chosen; the median being the middle value in the list ordered from smallest to largest (as data may not be symmetrically distributed) and the mode being the value that occurs most often. This research aims to find a common choice of speed limit, so the mode value is adopted as the most credible speed limit.

4.5.2 Task 1 Speed limit credibility rating result

The question was to rate speed limit perception in a given road picture with a value from very non-credible (0) to very credible (100). The higher the score, the more credibility the speed limit had. Respondents gave their answer on a visual analogue scale on paper. Figure 4-6 shows the rating score with standard errors, 70mph and 30mph were seen as non-credible for any of the eight rural roads. For 60mph, the rating was the highest on Straight + Shoulder and Straight road. The paired T-test was used to compare the credibility score between the two road layouts with the same speed limit level. The 60mph speed limit was only credible on Curve. There was no significant difference between Curve + Shoulder and Curve in terms of 60mph speed limit perception. Comparing Straight + CycleLane with Straight with 60mph speed limit, although they all presented 60mph as credible, 60mph was more credible on Straight (t (33) = -3.216, $p \leq .05$). There was no significant difference between Straight + Shoulder and Straight in terms of 60mph speed limit perception. 50mph was credible for all eight roads. For Curve + Shoulder + CycleLane, Curve + Shoulder, Curve, Straight + Shoulder + CycleLane, Straight + CycleLane, 50mph provided the highest score. 40mph was not credible on Straight + Shoulder or Straight but was acceptable on the other six roads. However, there was no significant difference between 50mph and 40mph on the three curved roads, Curve + Shoulder + CycleLane, Curve + Shoulder, and Curve + CycleLane. There was no significant difference between 60mph and 50mph on Curve only or the four straight roads. Therefore, we can assume 50mph and 40mph were equal on the three curved roads and 60mph and 50mph were equal on Curve only and the four straight roads.

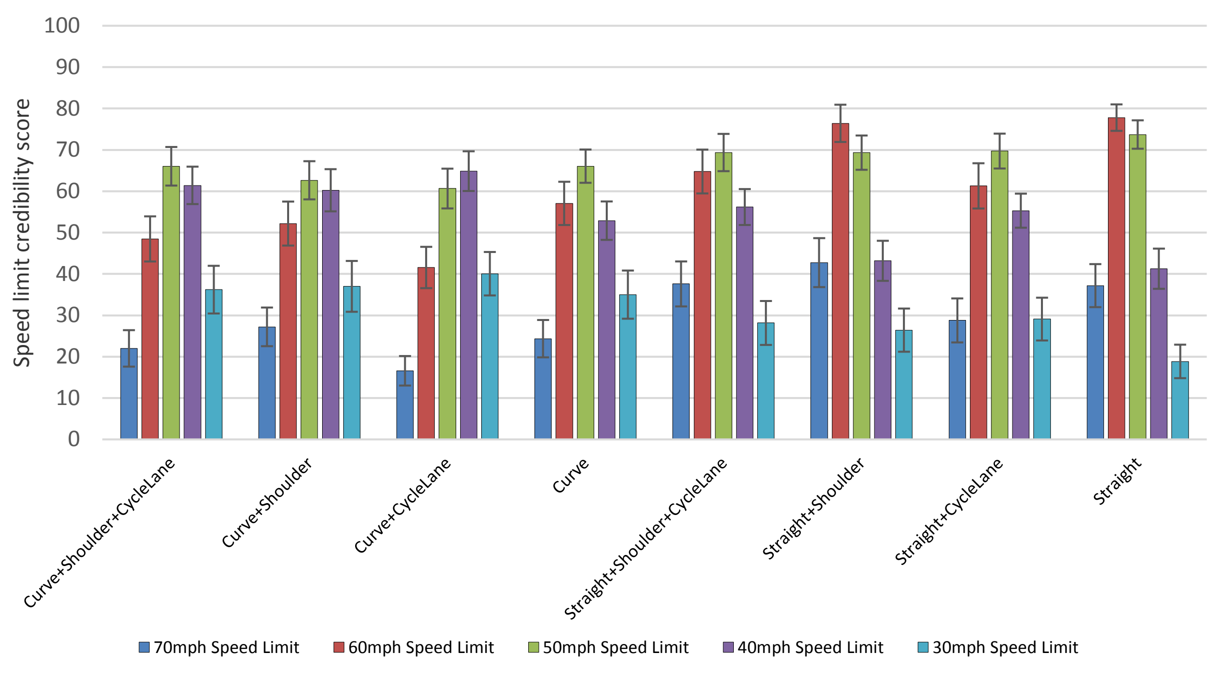


Figure 4-6: Credible speed limit rating score on eight roads

4.5.3 Task 1 Open questions word frequency result

It has been demonstrated that the credibility of a speed limit is highly influenced by the specific road layout and roadside environment. Regulating the speed limit is not an easy task because the speed limit credibility chosen shows a variation of 10mph or more for each road scene. It is necessary to investigate why the respondents had different opinions of credible speed limits. The open question asked the respondents to provide the reasons why they chose that speed limit.

For each of the eight road scenes, the respondents mentioned different points. Based on NVIVO word frequency analysis, the main issues for each road scene are summarised here.

A__Curve + Shoulder + CycleLane: Respondents mentioned curve/bend/corner, cycle lane and cyclist. The road was quite wide and spacious, room for evasive action. Each vehicle type had their own separate place.

B__Curve + Shoulder: Respondents mentioned the hard shoulder and wider roads. The hard shoulder provided extra road and a safe zone in case of emergency so a higher speed would be viable.

C__Curve + CycleLane: Respondents mentioned the cycle lane and cyclists, involving more risk/dangerous/safety considerations, and that vehicles may swerve into the cycle lane accidentally if driving too fast on the curve.

D__Curve: Respondents mentioned the curve. There was conflict perception about the curve: some perceived sharpness but some perceived it as gentle. Drivers perceived risk about the oncoming vehicle.

E__Straight + Shoulder + CycleLane: Respondents mentioned the cycle lane and cyclist, encouraging driving fast, and consideration for the cyclist.

F__Straight + Shoulder: Respondents mentioned the hard shoulder which encourages driving fast and overtaking.

G__Straight + CycleLane: Respondents mentioned the cycle lane and cyclist, considered the situation on in which to drive slower, but less risk to cyclists at higher speeds.

H__Straight: The road was wide open and straight to encourage driving fast but they also considered dangers/hazards.

D__Curve & H__Straight: Respondents did not mention cycle lane or cyclists.

A__Curve + Shoulder + CycleLane & E__Straight + Shoulder + CycleLane: Although the road was wider than the other types of roads, the respondents may have felt slightly confused about the complex road layout.

4.5.4 Task 1 Open questions themes classification

It is not surprising that the qualitative analysis generated the three main theme classifications, which were exactly the three factors of the road design: curve, cycle lane and hard shoulder. The discussion mainly focused on drivers' opinions of the speed limit credibility and risk perception of each road scene.

THEME 1: CURVE

Curve brought the main risk on the four curved roads. A lower speed limit was necessary to prevent accidents so the reduced speed for the bend was appropriate.

THEME 2: CYCLE LANE

The presence of a cycle lane brought two different opinions in terms of setting credible speed limits. Firstly, taking cyclists into account implied a lower speed limit, and secondly the cycle lane, encouraged a higher speed limit because the separated cyclists were safer. These two conflicting viewpoints affected the drivers' perceptions of speed limit credibility and driving behaviour, especially driving speed and lateral position. The presence of a cycle lane brought out opinions about risk perception. The cycle lane may encourage cyclists and thus bring unsafe feelings to drivers on both curves and straights.

THEME 3: HARD SHOULDER

The hard shoulder provided extra space for drivers in case of breakdown, and encouraged going faster with a higher speed limit because the respondents perceived it as safe in that road situation.

4.5.5 Task 2 Speed rating result

Task 2 was carried out in the driving simulator under the automation condition. After each 15 seconds of automated driving the respondents were required to answer on a visual analogue scale on paper. This measurement was used to rate the speed sensation at given speeds (40mph, 50mph and 60mph) on eight different types of roads (Figure 4-7). The y-axis speed rating score varied from -50 to 50, meaning the speed was felt to be too slow to too fast. A score within 5 can be taken as an appropriate speed due to the eye's discerning ability at the middle point in the visual analysing scale where error exists.

Drivers rated 40mph as appropriate on the four types of curved road. A repeated-measures analysis of variance (ANOVA) indicates that there was no significant difference between the four curved roads at 40mph automated speed (F (2.414, 79.654) = 2.873, $p > .05$, $\eta^2 = .08$). Drivers perceived 40mph on curved roads to be equally appropriate. However, 40mph was too slow on the straight road, so not an appropriate speed for driving.

The drivers rated 50mph as slightly fast for the curved road while slightly slow for the straight road. When a cycle lane was present on the straight road, the mean value of speed rating on Straight + Shoulder + CycleLane and Straight + CycleLane, showed 50mph to be appropriate. Drivers perceived 50 mph to be slightly slower than Straight

+ Shoulder and Straight. For the straight roads, the presence of a cycle lane raised drivers' awareness of cyclists implying they should adjust their speed to a safer level. The presence of a cycle lane on the straight road was an impact factor for speed perception, making 50mph appropriate. There was a significant difference between the four straight roads at a given 50mph automated speed (F (2.508, 82.775) = 3.033, $p < .05$, $\eta^2 = .084$). 50mph was more appropriate on a straight roads with a cycle lane.

Drivers rated 60mph to be suitable on the straight roads, but 60mph was too fast for the curved roads. One reason for this is that when the sharp curve was present, the visibility distance decreased, meaning the drivers' uncertainty increased and they had to slow down to achieve better anticipation (MASTER, 1998). Comparing the straight roads at a given speed of 60mph, there was no significant difference among the four (F (1.931, 63.717) = 2.045, $p > .05$, $\eta^2 = .058$). Straight only and Straight + Shoulder encouraged the drivers to select higher speeds due to the road layout being simple and drivers maybe not considering cyclists too much. Both 50mph and 60mph driving speed seemed appropriate for Straight + CycleLane. Whether 50mph or 60mph was more credible can be measured from other evidence.

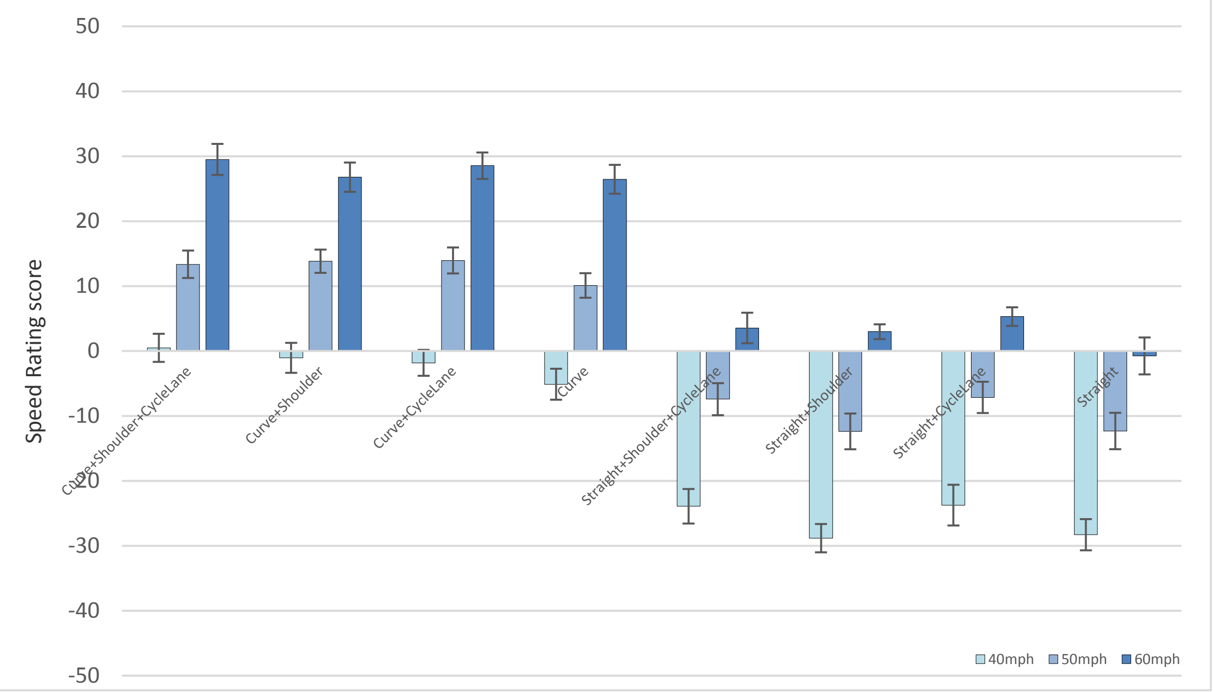


Figure 4-7: Task 2 speed rating result in three given speeds on eight roads

4.6 Results of risk perception

4.6.1 Task 1 Risk rating results

The drivers were asked questions about their perception of risk in terms of running off the road, hitting oncoming vehicles and hitting cyclists. The respondents gave answers on a sliding scale from extremely low risk (0) to extremely high risk (100), as shown in Figure 4-8. The participants were asked three questions about risk feeling:

Q8 What is the risk of your car running off the road here?

Q9 What is the risk of your car hitting the oncoming vehicle here?

Q10 What is the risk of your car hitting the cyclist here?

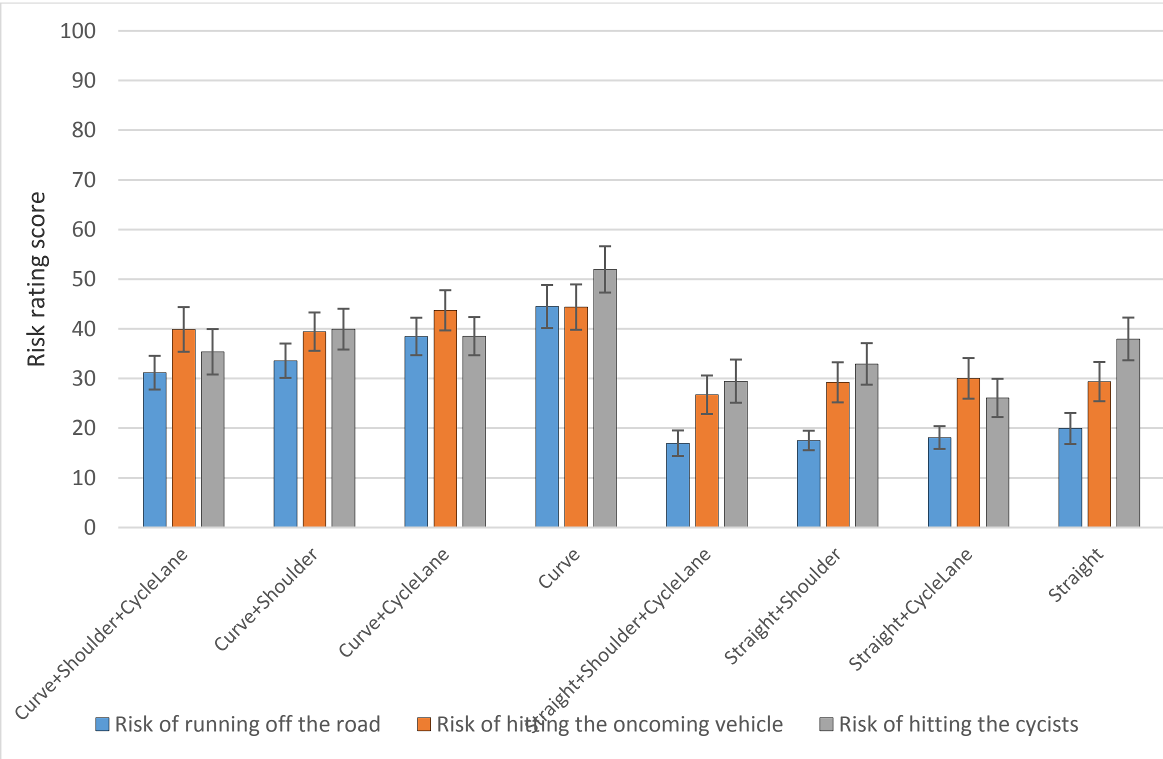


Figure 4-8: Risk evaluation on the rural single carriageway value from extremely low risk (0) to extremely high risk (100)

Combining the four curved roads with the four straight roads, there is a significantly higher risk of running off the road on the curve than the straight ($t(135) = 10.408$, $p \leq .05$); higher risk of hitting the oncoming vehicles on the curve than the straight ($t(135) = 7.545$, $p \leq .05$); and higher risk of hitting the cyclist on the curve than the straight ($t(135) = 5.821$, $p \leq .05$). Thus, for the risk of running off the road, the risk of hitting oncoming vehicles and the risk of hitting cyclists, the presence of the curve was an impact factor for respondents’ perceptions of risk.

For the risk of running off the road, drivers presented the lowest risk feeling on Straight + Shoulder + CycleLane, but not significantly different from other straight roads. The respondents perceived a greater risk of running off the road on the curve only than the curve with a shoulder ($t(33) = -2.857$, $p \leq .05$). The presence of a hard shoulder also decreased the respondents' risk perception of running off the road on the curved roads, but not on the straight roads. Comparing Curve + Cycle Lane with Curve only, there was no significant difference in the risk perception of running off the road and hitting oncoming vehicles.

The risk of hitting oncoming vehicles presented the lowest risk on Straight + Shoulder + CycleLane, but not significantly different from other straight roads. There was no significant difference in the risk of hitting the oncoming vehicle scores for the four curved roads.

The risk of hitting the cyclist presented the lowest risk perception on Straight + CycleLane. The respondents perceived a greater risk of hitting cyclists on the straight only than the straight with a cycle lane ($t(33) = -2.743$, $p \leq .05$). However, the respondents perceived the risk of hitting the cyclist on curved roads differently. They perceived a greater risk of hitting the cyclist on the curve only than the curve with shoulder ($t(33) = -4.117$, $p \leq .05$). They perceived a greater risk of hitting the cyclist on Curve only than Curve + Cycle Lane ($t(33) = -2.634$, $p \leq .05$). The presence of a cycle lane was an impact factor which decreased respondents' perception of risk of hitting cyclists on the curved road, but not the straight road. Thus, the presence of a cycle lane and the presence of a hard shoulder were impact factors which decreased respondents' perceptions of the risk of hitting cyclists on both straight and curved roads.

Therefore, there were risk perception differences between the eight road layouts and three potential accident types. First, the presence of a curve was an impact factor affecting the respondents’ perception of risk. Second, there was no significant difference in risk perception of running off the road and hitting oncoming vehicles for the straight roads. Third, the presence of a cycle lane and a hard shoulder provided an extra safety margin in case of running off the road or hitting cyclists.

4.6.2 Task 1 Compared risk rating results

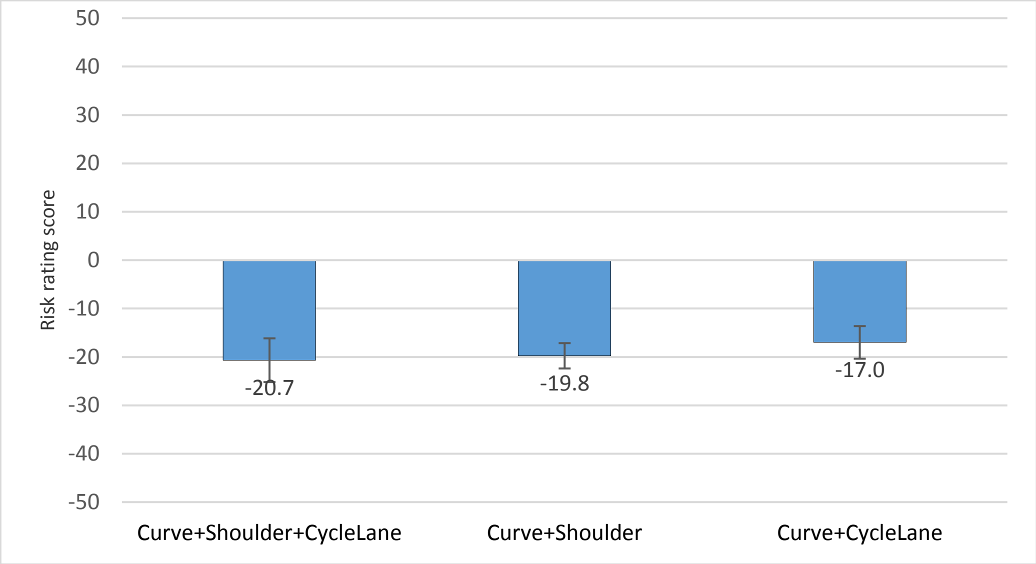


Figure 4-9: Task 1 Compared risk with curve baseline value from lower risk (-50) to higher risk (50)

Figure 4-9 shows the drivers' perception of risk compared with Curve only (curve baseline). The y-axis score goes from low risk (-50) to high risk (50) with 0 meaning no difference between the two roads. All three types of curved road presented a lower risk than the curve baseline. Compared to the curve baseline, Curve + CycleLane was perceived as lower risk, but not as much lower, than the other two roads, although there was no significant difference between Curve + Shoulder + CycleLane, Curve + Shoulder and Curve + CycleLane. Comparing the risk between the two roads, wider roads had greater safety perception.

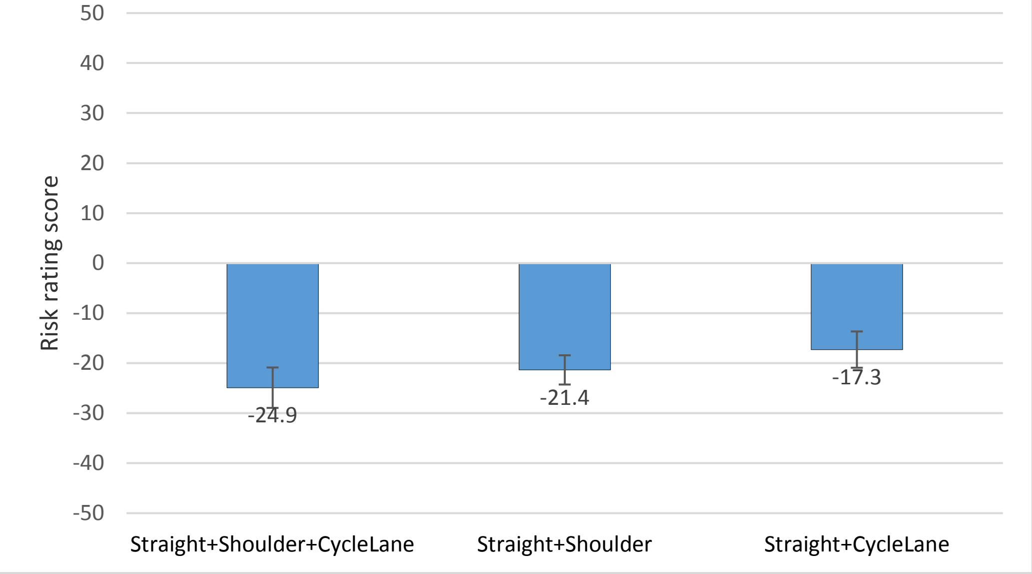


Figure 4-10: Task 1 Compared risk with straight baseline value from lower risk (-50) to higher risk (50)

Figure 4-10 shows the drivers' perception of risk compared with Straight only (straight baseline). All three types of straight road presented a lower risk than the straight baseline. Straight + Shoulder + CycleLane presented much lower risk than Straight + CycleLane but there was no significant difference between them. In addition, risk perception in the presence of a cycle lane had larger variation, because respondents had different opinions about the presence of a cycle lane in terms of risk perception. Comparing the risk between the two roads, wider roads had a much lower risk perception.

4.6.3 Task 2 Risk rating result

Task 2 was carried out in the driving simulator. After each 15-seconds of road stimuli, the respondents were required to give answers on a visual analogue scale on paper. The aim was to rate the risk in terms of safety at a given speed (40mph, 50mph and 60mph) on eight different types of roads (Figure 4-11). The risk rating score went from -50, very unsafe, to 50, very safe.

Drivers perceived 40mph to be safe on all types of curved and straight roads. Straight with a cycle lane was perceived as safer feeling than the other two road types. The 50mph speed limit provided a low sense of safe feeling on the four curved roads, thus 40mph was preferred on curved roads. Compared with the four curved roads at a given speed of 40mph, there was no significant difference among the four (F (3, 99) =

.1.467, p > .05, η^2 = .043) in terms of risk rating. Drivers perceived 50mph as safe on all the straight roads. A value exceeding 30 meant they had very safe feelings, better than at 40mph. 50mph provided a safer feeling on Curve + Shoulder + CycleLane than other curved roads, but there was no significant difference between the four curved roads at a given speed of 50mph (F (3, 99) = 1.499, p > .05, η^2 = .043). Although 40mph provided a safe feeling on the straight road, 40mph could not provide a very safe feeling due to 40mph not being credible on the straight road.

60mph was clearly too high on the curved road, thus had an unsafe feeling. Drivers perceived 60mph on Curve + CycleLane to have a higher risk than the other curved roads, but there was no significant difference between the four curves. Drivers perceived 60mph to be safe on all four straight roads. The value exceeding 30 meant it provided a very safe feelings on Straight + CycleLane, Straight + Shoulder, and Straight roads. However, there was no significant difference among the four straight roads at 50mph (F (3, 99) = .517, p > .05, η^2 = .015) and there was no significant difference at 60mph (F (3, 99) = .325, p > .05, η^2 = .010). The presence of a cycle lane on the straight road gave drivers a safe feeling but not approaching very safe. Compared to 60mph, 50mph was more suitable on Straight + CycleLane.

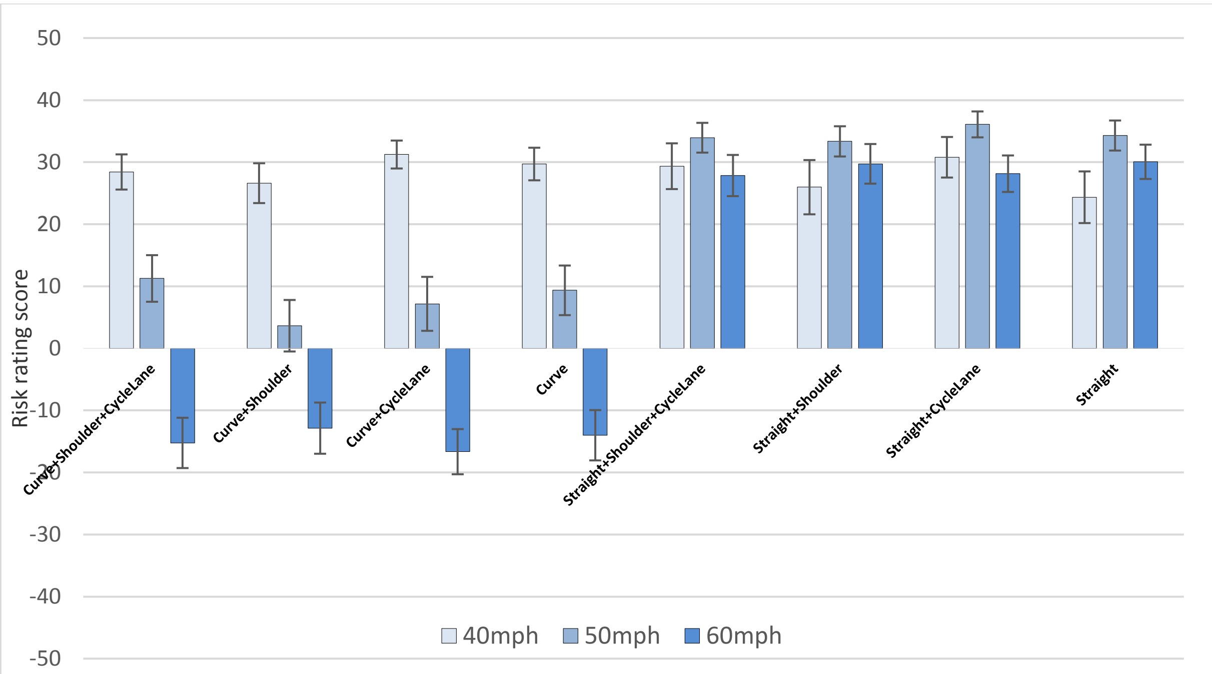


Figure 4-11: Task 2 Risk rating result in three given speeds on eight roads

4.6.4 Task 2 The relationship between speed rating and risk rating

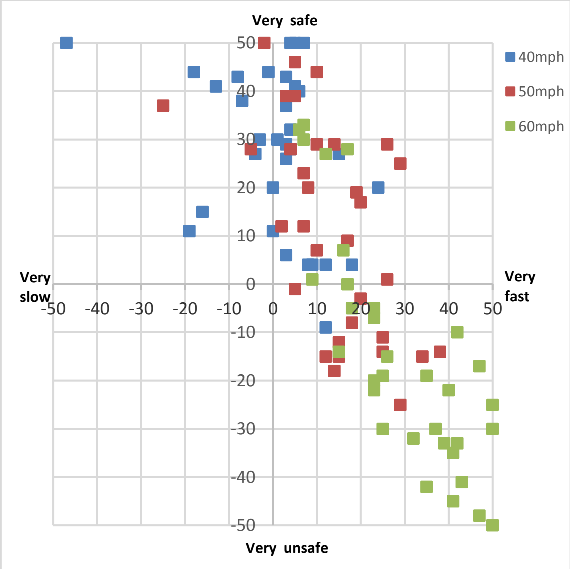
As the driving speed increased on the four curved roads, the more risk the drivers felt. All the respondents perceived 60mph as fast or very fast on curved roads and assessed their risk feeling from neutral to unsafe. 50mph was also considered fast for the curved road. 40mph gave appropriate speed and safety feelings to most drivers. 40mph was a more appropriate speed, giving a safe feeling for Curve + Shoulder and Curve only.

For the straight roads, the majority of the respondents felt safe at all speeds, 40mph, 50mph and 60mph. Straight + Shoulder at 60mph was an appropriate speed and gave a safe feeling. A small group of respondents perceived lower speeds on straight roads as unsafe, because slow speed may frustrate other drivers behind the own vehicle and lower speed is not appropriate on a straight road.

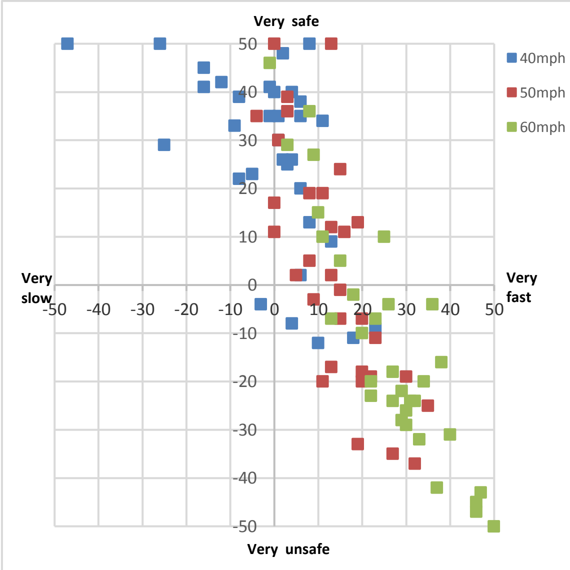
Two-dimension scatter plots are presented in Figure 4-12, with speed feeling on the x-axis and risk feeling on the y-axis, distinguished by three colours representing automated driving speeds of 40mph, 50mph and 60mph. The speed feeling axis goes from very slow (-50) to very fast (50) and the risk feeling axis goes very unsafe (-50) to very safe (50). Of the 8 road environments, as expected, the four curved roads had the same speed-risk pattern in the first quadrant and the fourth quadrant. As speed went up, drivers perceived the faster speed and feeling of safety decreased. The ratings for risk feeling began to rise when drivers experienced a speed at which they felt uncomfortable. This might because a lower speed limit was credible and a higher speed limit was not credible on the curved roads.

The four straight roads show a similar scatter plot pattern with most of the points fastened on the y-positive axis and the second quadrant. As speed went up, drivers perceived the faster speed but feelings of safety remained nearly unchanged. This illustrates that most of the drivers felt safe on the rural straight road no matter what the speed was. To be specific, when a 40mph speed limit was presented, the respondents felt it was very slow and not all of them felt very safe. Higher speed limits might be more acceptable in straight road situations. The plot pattern seems more scattered for Straight only, showing that the respondents perceived speed and risk with bias on Straight only roads. It should be noted that a small number of participants perceived the straight road with 40mph speed as unsafe. They perceived that lower speeds on the straight road might bring trouble for the own vehicle and the following vehicle.

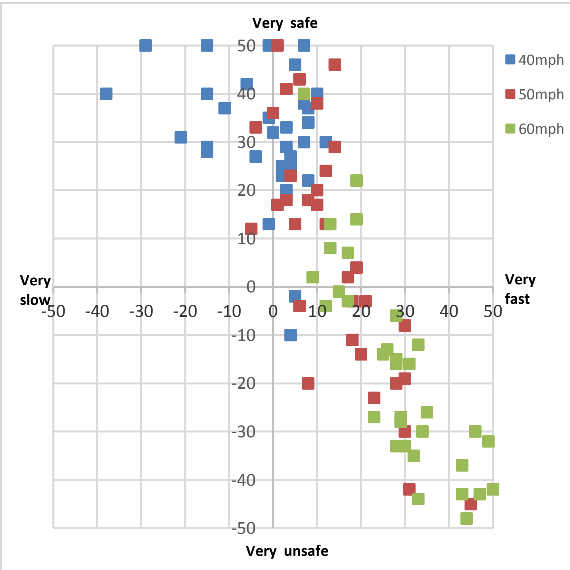
A__Curve + Shoulder + Cycle Lane



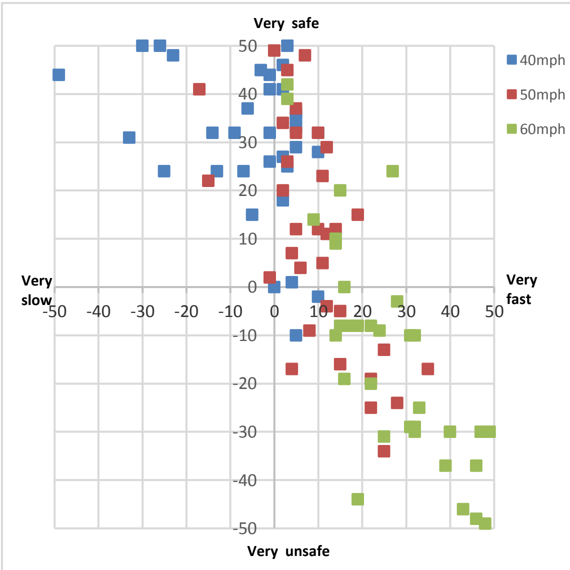
B__Curve + Shoulder



C__Curve + Cycle Lane



D__Curve



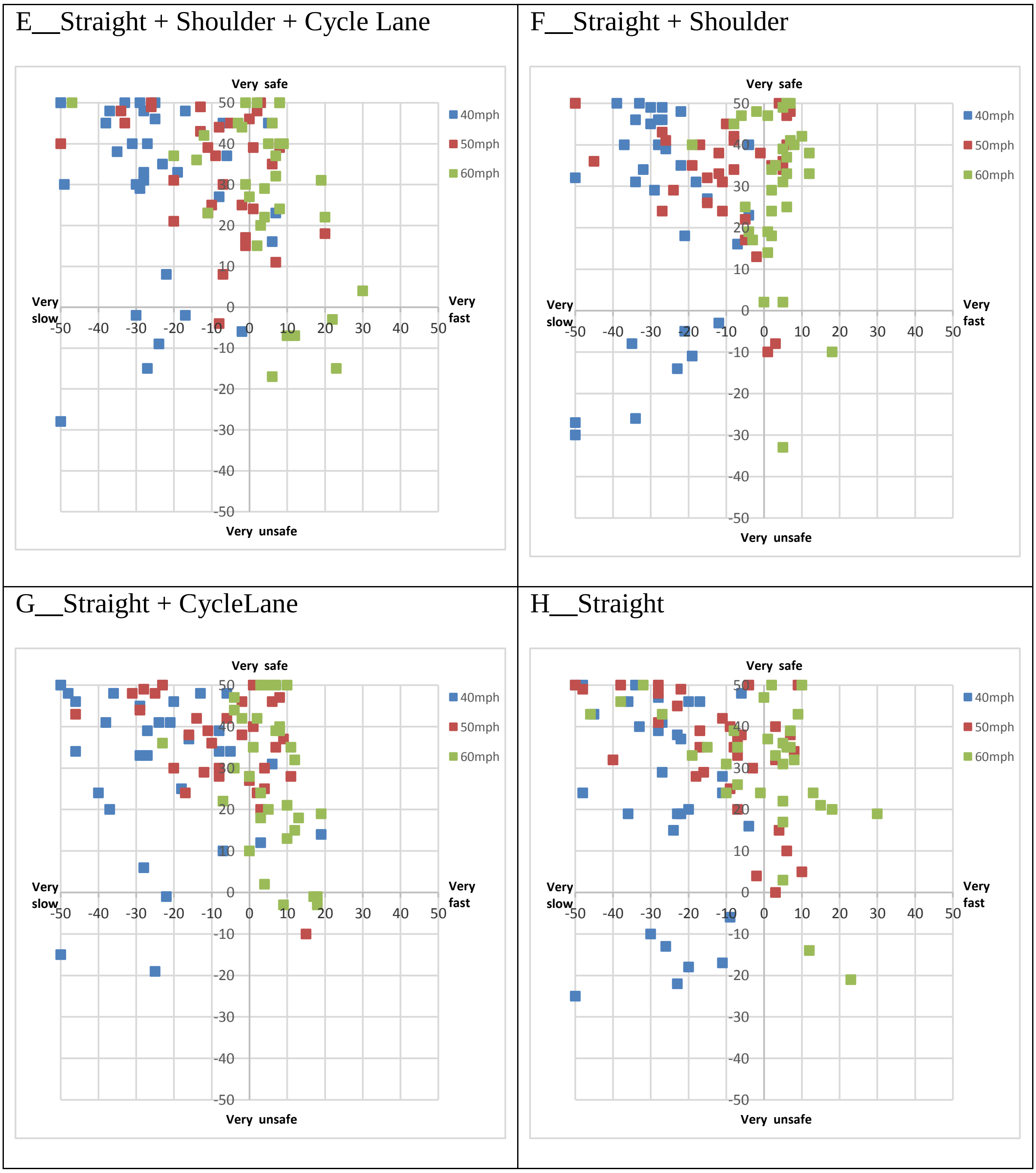


Figure 4-12: The relationship between speed rating and risk rating

So far, credibility has been determined by two main predictors, road layout and the roadside environment, and risk perception from a person's own estimate of the hazard level. It can be concluded from the results, firstly, that appropriate speed means that the speed limit is credible, and secondly that feeling safe at a given speed on a given road layout means that the speed limit is credible. Thus, speed limit credibility comes from appropriate speed and safe feeling together. Although there exist common conditions of feeling safe at a given lower speed, the lower speed limit is not always credible, and lower speed does not always bring safety.

In the automated driving situation, the participants were passively given a simulated road environment and driving speed. Passive acceptance of automated driving is explored because human-machine trust is very important for future vehicle performance. Appropriate trust can greatly improve human-machine interaction and the human should maintain a correctly calibrated level of trust that matches the objective capability of the machine system (Liu, 2010). The experimental results validate this trust. The two indicators, speed rating and risk rating, are an effective way of making assessments of subjective feelings of speed in a specific environment. There is a needed to balance the two factors such that speed is appropriate (neither too fast nor too slow) while drivers feel safe or very safe. The results show that when presented with a 40mph speed on the rural curved road, no matter what type of road layout there was, the automated driving presented a suitable condition to drivers. The same effect can be seen on the 50mph automated speed on the rural straight road with a cycle lane and 60mph on the rural straight road. It can be concluded that the credible speed limits provided by the above evidence can improve the drivers' trust of an automated vehicle.

4.6.5 Task 2 Risk response by SCR

Skin conductance response (SCR) was recorded during Task 2. The psychological mechanisms of SCR reflect the individual's arousal at a given stimulus, i.e. when arousal increases SCR increases and vice versa. Since arousal is a broad term referring to overall activation of an emotional response, SCR level in this experiment refers to the arousal of emotional factors in driving behaviour, which include risk feelings (Wilde, 1994; Taylor, 1964), task difficulty feelings (demand or workload) (Fuller, 2008c; Fuller, 2005; De Waard, 2002), comfort levels (Summala, 2007) and target feelings (Vaa, 2007) in the automated driving situation (road layout combined with speed). SCR combines these feelings to reflect the driver's arousal in a given road scenario and effectively distinguish scenarios. Thus, the results can be compared to measure how each road scenario matches with each speed, as shown in Figure 4-13. The lowest SCR in each road scene indicates the speed that gives the lowest perception of risk or most comfortable feeling, which can be assumed to be the most credible speed limit for that situation.

Generally, individuals' electrodermal activities differ (Boucsein, 2012). To draw more valid conclusions among individuals, the within-subject approach is used differentiate the risk perception generated by speed and road environment underlying changes in SCR, which is unbiased by between-subject differences in task performance. For within-subject scenarios, the raw SCR value is transformed into a standardised value by using feature scaling for data normalisation for a range of independent variables in data processing. The appropriate standardisation method depends on the research data and the conventions of the particular field of study. This method allows variables to have different means and standard deviations but equal ranges. In this case, there is at least one observed value at the 0 and 1 endpoints. The transformation method is 0-1 scaling (Equation 4-1):

$$z\,i = \frac{x\,i - \min(x)}{\max(x) - \min(x)} \qquad (4\text{-}1)$$

where x=(x 1 ,...,x n) and zi is the *ith* normalized data.

For the four curved roads, the SCR effect increased as the automated driving speed increased. The higher the driving speed, the higher the skin conductance response. Comparing the road scenes at 40mph driving speed, a higher SCR was recorded on Curve + Shoulder + CycleLane, while a lower SCR was recorded on Curve.

For the four straight roads, the SCR level did not increase as the speed increased but presented different shapes. There was a higher arousal on Straight + Shoulder and Straight at 60mph driving speed. The arousal on Straight was higher than other straight roads because there was no space for vulnerable road users on the Straight only road at 60mph. Respondents may have had uncertainty feelings about the situation. Straight + Cycle Lane presented the lowest SCR value at 60mph driving speed of all the straight roads. This illustrates that if a motor vehicle and cyclist ran separately in their own lanes, 60mph would be a more comfortable speed. For 40mph driving speed, Straight + Shoulder + CycleLane presented a higher SCR than Straight. At 50mph driving speed, Straight + CycleLane presented the lowest SCR value of all the straight roads.

Three conclusions can be generated from the risk response measured by SCR. Firstly, the presence of a cycle lane was an important factor for drivers leading to lower arousal at higher speeds. Secondly, the presence of a curve was an important factor in drivers having lower arousal in the lower speed automated scenario. Thirdly, changes in SCR levels, interpreted as changes in risk perception, only applied on the curved roads. On straight roads, the SCR did not generate a pattern representing risk perception.

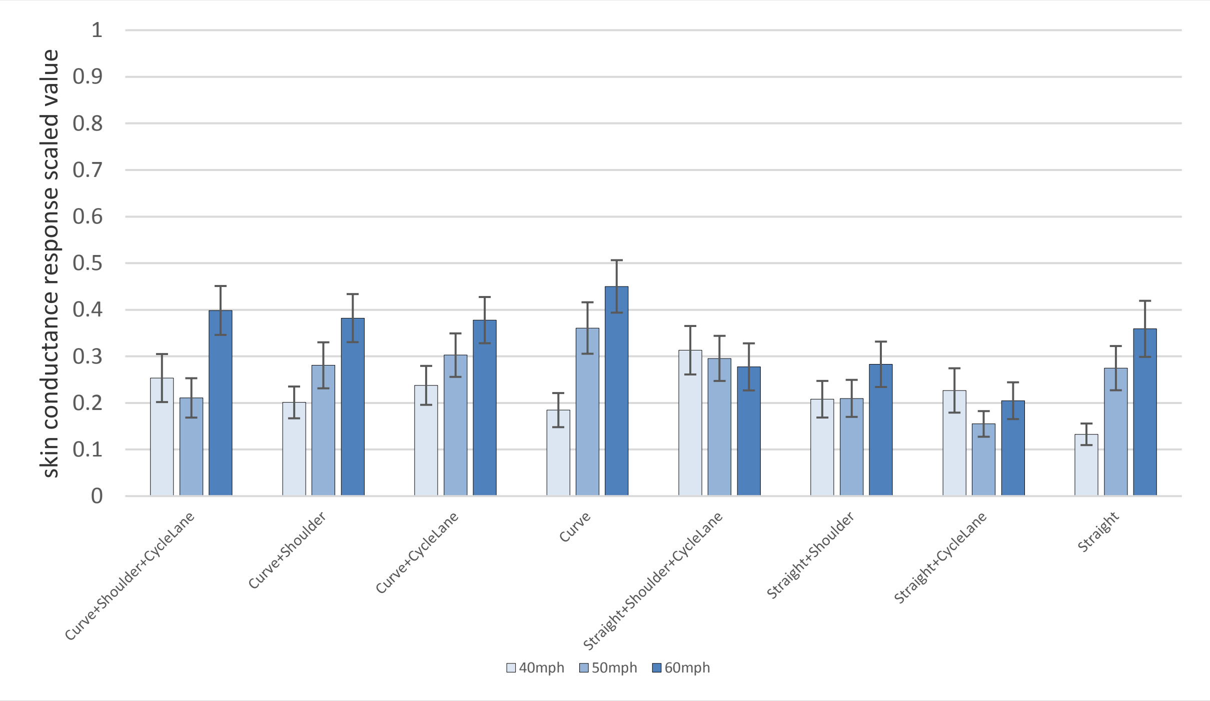


Figure 4-13: Task 2 Automated Driving Speed SCR Value in three given speeds on eight roads

4.6.6 Task 2 The relationship between subjective risk and objective risk

The elements of perceived risk, behavioural, cognitive and physiological, are associated (Heino et al., 1996). For example, drivers' feelings of risk and estimates of accident frequency are sensitive to levels of objective risk (Groeger and Chapman, 1991). Kweon et al. (2006) study the relationship between objective and subjective (self-reported) measures in the physical environment, demonstrating that they do not always coincide. Therefore, subjective risk rating needs to be compared with objective EDA measurement data to investigate whether the risk rating scores of each road scene correlate with the EDA response values.

To some extent, the objective risk measurement SCR did not equal the subjective measurement risk rating. The self-report risk rating reflected the drivers' feelings of risk only, whereas electrodermal activity represented the driver's emotional arousal level which does not indicate risk level alone. Objective risk measurement and subjective risk measurement were related to each other on curved roads. As the driving speed increased, both unsafe feeling and SCR increased. The subjective measurement supports the objective arousal which represents the individual's risk feeling. Objective risk measurement and subjective risk measurement are not comparable on straight roads due to no relationship being found between the two. Thus, changes in SCR levels cannot be interpreted as changes in risk perception on straight roads, but may relate to other feelings such as uncertainty or discomfort which were not measured in this research.

4.7 Credible speed limit decision

How can credible speed limit be measured in a given road environment? Based on the research results, five indicators present themselves: the most common choice of speed limit by drivers; the highest credible rating score value; indication of comfort with speed in automated driving; risk rating in the range from feeling safe to very safe; arousal indicated by skin conductance. Therefore, to decide on a credible speed limit, the different measurements provide different suggestions. The credible speed limit decision need to balance all five factors generated from the experimental measurement results. The mode value is chosen as the credible speed limit. Based on the results presented in Table 4-5, if the measurements are in agreement, that value can be chosen as the most credible speed limit for this type of road. If the measurements differ, there is a need to balance the five aspects to decide the most credible speed limit.

Table 4-15: Speed limit credibility indicators

	Task 1 Questionnaire result		Task 2 Automated driving result			Credible Speed Limit Decision
	Credibility chosen result	Credibility rating result	Speed rating result	Risk evaluation result	SCR Arousal	
A--Curve + Shoulder + Cycle Lane	40	50, 40	40	40	50	**40**
B--Curve + Shoulder	40	50, 40	40	40	40	**40**
C--Curve + Cycle Lane	40	40, 50	40	40	40	**40**
D--Curve	40	50, 60	40	40	40	**40**
E--Straight + Shoulder + Cycle Lane	50	50, 60	50,60	50	60	**50**
F--Straight + Shoulder	50, 60	60, 50	60	50	40	**60**
G--Straight + CycleLane	50	50, 60	50,60	50	50	**50**
H--Straight	60	60, 50	60	50	40	**60**

SWOV (2012d) state that it is possible to determine a limit that is credible for everyone, due to the fact that drivers are, to a large extent, influenced by the same road and environment features. To be specific, Task 1 and Task 2 show that 40mph is most credible for the four curved roads. 50mph is most credible for Straight + Shoulder + CycleLane and Straight + CycleLane. 60mph is most credible for Straight + Shoulder and Straight. Curved roads have credible speed limits lower than straight roads. The presence of a cycle lane on straight road makes the credible speed limit lower than a straight road without a cycle lane. The presence of a cycle lane is an important factor affecting credibility, which can be seen as extra infrastructure reminding drivers that cyclists may exist on that road, but roads without cycle lanes do not provide this clue and therefore drivers may neglect cyclists.

This research justifies speed limit credibility being determined by the two predictors, road layout and roadside environment and risk perception which comes from a persons' own estimate of the hazard level. The credible speed limit decision column in

Table 4-15 lists the most credible speed limits for each road type based on the five indicators. Although the static pictures and automated driving did not generate the exact same speed limit credibility conclusions, the combined indicators, single choice, credibility rating, speed rating, risk rating and electrodermal activity, lead to a reasonable and comprehensive decision.

Speed that was too fast or too slow did not generate a very safe feeling. Appropriate speeds on straight roads gave a very safe feeling to all the respondents but appropriate speed on curves did not bring a very safe feeling for all the respondents. These results show that a speed limit is more credible when the limit in force conforms with what the road user intuitively considers to be safe, determined by a broad range of road and road environment characteristics (van Nes et al., 2007). The credible speed limit can be used for long-term planning and for demonstrating the options for an inherently safe system.

4.8 Results of compliance with speed limit

4.8.1 Task 3 Compliance with speed limit result

It is widely known that road users choose their speed based on their visual impression of the road scene, rather than on speed limit signs. A non-credible speed limit causes uncertainty for drivers. If the speed limit does not follow from the road design, no matter whether it is within a built-up area, drivers are not informed properly about the appropriate speed. In addition, the differences between drivers' speeds on the same road can be explained by individual differences in risk tolerance and perceptions of risk (Wilde, 1982).

In Task 3, the manual driving task, the respondents needed to drive on each of eight road layouts with three different speed limit signs. A 3 (present speed limit) × 8 (road layout) repeated-measures analysis of variance (ANOVA) indicates that there were no reliable differences in driving speeds when presented with 40mph on the four curved roads ($F(3,132) = .111, p > .10$). There was no significant difference in speed across Straight + Shoulder + CycleLane or Straight + CycleLane when presented with a 50mph sign and no significant difference in speed across Straight + Shoulder or Straight when presented with a 60mph sign.

Figure 4-14 shows the mean driving speed when presented with speed limit signs. The four curved road groups were given a 40mph comparison and a one-way repeated measures ANOVA was performed. Since the exact level provided was greater than alpha .05, the results are not significant, in that there was no significant difference between driving speeds among the four curved road groups with a 40mph speed limit. The paired sample T-test shows that there was no significant difference in mean driving speed between Straight + Shoulder and Straight when presented with a 60mph speed limit and no significant difference in mean driving speed between Straight + Shoulder + CycleLane and Straight + CycleLane when presented with the 50mph speed limit. Based on the different road layouts, all driving on the curved road was compliant with both 50mph and 60mph limits and all driving on the straight road was compliant with the 60mph limit. Thus, the mean speed was not enough to reflect the real compliance level. The proportion of driving time spent above the speed limit is another evaluation method for compliance with the speed limit level.

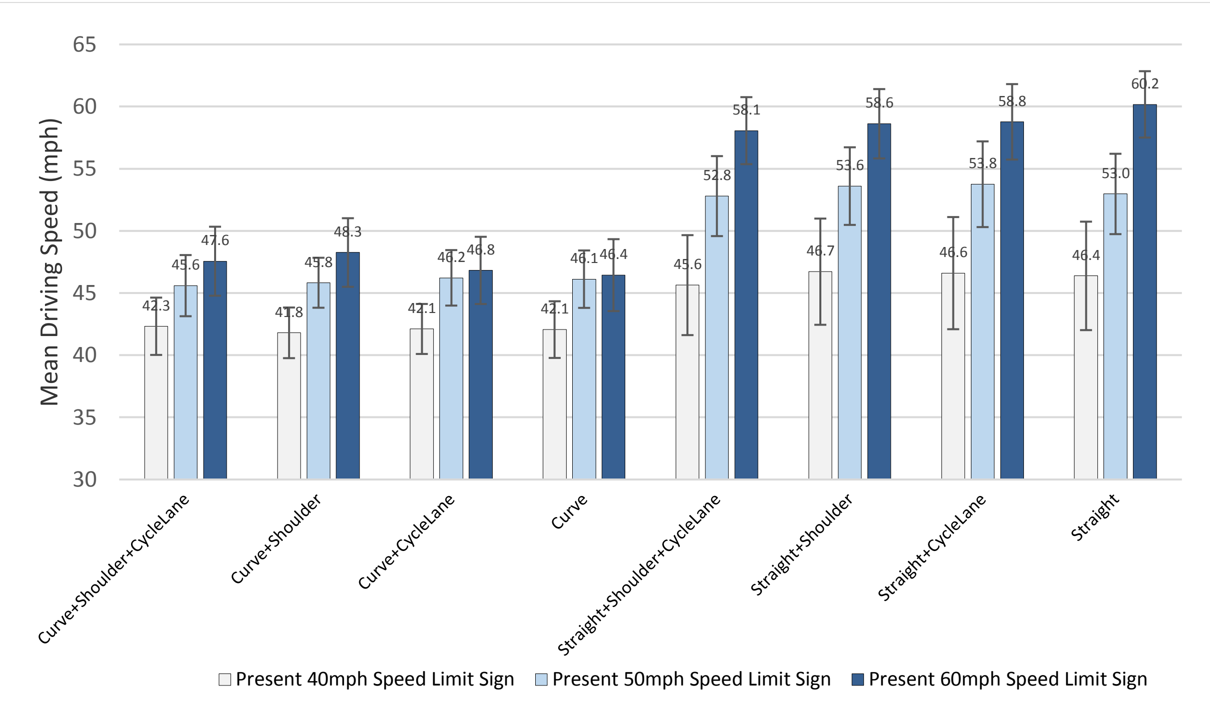


Figure 4-14: Task 3 Mean driving speed in three given speed limits on eight roads

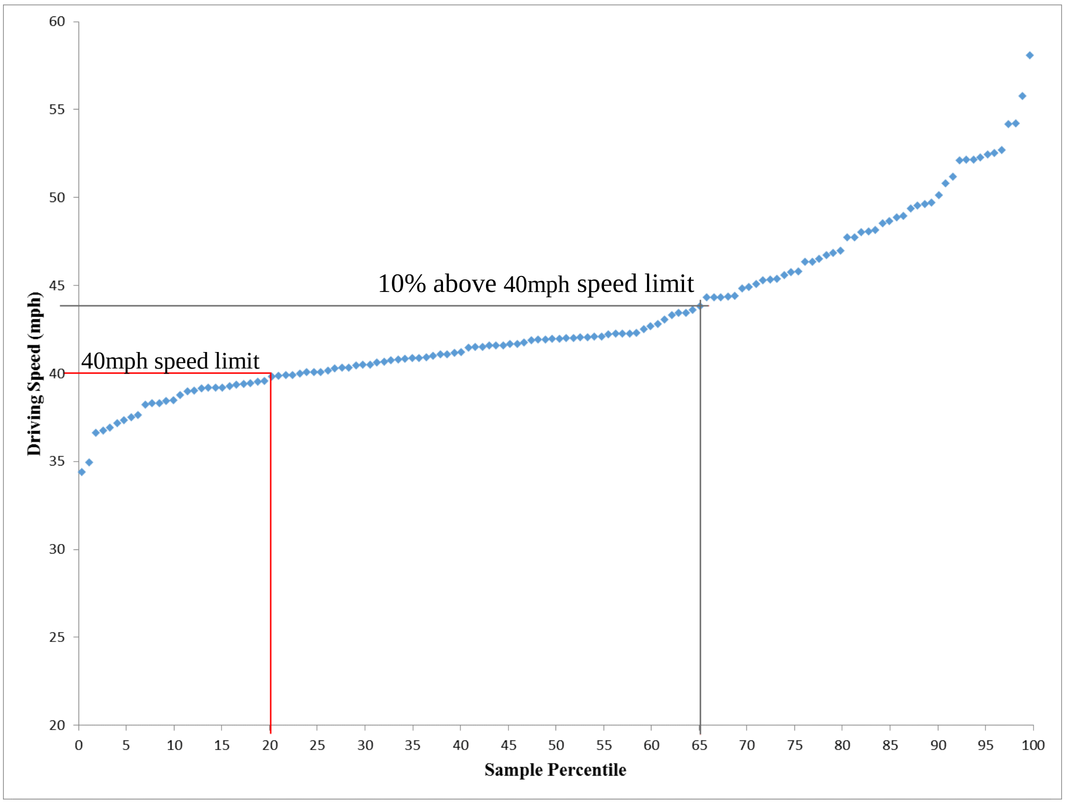


Figure 4-15: Normal probability plot for driving speed with 40mph speed limit

As the normal probability plot shows, on rural single carriageway curved roads, 20 percentile of all drivers' driving speeds reached the 40mph speed limit. Using this as the base point, the percentiles of vehicles travelling up to 10% over the speed limit are checked. The 85th percentile speed for this road segment is roughly 48mph. The majority of drivers exceeded the speed limit; 44mph (10% above 40mph speed limit) included the 65th percentile of all drivers' speeds (Figure 4-15).

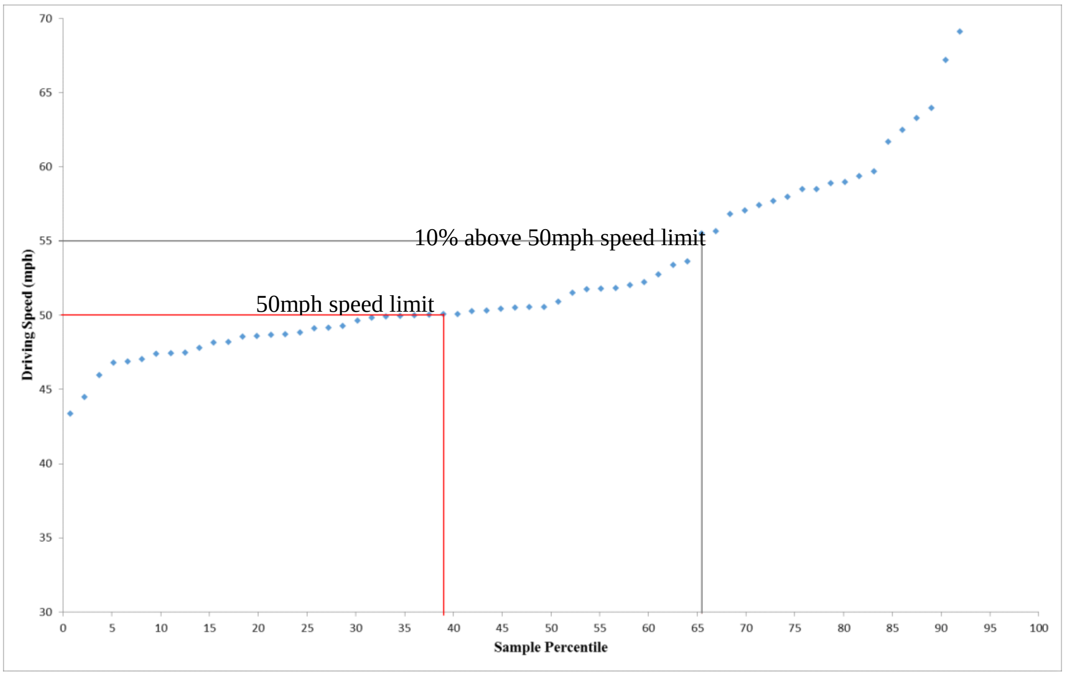


Figure 4-16: Normal probability plot for driving speed with 50mph speed limit

On a rural single carriageway with a cycle lane, driving speeds of 50mph only reached roughly the 38th percentile of all drivers, while 55mph (10% above the 50mph speed limit) reached roughly the 65th percentile of all drivers. The majority of drivers exceeded the speed limit, but within 10% above the 50mph speed limit (Figure 4-16).

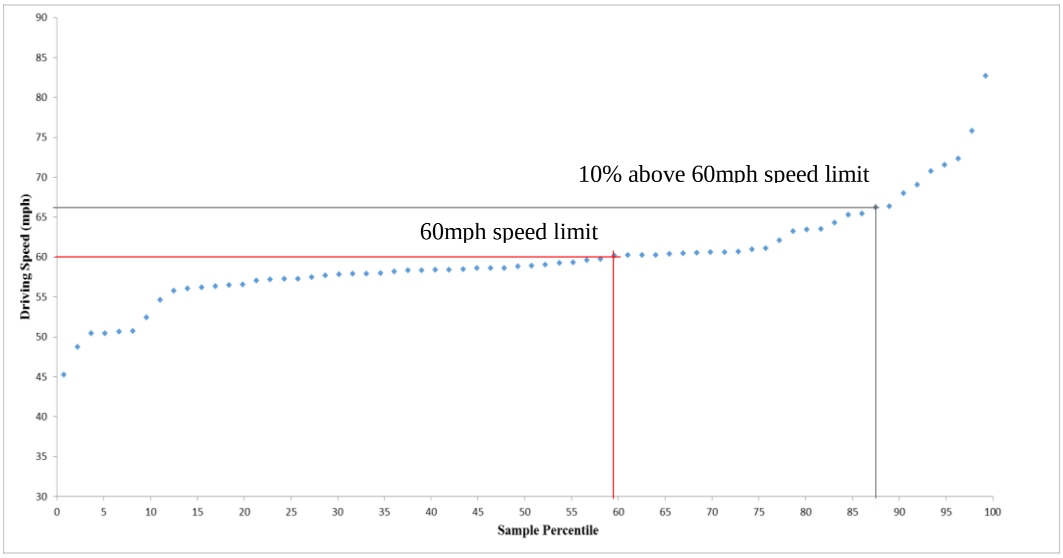


Figure 4-17: Normal probability plot for driving speed with 60mph speed limit

On rural roads, the normal probability plot shows the 85th percentile of driving speed was below 66mph (10% above 60mph speed limit). In this situation, a 60mph speed limit would be very credible, as most drivers drove below 60mph on the rural single carriageway straight road (Figure 4-17).

Table 4-16 shows the proportion of time spent exceeding the speed limit on the eight roads with the three given speed limits. Drivers spent more time above the speed limit on the straight roads than the curved roads. Drivers frequently exceeded the speed limit for up to 80% of the time on the straight road with a 40mph speed limit, 60% on the straight road with a 50mph speed limit, and 40% on the straight road with a 60mph speed limit. As the speed limit increased, drivers spent less time above the speed limit. It is clear that the speed limits themselves are insufficient to keep speeds at the desired level without any substantial enforcement measures. The percentage of driving time spent 10% and 20% above the speed limit thresholds are listed in Table 4-17 and Table 4-18.

Table 4-16: Percentage of driving time spent above the speed limit (%)

Speed limit presented as	Curve + Shoulder + Cycle Lane	Curve + Shoulder	Curve + Cycle Lane	Curve	Straight +Shoulder + Cycle Lane	Straight + Shoulder	Straight + Cycle Lane	Straight
40mph	65.0	58.9	64.2	63.3	68.8	81.1	79.9	82.5
50mph	20.2	19.7	20.9	17.6	53.5	58.3	64.3	59.4
60mph	3.2	3.4	0.6	1.9	28.4	38.9	39.0	38.1

Table 4-17: Percentage of driving time spent over 10% above the speed limit (%)

Speed limit presented as	Curve + Shoulder + Cycle Lane	Curve + Shoulder	Curve + Cycle Lane	Curve	Straight +Shoulder + Cycle Lane	Straight + Shoulder	Straight + Cycle Lane	Straight
40mph	29.7	28.7	23.4	28.3	40.8	37.6	39.0	39.2
50mph	3.8	1.6	5.8	7.8	26.5	32.3	32.2	25.5
60mph	0.7	0.4	0.0	0.0	6.6	11.3	10.5	11.6

Table 4-18: Percentage of driving time spent over 20% above the speed limit (%)

Speed limit presented as	Curve + Shoulder + Cycle Lane	Curve + Shoulder	Curve + Cycle Lane	Curve	Straight +Shoulder + Cycle Lane	Straight + Shoulder	Straight + Cycle Lane	Straight
40mph	15.8	9.5	14.1	14.5	25.2	29.1	24.1	20.5
50mph	0.5	0.0	0.6	1.7	13.6	19.3	15.0	13.4
60mph	0.0	0.0	0.0	0.0	2.2	1.7	5.1	5.5

Although 40mph was more credible on curved roads and 50mph was more credible on straight roads with a cycle lane, for compliance, more than half the driving time exceeded 40mph on the curved road and more than half the driving time exceeded 50mph on the straight road with a cycle lane. For Straight + Shoulder and Straight, the compliance level with a 60mph speed limit was better than other road types, but still almost 40% of driving time exceeded the speed limit (Figure 4-18). These results are not surprising, as speed frequently exceeds the speed limit, with the number of drivers speeding being up to 80% (Kallberg et al., 1999). In this aggregate data research, although credibility can be argued to be an essential element of compliance, the relationship between speed limit credibility and compliance level show that, even if the speed limit is credible in a set of circumstances, drivers may not comply with it. It needs to be ensured that driving speeds remain below the credible speed limit. More credible limits, integrated with warning signs, are expected to make the average driving speed closer to the limit, and less time spent speeding.

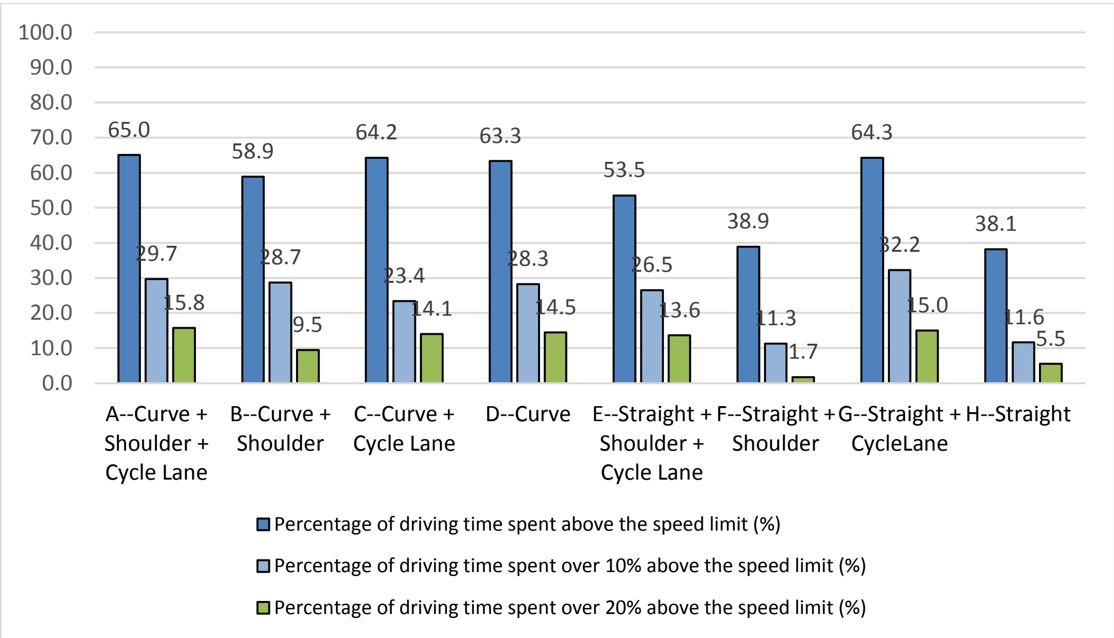


Figure 4-18: Compliance with credible speed limit level for eight roads

4.8.2 Task 3 Lateral position results

Lateral position (LP) refers to the distance between the centre of the car and the central line of the rural single carriageway. Behavioural validity is relatively good for both speed and lateral position in a driving simulator (Törnros, 1998). The subjects positioned the car either further away or closer to the central line in a given road layout. The LP graph (Figure 4-19) shows the drivers' lateral driving behaviour, which reflects the risk perception of drivers trying to avoid oncoming vehicles or avoid cyclists. Generally, higher LP was shown on curved roads than straight roads for each speed limit group. This illustrates that drivers avoid driving close to oncoming vehicles on curved roads. With the 40mph speed limit, drivers kept far from the central line on Curve + Shoulder + CycleLane and Curve + Shoulder. However Curve + Shoulder + CycleLane had a significantly greater LP than Curve + CycleLane ($t = 1.789$, $p < .05$). There was no significant difference between the LP on Straight + Shoulder + CycleLane or Straight + CycleLane when presented with the 50mph speed limit. There was a significant difference between Straight + Shoulder and Straight, in that LP on Straight + Shoulder was greater than LP on Straight when presented with the 60mph speed limit ($t = 1.67$, $p < .05$).

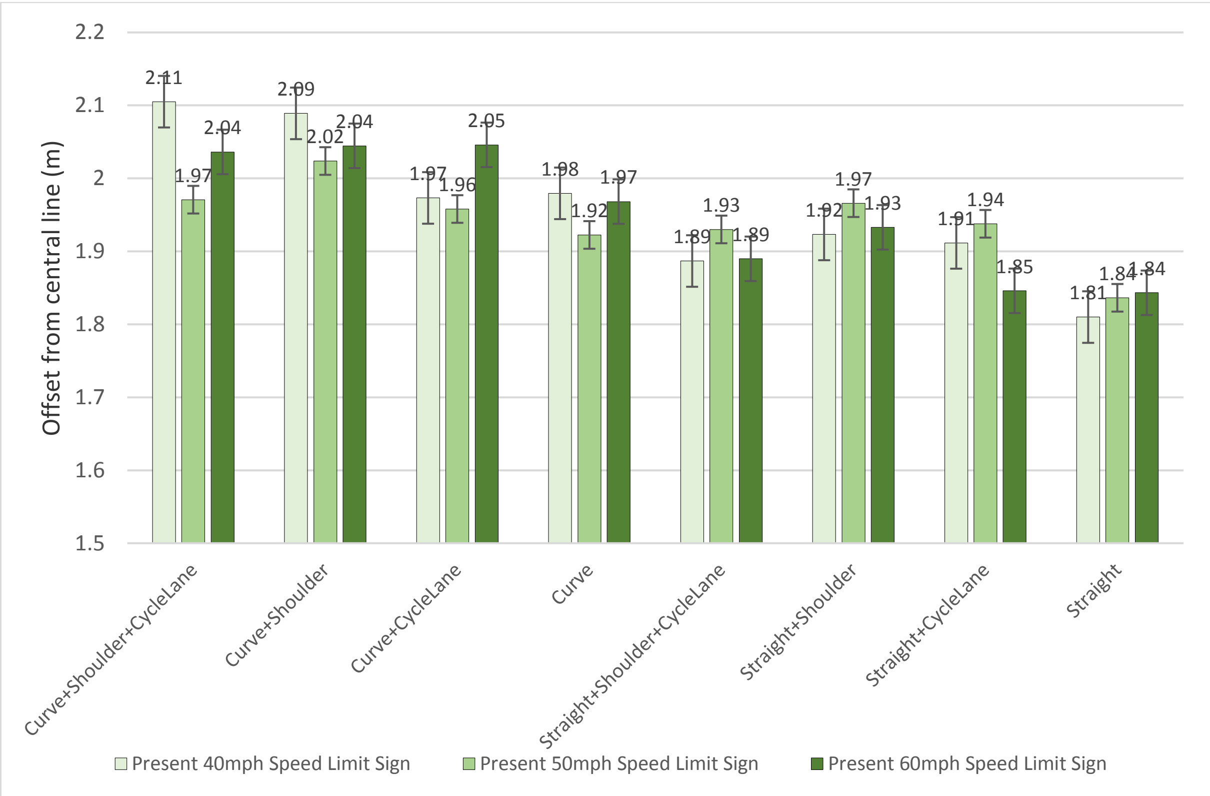


Figure 4-19: Mean lateral position on eight roads in a given speed limit sign

The study found that lateral position was influenced by the presence of the curve on the rural single carriageway. The difference in driving behaviour shows that drivers altered their speed or lateral position to balance their risk situation or awareness of the speed limit. Safety margin is used as the control variable in the hierarchical model of behavioural adaptation or risk compensation, and drivers tend to react to changes in traffic conditions or in their own skills or state, consistent with their motives (Summala, 1996; Summala, 1997; Carsten, 2013).

4.8.3 Task 3 Spot driving speed behaviour results

Thirty-four participants' driving speed performance was monitored at ten measurement points along the driving scenarios, i.e., P1 = -160m; P2 = -130m; P3 = -100m which was 100m before the speed limit sign; P4 = 0, speed limit sign; P5 = 100m, curve entry; P6 = 275.5m, middle of the curve; P7 = 415m, curve end; P8 = 515m, 100m after the curve; P9 = 615m, 200m after the curve; and P10 = 715, 300m after the curve. The point -130m was where drivers could first see the speed limit sign.

The spot speed was calculated for each participant at each position in the manual driving task. The average speed for each spot position is shown in Figure 4-20, which also shows the average spot speed of the 34 participants and the stand error. It appears that the provision of speed limit advice to drivers resulted in reduced speed on the approach to the speed limit sign. For the sharply curved road, there were demonstrable reductions in speed followed by subsequent increases after the curve finished.

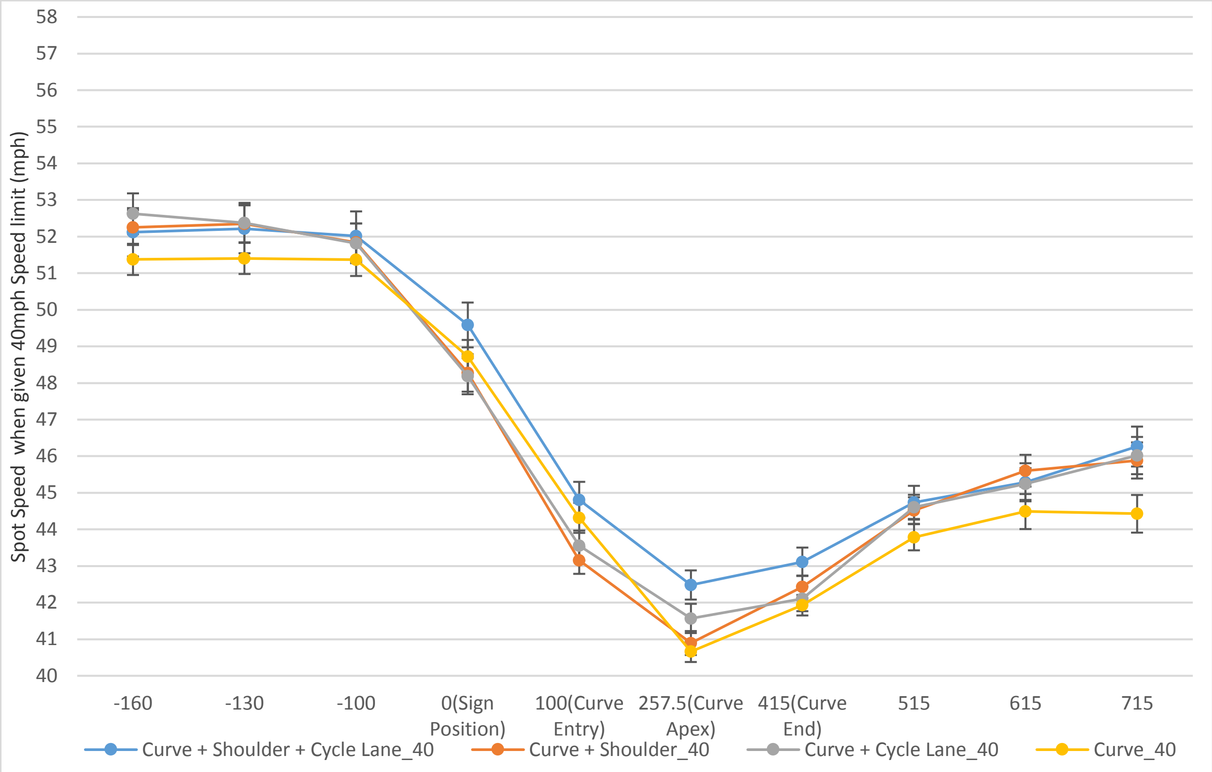


Figure 4-20: Point speed on rural curved roads with 40mph speed limit sign

When presented with the credible speed limit of 40mph, drivers still exceeded the limit, although they slowed their driving speed after the curve entry (Figure 4-20). Drivers presented higher speeds on Curve + Shoulder + CycleLane than the other curved roads. Drivers presented the lowest speed on the curve apex of Curve only, which shows that narrower roads encourage lower speed than wider roads. Wider lanes encouraged the drivers to have higher driving speed on the curved road sections.

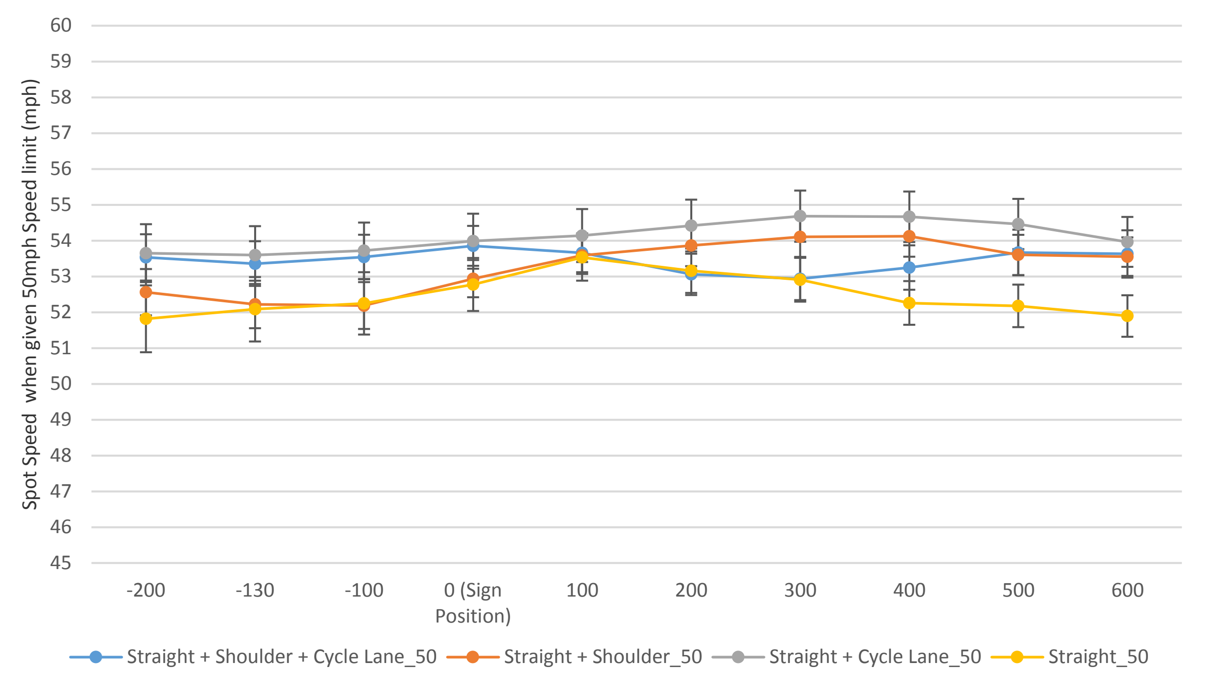


Figure 4-21: Point speed on rural straight roads with 50mph speed limit sign

When presented with the 50mph speed limit on the straight road, the spot speed kept steady before and after the 50mph speed limit sign (Figure 4-21). However, the speed was above the 50mph speed limit most of the time. Although 50mph was credible on the straight road with a cycle lane, the spot driving speed was still about 4mph over the speed limit before and after the sign on Straight + CycleLane.

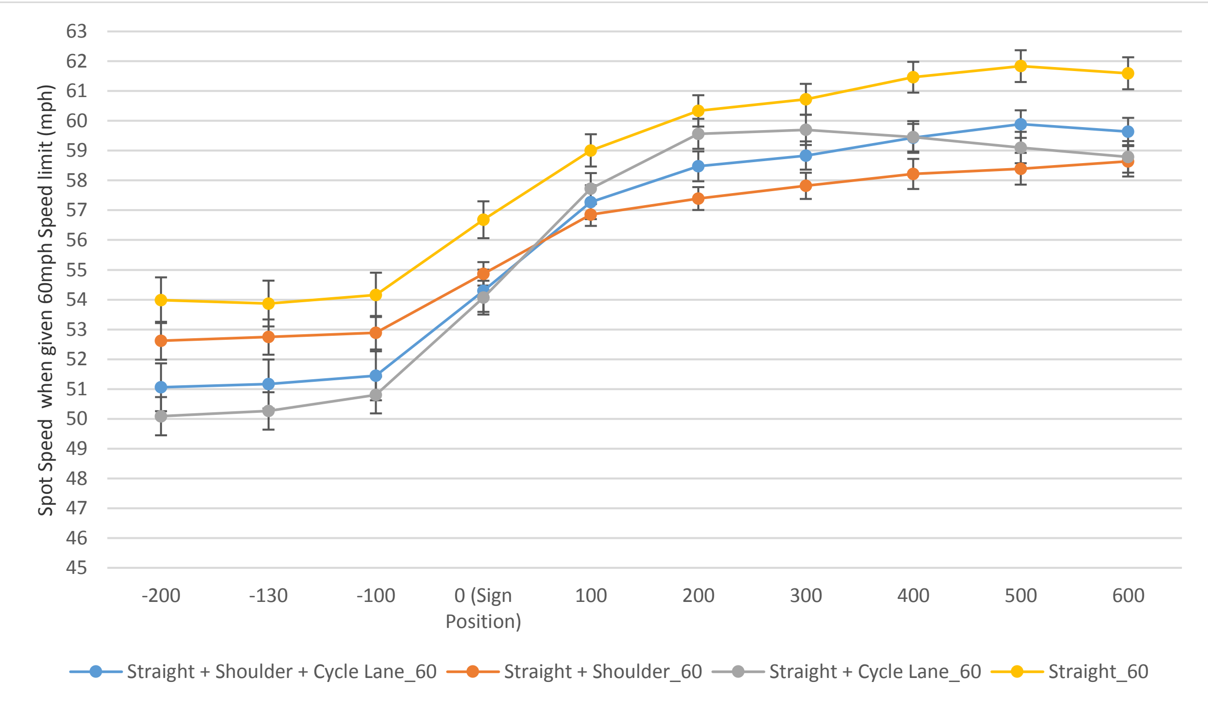


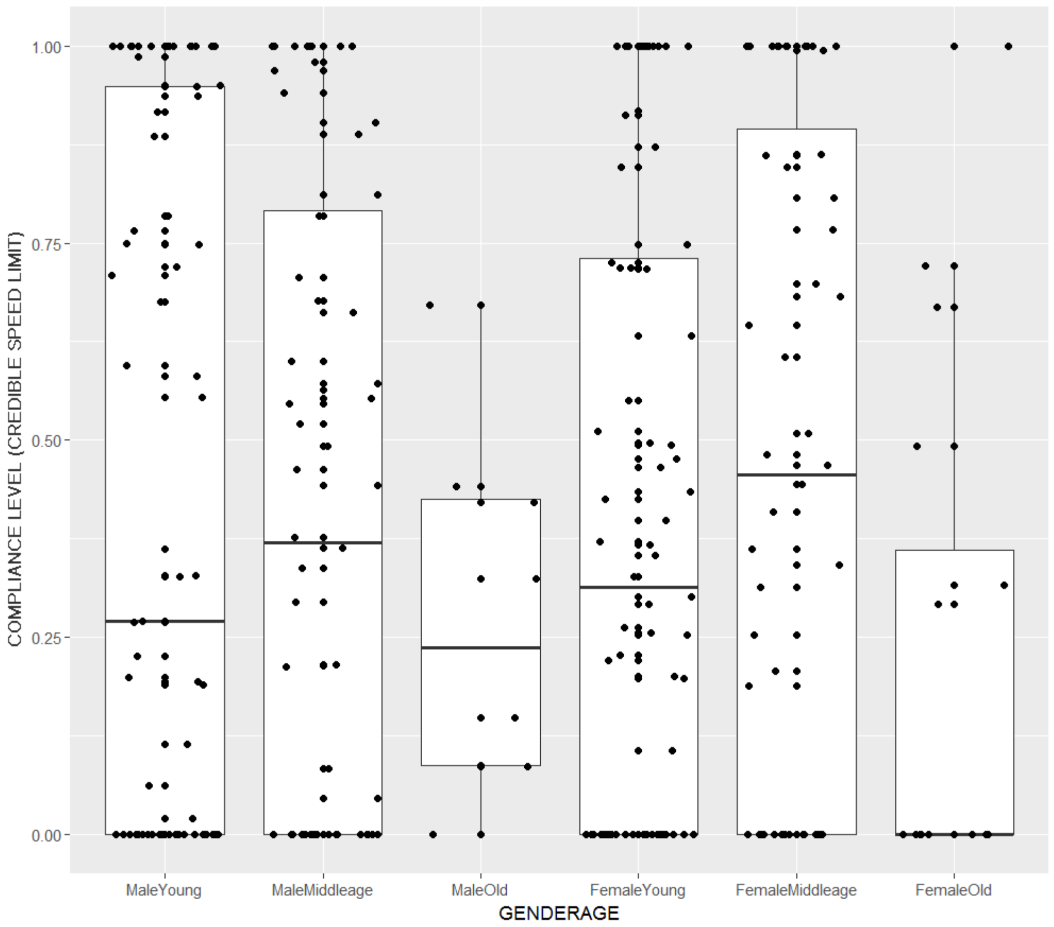
Figure 4-22: Point speed on rural straight roads with 60mph speed limit sign

When presented with the 60mph speed limit on the straight road, drivers increased their speed after seeing the speed limit sign (Figure 4-22). Before the speed limit sign, the drivers had a spot driving speed within 60mph, with a higher speed on Straight and a lower speed on Straight + CycleLane. When the cycle lane was presented, the drivers may have anticipated cyclists and, thus, had a lower speed. After passing the sign position, the drivers accelerated until they reached a steady level, which was approximately 60mph. However, on the Straight only road, some drivers reached a slightly higher speed above 60mph 300m after the speed limit sign, while others were compliant with the 60mph speed limit.

4.8.4 Who is compliant and who is not?

Human factors affecting compliance with speed limit also merit research. Compliance is classified into three levels, compliance with the credible speed limit, compliance with the credible speed limit + 10%, and compliance with credible speed limit + 20%. Respondents' demographics can be categorised into six groups: male young, male middle-aged, male old, female young, female middle-aged, and female old, with young drivers ≤ 25, middle-aged drivers between 26 and 55, and old drivers ≥ 56. The age categorisation criteria are described in Section 3.3.6.

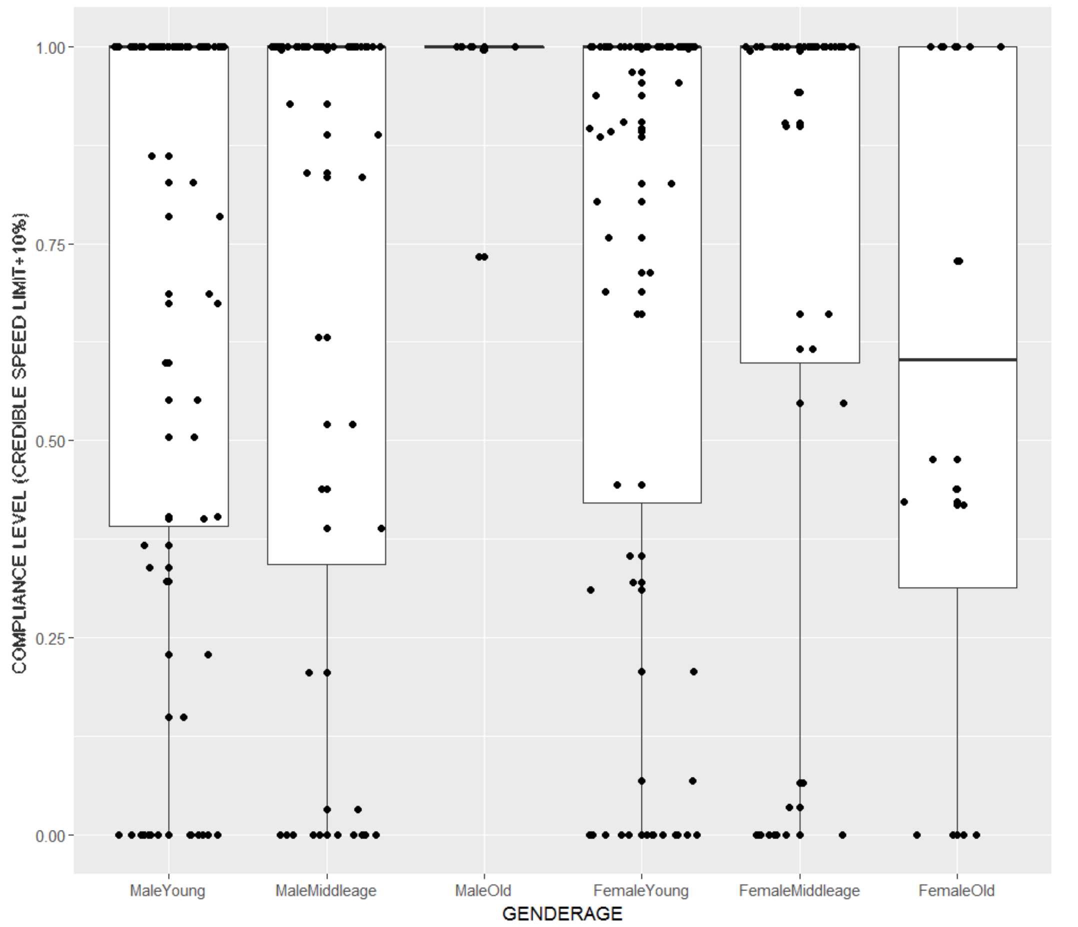
A box-plot is used to visualise the difference between compliant behaviour by demographic group. The mean, median and compliance percentage are presented in Figure 4-23, Figure 4-24 and Figure 4-25. The x-axis denotes the six gender and age groups: male young drivers, male middle-aged drivers, male old drivers, female young drivers, female middle-aged drivers and female old drivers. The y-axis denotes compliance with credible speed limit on a scale ranging from 0 (no compliance at all) to 1 (full compliance).



	Male young	**Male middle-aged**	**Male old**	**Female young**	**Female middle-aged**	**Female old**
Number of drivers (N)	9	7	1	9	6	2
Total number of points (N*8)	72	56	8	72	48	16
Mean	0.43	0.41	0.27	0.40	0.47	0.22
Median	0.27	0.37	0.24	0.31	0.46	0.00
Compliance percentage	22.2%	14.3%	0.0%	18.1%	22.9%	6.3%

Figure 4-23: Compliance with speed limit level for gender age groups

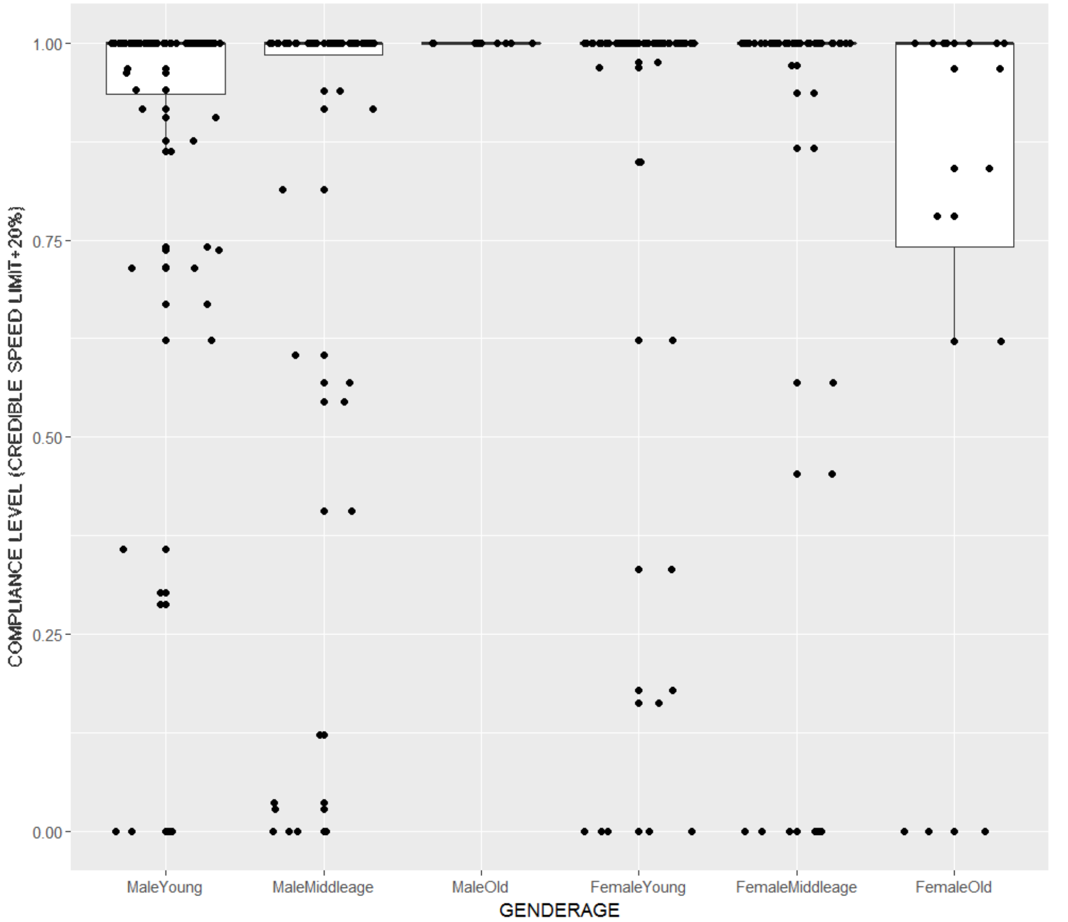
A box-plot shows the variation in samples of a statistical population without making any assumptions about the underlying statistical population. In Figure 4-23, the mean value proximity of male young, male middle-aged and female middle-aged indicates that those drivers intended to comply with credible speed limits more than the other groups. For the female middle-aged group, the mean value is in relation to the median value (the middle point in the list of numbers), which denotes that the compliance level distribution is symmetrical. The compliance percentage was calculated by the number of points with compliance level = 1 divided by the total number of points. Due to the skewed distribution found on all the gender and age groups, the median value was used to explain the compliance level for each group. The female middle-aged group had the highest compliance level of all the groups. The female older group had lower compliance with the credible speed limit.



	Male young	**Male middle-aged**	**Male old**	**Female young**	**Female middle-aged**	**Female old**
Number of drivers (N)	9	7	1	9	6	2
Total number of points (N*8)	72	56	8	72	48	16
Mean	0.72	0.71	0.97	0.73	0.74	0.59
Median	1.00	1.00	1.00	1.00	1.00	0.60
Compliance percentage	61.1%	58.9%	75.0%	54.2%	62.5%	43.8%

Figure 4-24: Compliance with speed limit+10% level for gender age groups

In Figure 4-24, compliance with the speed limit + 10% level is shown. The distribution of each gender age group shows that more than half the respondents were compliant with the speed limit + 10%, except for the female old drivers group. As shown in Figure 4-25, more than 70% of the respondents were compliant with the speed limit + 20%.



	Male young	Male middle-aged	Male old	Female young	Female middle-aged	Female old
Number of drivers (N)	9	7	1	9	6	2
Total number of points (N*8)	72	56	8	72	48	16
Mean	0.87	0.84	1.00	0.89	0.85	0.76
Median	1.00	1.00	1.00	1.00	1.00	1.00
Compliance percentage	70.8%	75.0	100.0%	83.3%	77.1%	56.3%

Figure 4-25: Compliance with speed limit+20% level for gender age groups

Combining the three levels of compliance, the following conclusions can be drawn:

- Male young drivers tend to have compliance with the speed limit
- Male middle-aged drivers tend to have compliance with the speed limit
- Male old drivers tend to have compliance with speed limit + 10%
- Female young drivers tend to have compliance with speed limit + 10%
- Female middle-aged drivers tend to have compliance with the speed limit
- Female old drivers tend to have compliance with speed limit + 20%

Previous research shows that low driving experience induces high risk (Vlakveld, 2011). Drivers in the 21-29 age group are more likely to speed than older drivers (Stradling et al., 2003). However, based on visual inspection of the box-plots, there is a distinction between male and female drivers in driving speed and, thus, risk perception differs. Male drivers are more cautious than the female. Speeding drivers, especially older female drivers, should be targets for anti-speeding campaigns.

4.9 Discussion

This experiment evaluates the interaction of road layout factors on rural single carriageways in terms of speed limit credibility, risk perception and compliance with the speed limit. This experiment justifies a credible speed limit being set based on subjective and objective driver measurements from questionnaires and driving simulator studies. It provides a valid methodology to evaluate credibility which can be adopted for further research.

Setting a credible speed limit is strongly based on road design. The research confirms that the road layout design was good overall, in that respondents gave valid responses. The experiment generated significant results that distinguish the eight road layouts in terms of credibility perception and risk perception. For the combination of road factors, despite the situation being uncommon on normal rural single carriageways, the drivers gave good, robust responses. Although the credibility of the speed limit is determined by a combination of factors and the number of possible combinations is large, the road design used only considered the potential risk road factors and forgiving road factors of a road layout.

The relationship between road width and driving speed when a credible speed limit is presented has been investigated. It is worth noting that, on curved roads, when presenting a credible speed limit of 40mph, as the road layout becomes wider, drivers' speed choice increases. Previous studies found a positive association between roads of increased shoulder width and higher speeds (Giles, 2004). However, on a rural straight road, driving speed is not associated with road width when drivers are presented with a 60mph speed limit. A straight road with a 60mph limit makes drivers choose a higher speed than other types of straight road. A straight road with a cycle lane encourages drivers to drive slowly when a 60mph limit is presented. This is evidence for a lower credible speed limit (50mph) on a straight rural road with a cycle lane.

Curved roads and roads with a cycle lane need lower speed limits because of the potential risk presented. Setting a credible speed limit would help increase compliance, which is also affected by road design. Setting a credible speed limit is important. The wider implications of setting credible speed limits relate to better speed management, mainly changing guidance on speed limit setting to match road layouts and the roadside environment. The quantitative relationship between the speed limit and compliance with the speed limit needs to be explored in further studies.

It is clear that the speed limit itself is insufficient to manage speed or keep it at a desired level. To strengthen speed limit credibility and increase compliance with the speed limit, measures must work together. Examples of such combinations of measures are speed limit combined with roadside warning sign; speed limit combined with speed enforcement (speed cameras); and speed limit combined with road markings. The Task 3 (manual driving) results indicate the problem that driving speed may have a lower compliance level based on the road layout. How to convert credibility to compliance is the next research question. There is a need to investigate what intervention advice can be given to drivers. Due to credibility not, of itself, being sufficient to deliver a high compliance level, further study is needed to improve compliance with speed limits.

Chapter 5 Modelling the relationship between speed limit credibility, risk perception and compliance with speed limit

5.1 Research model and hypotheses

The rural single carriageway road layout and the roadside environment factors have been proven to affect speed limit credibility, subjective risk perception and compliance with speed limits. The hypotheses are to test whether there is a significant relationship between risk perception and credibility, risk perception and compliance, and credibility and compliance (See Figure 5-1). The theoretical basis for the research model for the hypotheses is listed as follows. First, in the literature, Wilde's risk homeostatistics, Näätänen & Summala's zero risk model (Näätänen and Summala, 1974) and Fuller's Risk Allostasis model (Fuller, 2008b) proposed that risk exists during the task of driving and that risk and driving speed are correlated. In addition, there is no existing research on the relationship between risk perception and compliance with the speed limit in a given road environment. Second, the relationship between different motives and speed variability may perhaps be influenced by the credibility of the speed limits in Shinar (2007). In addition, SWOV (2012d) comments that credible speed limits are supposed to result in drivers obeying (safe) speed limits better. Third, there is an unknown causal relationship between risk perception and credibility from the previous study which needs to be tested in this subsequent study. The above points are assumed to justify the indicated path linkages (Figure 5-1). Figure 5-1 shows the data from Experiment 2. The credibility rating from Task 1 is a continuous variable from very non-credible (0) to very credible (100). The risk feeling rating from Task 2 is a continuous variable from very unsafe (0) to very safe (100). Compliance with speed limit from Task 3 is given as a percentage of time compliant with the speed limit, which varies as a continuous variable from non-compliance (0) to compliance (1). Consequently, in a given rural single carriageway environment:

- **Hypothesis 1**: Higher risk perception will have a positive influence on compliance with speed limit
- **Hypothesis 2**: Credible speed limit will have a positive influence on compliance with speed limit
- **Hypothesis 3**: Higher risk perception in a given speed will have a negative influence on speed limit credibility

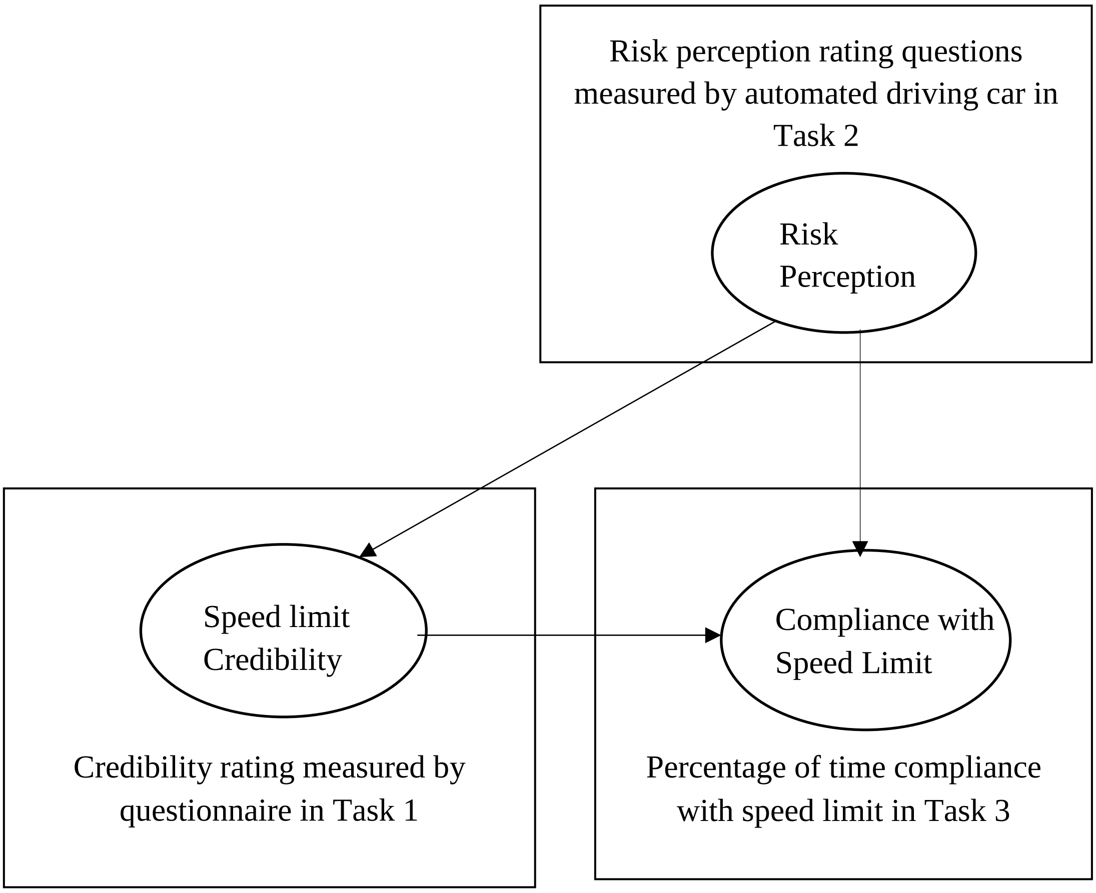


Figure 5-1: Experiment 2 theoretic model

5.2 Investigating the relationship between risk perception and compliance with speed limit

5.2.1 Pool regression model

Linear regression models can be used to examine the linear relationship between each pair. Before fitting the regression model, the data has to meet the following assumptions.

(1) Linearity - the liner relationship between independent variables and dependent variable and the residual plot have no patterns

(2) Absence of collinearity - the independent variables (fixed effect) are not correlated with each other

(3) Homoscedasticity - the residuals in the model have a similar amount of deviation from predicted values.

(4) Normality of residuals

(5) Absence of influential data points

(6) Independence- each subject should only contribute one data point

Compliance with speed limit is used as the dependent variable and risk perception is considered to be the explanatory variable. Model 1 is a simple linear model also called a "constant coefficients model", which assumes that the regression coefficients are constant across units and time periods. The equation is as follows:

$$Yij = \alpha + \beta Xij + \varepsilon ij \tag{5-1}$$

The variable Y in Equation (5-1) is the dependent variable, variable α is the intercept, variable X is a vector of independent variables, the addition of the i and j denote the individual driver and road situation, respectively, which shows the repeated observations on the same unit; variable β represents the regression coefficients, and variable ε is the error term.

5.2.2 Fixed effect model

However, the simple linear model with an intercept and slope (Equation 5-1) completely ignores the group nature of the data (Table 5-1 Model 1). In addition, the classical regression method has a heterogeneity problem for data of longitudinal format. Therefore in Model 2, Mixed-Effect Models (Multilevel regression) (Worrall, 2010) were fitted. Linear mixed effect models are the extensions of linear regression models for data that are collected and summarised in groups. This method is used to quantify the relationship between risk perception and driving speed. The fixed effects model in matrix notation is shown in Equation (5-2):

$$Yij = \alpha i + \delta j + \beta Xij + \varepsilon ij \tag{5-2}$$

First, for the addition of the i and j subscripts in Equation (5-2), X_{ij} represents the explanatory variable of the ith driver in jth speed limit/road type situation. Equation (5-2) adds an intercept for each unit, denoted by αi. Second, it adds δj, which denotes a dummy variable for each speed limit and road type. It assumes that the regression coefficients are constant across drivers and speed limit/road type.

However, Equation (5-2) makes no attempt to explicitly model the repeated observations. In other words, the fixed effects estimation ignores the possibility that individual to individual variation sheds light on the relationship between x and y.

5.2.3 Mixed effect model

Fixed effects and random effects models address some of the problems associated with estimating the constant coefficients model. In addition, a key assumption underlying the random effects approach is zero correlation between the error term and predictor variables. The predictor variables should be correlated with the unobserved unit-specific error terms. Thus, the driver is the random effect that there is no correlation between the error term and predictor variable. The mixed effects model is shown in Equation (5-3):

$$Yij = \alpha i + \beta Xij + \nu i + \omega j + \varepsilon ij \qquad (5\text{-}3)$$

Treatment levels are usually fixed effects, while subjective effects are almost random effects. It is clear that, in each group, there is random subject to subject variation in the intercept. Equation (5-3) assumes that the unobserved differences between drivers are random variables, where υi and ωj denote separate error terms. They represent between-driver variation and are the disturbance terms associated with the analysis. For the fixed effect part, if a predictor does not vary over time, it is perfectly collinear with the unit dummies in a fixed effects setting. With the use of unit-specific dummy variables in a fixed effects context, we can control for unobserved differences between each speed limit. If the F-test for all the unit dummies is significant, they should be modelled. In Model 2, the road type explanatory variable is coded as 0 for the curved road and 1 for the straight road. In Model 3, the 40mph speed limit explanatory variable is coded 0, the 50mph speed limit 1, and “the 60mph speed limit 2. Model 4 fits a multilevel regression with a fixed effect for both limits and road types, and a random effect for the individual drivers. Since repeated measures are used, there is the possibility of unobserved heterogeneity across individuals (Breslow and Clayton, 1993). Generalised linear mixed models can account for this heterogeneity through random effects.

Table 5-1: Multilevel models for the road effect of risk perception on compliance with speed limit

	Model 1 Linear regression	tStat	Model 2 (effect of road type)	tStat	Model 3 (effect of speed limit)	tStat	Model 4 (effect of road type and speed limit)	tStat
Fixed Effect								
Intercept (se)	0.32*** (0.02)	15.25	0.44*** (0.04)	10.56	0.15*** (0.04)	4.09	0.34*** (0.04)	8.50
Risk (se)	0.01*** (0.001)	13.67	0.01*** (0.00)	10.66	0.01*** (0.00)	10.91	0.00*** (0.00)	4.26
roadtype_straight (se)			-0.17*** (0.03)	-6.37			-0.26*** (0.02)	-11.20
limit_50 (se)					0.27*** (0.03)	10.51	0.30*** (0.02)	12.17
limit_60 (se)					0.42*** (0.03)	15.03	0.48*** (0.03)	18.21
Random Effects								
Driver intercept 'std' (CI)			0.18 (0.14, 0.23)		0.18 (0.14, 0.23)		0.18 (0.14, 0.24)	
Error Res Std (CI)			0.34 (0.32, 0.35)		0.30 (0.29, 0.32)		0.28 (0.27,0.29)	
Degrees of freedom	814		813		812		811	
Adjusted R^2	0.19		0.38		0.51		0.58	
LogLikelihood			-300.54		-216.65		-158.49	
AIC			611.08		445.30		330.97	

*** p<.01 ** p<.05 *p<.1
(se)-standard error; (CI)-confident interval

The comparative model results are shown in Table 5-1, which gives each parameter, with its standard error (the difference between the predicted and observed value) in parentheses. The Akaike information criterion (AIC) (Akaike, 1998) is a widely-used measure for comparing models with different error distributions, valid for both nested and non-nested models, and avoiding multiple testing issues (Hu, 2007). The preferred model is the one with the minimum AIC value. The interaction of risk and road type is clearly reasonable and needed in this model, as is the random intercept. The lower AIC shows that Model 4 is most effective. Model 4 performs the best because the predicted value can explain the variance of risk as a direct effect of compliance with speed limit controlled by road type and speed limit. In addition, for the Adjusted R^2, the Log Likelihood value shows Model 4 to be statistically significantly better than the other models ($p<.001$).

Model 4, the mixed-effect model, fits the multilevel regression with a fixed effect for all speed limits (40mph, 50mph and 60mph) and both road types (curved, straight), and a random effect for individual drivers. All the coefficient results are statistically significant. As limit_40 and roadtype_curve are the baselines, the fixed intercept value of 0.34 shows that the compliance level on a 40mph speed limit curved road is 34%. The intercept for the straight road with 40mph speed limit is 0.08, which is significantly lower than the curved road with 40mph ($t=-11.202$, $p<.05$). For each presented 50mph and 60mph speed limit, the coefficient value should be added to the baseline 40mph intercept. The risk coefficient of 0.0022 represents the average gain in compliance level for each increase in perception of risk for the baseline 40mph on the curved road. The positive sign means that as the risk perception increases, drivers have a greater intention to comply with the speed limit in manual driving. For the random effect, the effect of individual drivers represents the difference in slope for each road type and speed limit. Here, the random effect can explain the percentage of explanatory standard deviation, which is 39.3%.

Drivers do perceive risk and respond in predictable ways, which supports H1: Higher risk perception has a positive influence on compliance with speed limits. The more risk feeling there is at a given speed, the more compliance there is with that speed limit. From Model 4, the coefficient results show that drivers have the highest compliance level on the curved road with a 60mph speed limit, due to the speed limit being too high for the higher risk perception. In contrast, drivers have the lowest compliance level on the straight road with 40mph speed limit. Most drivers exceed 40mph because they feel very safe in a lower speed situation on straight roads. The model confirms that risk rating for a given speed and road environment affects compliance with the speed limit. In addition, compliance with the speed limit level is affected by whether the speed limit is credible or not, which is analysed in the next section.

5.3 Investigating the relationship between speed limit credibility and drivers' compliance with speed limit

Binary logistic regression model

In order to build a relationship between the independent variable, speed limit credibility, and the dependent variable, compliance with credible speed limit level, the data pattern was examined. The level of compliance with the speed limit was originally to be given as a percentage of time compliant with the speed limit as a continuous variable from non-compliance (0) to compliance (1). However, most of the data points turned out to be either 0 or 1; therefore the dependent variable was transformed into a dichotomous outcome. To make this classification for all the data, the dichotomous term was given a threshold of 0.5. If the proportion of time compliant with the speed limit was greater than 0.5, compliance was classified as 1, otherwise as 0. Thus, the relationship between speed limit credibility and drivers' compliance was formulated as a binary logistic regression model. The logistic regression function is written as:

$$\mathrm{logit}(\mathrm{Y}) = \ln\left(\frac{\mathrm{x}}{1-\mathrm{x}}\right) = \alpha + \beta X \qquad (5\text{-}4)$$

According to Equation (5-4), the relationship between logit (Y) and X is linear. The value of the coefficient β determines the direction of the relationship between X and the logit of Y. When β is greater than zero, larger (or smaller) X values are associated with larger (or smaller) logits of Y. Conversely, if β is less than zero, larger (or smaller) X values are associated with smaller (or larger) logits of Y.

$$\mathrm{x} = \mathrm{Probability}\,(\mathrm{Y} = \mathrm{outcome\ of\ interest} \mid \mathrm{X} = \mathrm{x}) = \frac{\mathrm{e}^{\wedge}(\alpha + \beta \mathrm{X})}{1 + \mathrm{e}^{\wedge}(\alpha + \beta \mathrm{X})} \qquad (5\text{-}5)$$

In Equation (5-5), x is the probability of the outcome of interest or event, such as driver compliance with the speed limit or not, α is the Y-intercept, β is the regression coefficient, e=2.71828 is the base of the system of natural logarithms, X is a continuous explanatory variable, and Y is categorical dependent variable. Here X stands for the credibility score (from 0 very non-credible to 100 very credible) and Y represents 1-compliance and 0-non- compliance. The dataset only covers the credible speed limit on eight road types. Credible speed limits were defined as speed limits which are accepted by most drivers without the need for enforcement in a given road layout. The credible speed limit was evaluated to be 40mph on the curved road with 200m radius, 50mph on the straight road with a cycle lane, and 60mph on the straight road without a cycle lane. The non-credible speed limits are excluded from the dataset.

Table 5-2: Logistic regression model estimating effects of credibility on compliance (N = 272)

	Compliance with speed limit	Compliance with speed limit+10%	Compliance with speed limit+20%
Credibility Score			
β credibility	.00	.01*	.02**
se	.01	.01	.01
P Value	.43	.08	.00
odds ratio	1.00	1.01	1.02
Constant			
α constant	-.68**	.42	.78*
se	.34	.35	.41
P Value	.04	.22	.06
Chi square	.64	2.99	8.57
Chi square p value	.43	.08	.00
-2 Log likelihood	363.97	315.41	196.39

*** p<.01 ** p<.05 *p<.1

The one predictor logistic model is fitted to the data to test the research hypotheses regarding the relationship between credibility and compliance with the speed limit. According to the model test in Table 5-2, the positive coefficient for the credibility score predictor suggests that, all other variables being equal, the log of the odds of a driver perceiving speed limit credibility level is positively related to compliance with the speed limit. In other words, the higher the credibility rating, the more likely the driver is to comply with the speed limit. For every unit increase in credibility score, the log odds of compliance with speed limit increases by α constant. The three relationships have an odds ratio>1, which means increased speed limit credibility is associated with higher odds of speed limit compliance.

A credibility score with a higher p-value suggests a weak association of credibility with the probability of compliance with the speed limit. However, credibility score is a significant predictor of compliance with the speed limit+10% (p<.1) and compliance with the speed limit+20% (p<.05). As the threshold gets higher, the significance level of the compliance odds increases. The test of the intercept (constant) result (p>.05) suggests that an alternative model without the intercept might be applied to the data. For the model summary, the -2 Log likelihood is a descriptive measure of goodness-of-fit. The mode of relationship between credibility and compliance with the speed limit+20% fits better than the other models. In addition, the likelihood ratio chi-square with a p-value <.05 shows that the model as a whole fits significantly better than an empty model without predictors.

Therefore, the probability for compliance with speed limit can be expressed as

$$\frac{e^{\wedge}(\alpha \text{ constant} + \beta \text{ credibility} * \text{CREDIBILITY SCORE})}{1+ e^{\wedge}(\alpha \text{ constant} + \beta \text{ credibility} * \text{CREDIBILITY SCORE})} \qquad (5\text{-}6)$$

Applying Equation (5-6), the marginal effect indicates that as the average credibility score increases by 1, the probability of compliance with the speed limit increases by 0.1%; the probability of compliance with the speed limit+10% increases by 0.18%; and the probability of compliance with the speed limit+20% increases by 0.23%. The relationship between credibility score and probability of compliance with speed limit of the three different thresholds is plotted in **Error! Reference source not found.Error! Reference source not found.**. The credibility value ranges from very non-credible (0) to very credible (100). Larger credibility values are associated with higher probabilities of driver compliance with the speed limit. If the speed limit credibility changes from very non-credible to very credible, there is an 8% increase in compliance with the speed limit, an 18% increase in compliance with the speed limit+10% and a 24% increase in compliance with the speed limit+20%.

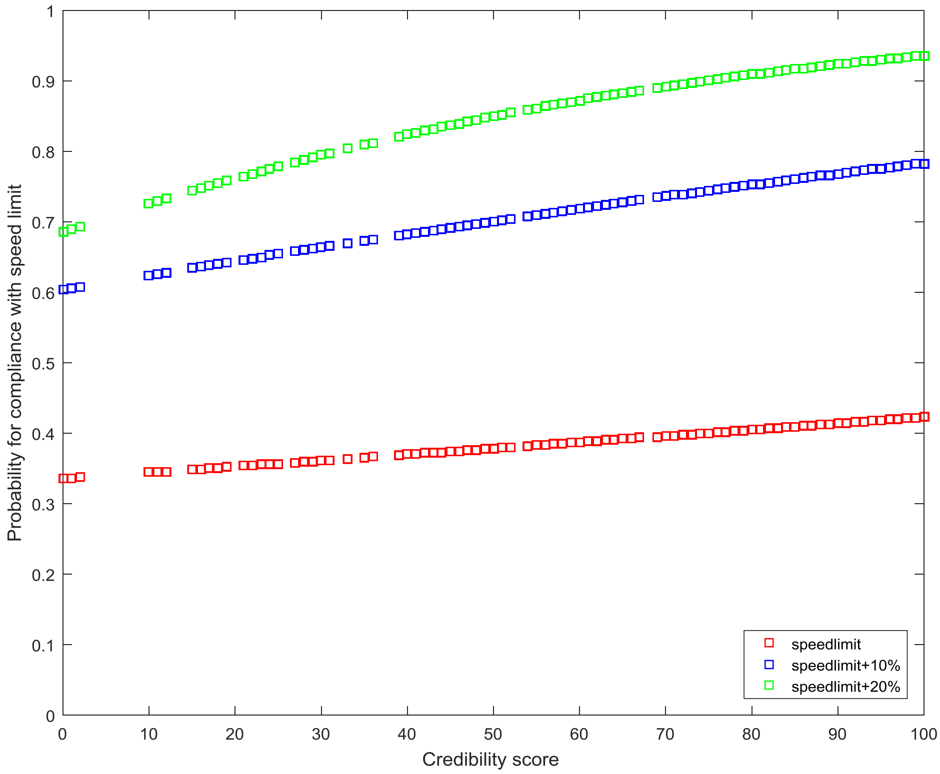


Figure 5-2: The relationship between speed limit credibility and the probability of drivers' compliance with the speed limit

Four practical conclusions can be drawn from the relationship.

- First, these results confirm the SWOV (2012d) comments that credible speed limits are supposed to result in drivers obeying speed limits more.
- Second, as the threshold increases, the slope of compliance level increases. It can be seen that a credible speed limit has an important effect on compliance with the speed limit. If the speed limit is more credible, some speed limit offenders are more compliant with the speed limit, thus extreme violations go down.
- Third, there is a notable issue that even if the credibility score is 0, there is still a 35% probability of compliance with the speed limit. This means obedient drivers generally comply with the speed limit regardless of the speed limit credibility.
- Fourth, credibility is a factor that affects compliance, but not the only factor. For practical implementation, it is possible that a more credible speed limit perceived by drivers encourages more compliant and less reckless driving, which, in turn, should lead to a decrease in road accidents and fatalities.

5.4 Investigating the relationship between risk perception and speed limit credibility

Mixed effect model

The relationship between risk perception and speed limit credibility is explored using linear regression and a mixed effect model. Drivers' risk perception in a given road environment and speed is assumed to affect the perception of speed limit credibility. Model 5 builds a linear regression between risk perception and speed limit credibility. Model 6 adds the fixed explanatory variable road type. Model 7 involves the speed limit as a fixed effect. Model 8 involves both speed limit and road type as fixed effects (Table 5-3). Model 6, Model 7 and Model 8 also involve individual drivers as a random effect.

Table 5-3: Multilevel models for the road effect of risk perception on affect speed limit credibility

	Model 5		**Model 6**		**Model 7**		**Model 8**	
	Linear regression	**tStat**	**effect of road type**	**tStat**	**effect of speed limit**	**tStat**	**effect of road type and speed limit**	**tStat**
Fixed Effect								
Intercept (se)	70.14*** (1.50)	46.85	71.59*** (2.82)	25.40	62.49*** (2.48)	25.23	65.72*** (2.888)	22.75
Risk (se)	-0.31*** (0.04)	-8.39	-0.32*** (0.04)	-7.72	-0.37*** (0.04)	-9.76	-0.42*** (0.04)	-9.52
roadtype_straight (se)			-2.05 (2.02)	-1.02			-4.32** (1.99)	-2.17
limit_50 (se)					15.44*** (2.12)	7.29	15.79*** (2.12)	7.46
limit_60 (se)					13.42*** (2.25)	5.96	14.46*** (2.29)	6.30
Random Effects								
Driver intercept 'std' (se)			10.41 (7.74, 14.01)		10.50 (7.84,14.06)		10.54 (7.88,14.10)	
Error Res Std (se)			25.39 (24.16, 26.68)		24.49 (23.30, 25.73)		24.41 (23.23, 25.65)	
Degrees of freedom	814		813		812		811	
Adjusted R^2	0.08		0.20		0.25		0.26	
Log Likelihood			-3824.60		-3796.20		-3793.90	
AIC			7659.20		7604.40		7601.70	

*** p<.01 ** p<.05 *p<.1

According to the four models tested, the overall effect of risk feeling is highly significant for credibility rating in a given road scenario. The more risk feeling, the less credible the speed limit. In Model 5, the linear regression cannot explain many of the explanatory variables, as the R^2 value is quite low. In Model 6, the road type coefficient is not statistically significant. In Model 7 and Model 8, the fixed effect speed limit is significant for the relationship. A straight road with a 40mph speed limit is perceived as having low credibility. As the risk perception increases, the credibility rating becomes even lower. A non-credible speed limit brings a higher risk rating. Drivers perceive that driving at 40mph on a safe road places the own car and other vehicles in a very slow speed situation, which might lead to an unsafe feeling. A curved road with a 60mph speed limit is perceived as more risky than other situations, while a curved road with a 40mph speed limit and a straight road with a 50mph limit have lower risk perceptions than other situations. A curved road with a 60mph limit and a straight road with a 40mph speed limit are seen as having the least credible speed limits compared to the other situations. Drivers perceive more risk on a curved road than a straight road, given the same speed limit. Adding road type and speed limit in Model 8, does not make any significant improvement. As the adjusted R^2 value for the mixed effect models (Model 6, Model 7 and Model 8) is low. Therefore, it can be concluded that speed limit credibility level not only comes from risk perception but also from the road layout and roadside environment. Together, road layout and the roadside environment are the main contributors to speed limit credibility.

In addition, the random effect in the model needs to be emphasised. The standard deviation of the random-effects term for the individual driver is above 10 and standard deviation of error residuals is above 20. Likewise, the standard deviation of the random effects term for risk is 0.179. And the correlation between the random-effects terms of intercept and risk is -0.725. Here, the random effect can explain the percentage of explanatory standard deviation, which is

$$\frac{10.5}{10.5 + 24.486} = 0.3001$$

However the residual for each fitted fixed effect is quite large, which illustrates that individual perceptions of risk and perceptions of credibility are different from each other in a given road scenario. In addition, both risk rating and credibility rating have larger variations because of the nature of subjective measurement, which has bias.

5.5 Discussion

The research develops a subjective measurement of speed limit credibility, a subjective measurement of risk perception and an objective measurement of compliance. The three indicators are used to develop the relationships between each two. The research confirms the three hypotheses:

Hypothesis 1: As drivers feel more risk in a given road environment, they might decrease their driving speed and obey the speed limit.

Hypothesis 2: As the speed limit is more credible, drivers are more compliant with the speed limit.

Hypothesis 3: Risk perception in a given speed has a negative influence on speed limit credibility. Non-credible speed limit is associated with higher risk feeling.

This result confirms the SWOV (2012d) comments that credible speed limits are supposed to result in drivers obeying speed limits more. More credible speed limits can make speeding drivers slow down, especially extreme offenders. A credible speed limit has an important effect on compliance with the speed limit. If the speed limit is more credible, most of the speed limit offenders will be more compliant with the speed limit, thus extreme violations will goes down. In addition, if the credibility score is 0, there is still a 35% probability of compliance with speed limit. That means obedient drivers will generally comply with the speed limit regardless of speed limit credibility. Credibility is a factor that affects compliance, but not the only factor. Other various factors affect compliance as well.

It is noted that both road type and speed limit are taken into consideration, which indicates that both speed limit credibility and risk feeling are the main factors for compliance with the speed limit. Speed limit is also the main factor affecting the relationship between risk perception and speed limit credibility. As drivers feel more risk in a given road environment, they might decrease their speed and perceive the speed limit as less credible. When the speed limit is more credible, drivers are more compliant with the speed limit. This result has confirmed the proposition of Fuller (2005) and Taylor (1964) that feelings of risk provide an input to the decision mechanism from which speed choice is determined. Here the relationship between risk perception and speed limit credibility have been confirmed in an experimental context. Both presence/absence of shoulder and presence/absence of cycle lane were not taken into consideration, because the variation of those parameters was much less important than curved road features. There are practical implications for road design. The research provides advice to local highway authorities on matching credible speed limits to rural single carriageway infrastructure in order to provide safe conditions for all road users.

In addition, the structure and properties of the multilevel models are usefully exploited to investigate the relationship between risk perception and driving speed, and risk perception and speed limit credibility, including the explanatory effects of speed limit, road type and individual driver. Logistic regression is suitable for investigating the relationship between credibility and compliance with the speed limit.

Chapter 6 Driving behaviour classification

6.1 Research model

It is hypothesised that drivers adopt different attitudes in a given road layout and the roadside environment which will influence drivers' speed behaviour. In the design of advanced intelligent driver assistance systems, there is a trend that the system can analyse driver's ability and behaviour, understand driver's intention and communicate with driver's behaviour habit, which can build trust between human –machine. Management can also occur through earlier decision and therefore can generate less conflict between the system and a driver's action. That is of benefit for human and machine mutual trust in the near future. For example, such a system can potentially reduce speeding behaviour by predicting inappropriate driving speed. For potential speeding drivers approaching a curved road, the system can provide an early in-car warning system (LeBlanc, 2006). The data were collected from the controlled experiment using both questionnaire and driving simulator.

Based on the above relationship between speed limit credibility, risk perception and driving speed in a given credible speed limit, it can be concluded that both credibility and risk perception affect driving speed. Generally, although both credibility chosen result (choose one credible speed limit from a list of speed limits) and credibility rating result (rating credibility value in a given road scenario) can help to identify a credible speed limit, they cannot predict whether drivers comply with the speed limit or not. Speed rating result perception itself also cannot predict driving behaviour. Therefore, based on the speed limit credibility perception and risk perception, the machine learning algorithm can determine the level of compliance with speed limit for individual drivers and, as a consequence, take effective actions, such as adaptive in-vehicle speed limiters for those speeding drivers, for better compliance.

6.2 Model dataset

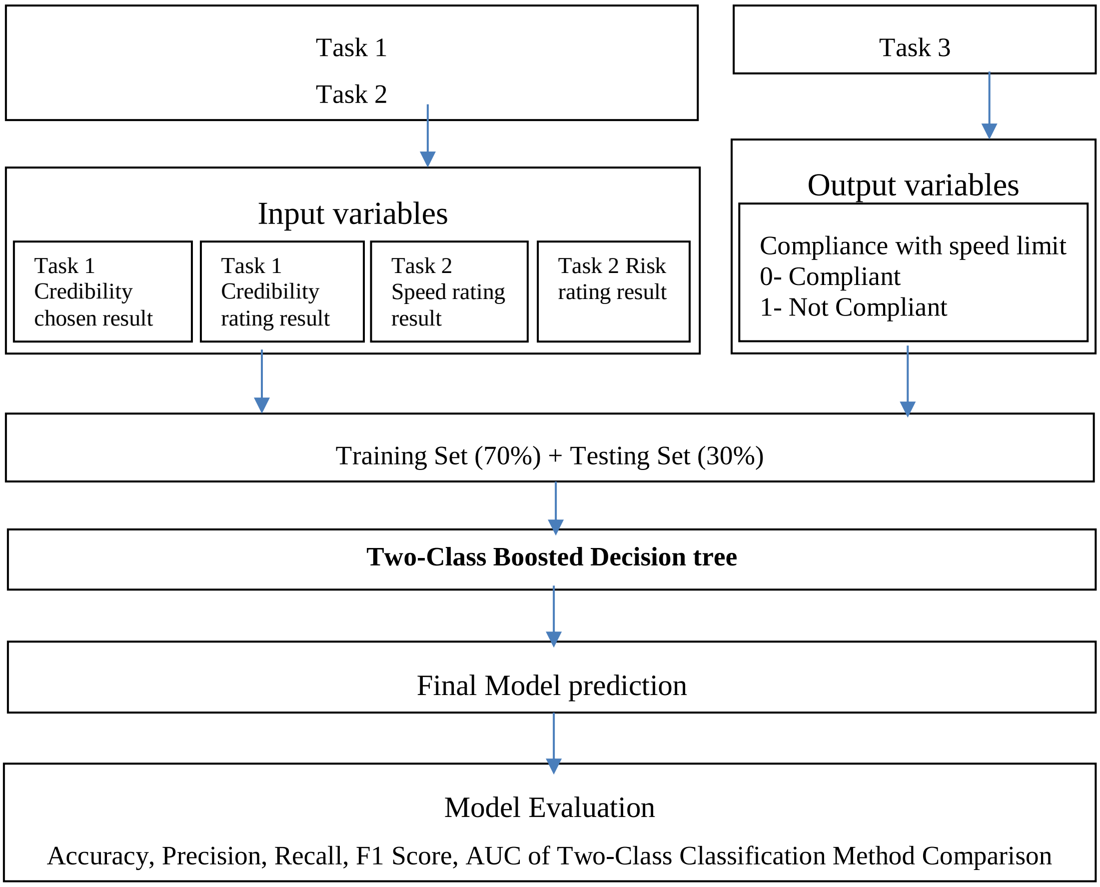


Figure 6-1: Driving behaviour classification framework

Whether compliance can be predicted by both credibility and risk perception together or independently needs to be tested. Using a classification method can make a prediction for exceeding behaviour in terms of predicted probability. Observation of driver compliant/non-compliant behaviour from controlled laboratory experiment datasets can be used to train machine learning algorithms. The trained models can be used to predict future driving behaviour decisions for implementation in in-vehicle safety systems. Figure 6-1Figure 5-1 shows the data from Experiment 2 are used in the analysis as well. The input variables emanate from both Task 1 and Task 2. The output variable emanate from Task 3. The features (or "input variables") are a combination of different perception factors:

- **Speed limit choice** from Task 1 Questionnaire
- **Speed limit rating** from Task 1 Questionnaire

- **Speed rating** from Task 2 Automated Driving
- **Risk rating** from Task 2 Automated Driving

The response (or "output variable") driving behaviour is the driving speed from Task 3. The level of compliance with the speed limit was originally to be given as a percentage of time compliant with the speed limit as a continuous variable from non-compliance (0) to compliance (1). To make this classification for all the data, the dichotomous term was given a threshold of 0.5. If the percentage of time compliant with the speed limit was greater than 0.5, it was classified as 1, otherwise as 0.

- **Value 1**- Compliant means that the participant did not drive faster than road speed limit
- **Value 0**- Non-Compliant means that the participant drove faster than speed limit

In total, there was a 34 row dataset. The dataset was randomly split into 70% for a learning set and 30% for a testing set. The learning samples were randomly selected by a computer. Ripley (ed. 2007) explained the meaning of each dataset. A **training set** is a set of data used in learning potentially predictive relationships to fit the parameters to the classifier. A **test set** is a set of data used to assess the performance of a fully-specified classifier, strength and utility of a predictive relationship. A validation set is a set of data used to tune hyper parameters of a classifier.

6.3 Test Method

In this research, Two-Class Boosted Decision Tree machine learning classification methods were used to capture driving behaviour, which offers the best solution among other classification methods. Other classification methods include Two-Class Averaged Perceptron, Two-Class Bayes Point Machine, Two-Class Decision Forest, Two-Class Decision Jungle, Two-Class Locally-Deep Support Vector Machine, Two-Class Logistic Regression, Two-Class Neural Network and Two-Class Support Vector Machine. A Two-Class Boosted Decision Tree creates a binary classifier using a decision tree algorithm. A boosted decision tree is an ensemble learning method in which the second tree corrects for the errors of the first tree, the third tree corrects for the errors of the first and second trees, and so forth. Predictions are based on the entire ensemble of trees together that makes the prediction (Barga et al., 2015). The algorithm of a boosted decision tree is described in the appendix.

The Two-Class Boosted Decision Tree classification method performed best for two reasons. First, the decision tree is a classifier that partitions data recursively into the form of tree structure with each internal node representing a test on an attribute, while each branch represents the outcome of the test and each leaf node represents a class label (Quinlan, 1986). The path from root to leaf represents classification rules. Second, boosting is a technique consisting of iteratively learning weak classifiers with respect to a distribution and adding them to a final strong classifier The data are reweighted after a weak learner is added (Freund and Schapire, 1995). Two-Class Boosted Decision Tree uses boosting procedure for decision tree classifier. ID3 (Iterative Dichotomiser 3), CART (Classification and Regression Trees), and C4.5 (Quinlan's next iteration) decision tree and AdaBoost (Adaptive Boosting) are widely used algorithms for data training. ID3 and C4.5 use Shannon Entropy to pick features with the greatest information gain as nodes. CART uses Gini Impurity, which is a measure of the homogeneity/purity of the nodes. The heuristic is to choose the attribute with the maximum Information Gain or Gain ratio based on information theory (Quinlan, 1986). By minimising the Gini Impurity the decision tree can separate the data better.

6.4 Test criteria

Table 6-1: Table of confusion explanation

True Positive (TP)	The driver is not compliant with speed limit and the prediction result is non-compliance
False Negative (FN)	The driver is not compliant with speed limit but the prediction result is compliance
True Negative (TN)	The driver is compliant with speed limit and the prediction result is compliance
False Positive (FP)	The driver is compliant with speed limit but the prediction result is non-compliance

In this research case, one target is to quantify the performance of a classifier and give a higher score for this classifier than the other classifier, which is evaluated by the following indicators. The machine learning models are evaluated using both the classification accuracy and the true positive rate, as the goal is to get the most accurate model with the true positive rate Table 6-1. In other words, it needs to predict the speeding behaviour correctly.

- **Accuracy score** means how many true positive and true negative of the total are correctly classified ACC= (TP+TN)/ (TP+TN+FN+FP).
- In addition, the **Precision** is called the positive predictive value PPV=TP/ (TP+FP).
- The **Recall** is also called true positive rate TPR=TP/ (TP+FN). The target is to decide to maximize the True Positive Rate which means when it is actually YES, how often it predicts YES, calculated by "True Positive/Actual YES". The recall value is 1 means all the drivers exceeding speed limit behaviour are predicted by the classifier method correctly. Maximising the recall value is also the determination of how to set the classification threshold.
- The **F1 Score** is the harmonic mean of precision and sensitivity, F1=2TP/ (2TP+FP+FN).
- In a ROC (area under the receiver-operating characteristic curve) the true positive rate (Sensitivity) is plotted in function of the false positive rate (100-Specificity) for different cut-off points. Each point on the ROC curve represents a sensitivity/specificity pair corresponding to a particular decision threshold. The closer the ROC curve is to the upper left corner, the higher the overall accuracy of the test (100% sensitivity, 100% specificity) (Zweig and Campbell, 1993). The value is called **AUC** (Area Under the Curve) which ranges from 0.5 (no discrimination) to 1.0 (absolute prediction). In this case, AUC <0.5 was excluded from further data analyses.

6.5 Two-Class classification model result

Credibility chosen result, Credibility rating result, Speed rating result and Risk rating result are used as four predictive input variables: Credibility chosen result from Task 1, Credibility rating result from Task 1, Speed rating result from Task 2 and Risk rating result from Task 2. There are two classes of outcome, if the individual's proportion of driving time exceeding the speed limit is greater than 50% (50% is arbitrary set as a threshold), the outcome is non-compliant. If the individual's proportion of driving time exceeding the speed limit is 0 or less than 50%, the outcome is compliant. Therefore, output of 0 means compliance with the speed limit;

1 means exceeding the speed limit. The following test results go through each classification method and only list the methods with high accuracy score above 0.700 and high AUC value above 0.500. An accuracy value of less than 0.700 is not taken into account. An AUC value less than 0.500 represents a non-successful prediction of true negative value, even if the accuracy value meets the requirement. The evaluation output with Two-Class Boosted Decision tree classification methods are presented in Table 6-2. Input with road type has higher accuracy and recall value, which illustrated speed limit compliance is dependent on different road type. Therefore, compliance performance with speed limit for each road type is explored further in

Table 6-3. The evaluation model shows that Two-Class Boosted Decision Tree performs better for Curve + Shoulder + Cycle Lane with credible speed limit 40mph, Curve + Shoulder with credible speed limit 40mph, Curve with credible speed limit 40mph, Straight + Cycle Lane 50mph, and Straight 60mph but not for other road types. The disadvantage of the decision tree is that data may be over-fitted or over-classified if a small sample is tested; for example, the accuracy value of each road is lower than that of the combined eight road layout. Straight road driving behaviour cannot be predicted accurately.

Table 6-2: Two-Class Boosted Decision Tree classification result for compliance with speed limit for eight road types

Road Layout	Input variables:	Output variable:	Evaluate Model				
			Accuracy	Precision	Recall	F1 Score	AUC
Rural single carriageway combined 8 road types	Credibility chosen result, Credibility rating result, Speed rating result, Risk rating result	Compliance	0.76	0.83	0.80	0.82	0.70

Table 6-3: Two-Class Boosted Decision Tree classification result for compliance with speed limit for each road type

Input variables: Credibility chosen result, Credibility rating result, Speed rating result, Risk rating result Output variable: Compliance					
Road Layout	Evaluate Model				
	Accuracy	Precision	Recall	F1 Score	AUC
A_ Curve + Shoulder + Cycle Lane with credible speed limit 40mph	0.70	0.67	1.00	0.80	0.60
B_ Curve + Shoulder with credible speed limit 40mph	0.70	0.80	0.67	0.73	0.75
C_ Curve + Cycle Lane with credible speed limit 40mph	0.30	0.38	0.60	0.46	0.06
D_ Curve with credible speed limit 40mph	0.70	0.71	0.83	0.77	0.79
E_ Straight + Shoulder + Cycle Lane 50mph	0.60	0.71	0.71	0.71	0.38
F_ Straight + Shoulder 60mph	0.50	0.50	0.40	0.44	0.62
G_ Straight + Cycle Lane 50mph	0.70	0.70	1.00	0.82	0.31
H_ Straight 60mph	0.80	0.83	0.83	0.83	0.81

Furthermore, the Two-Class Boosted Decision Tree classification method has been used for testing output compliance level with different thresholds: Compliant +10%, and Compliant +20%. The evaluation results show that recall value lower than 0.3 could not predict drivers’ speeding behaviour correctly for both combined road type and individual road type.

6.6 Model evaluation

Evaluation is a standard way to measure the performance of the model (Klein, 2017). Various train model modules were used to make predictions on datasets using the score model module. The evaluation is based on the scored labels/probabilities along with the true labels.

The result shows that the classification for combined road layout can be predicted by the Two-Class Boosted Decision Tree classification method. The evaluation model reached high accuracy with fewer overfitting features. First, this research result gives the reference of classification methods used from speed limit perception and risk perception to classify driving behaviour. Task 1 and Task 2 can work together to reach the prediction target depending on different rural road types. Second, for the road layout and the roadside environment with curve, it is identifiable that the behaviour can be predicted by an individual's perception when given credible 40mph speed limit rather than a normal 60mph speed limit. Third, Two-Class Boosted Decision Tree works best among other classification methods which are driven by both the nature of the data and the questions to be answered. Generally, the decision tree method is good at making an assessment for individual characteristics by using layer variables and decision nodes. Boosted trees incrementally build an ensemble by training each new data to emphasise the training instances previously mis-modelled (Hastie and Tibshirani, eds. 2001). Fourth, for compliant +10% and compliant +20% thresholds, as the threshold was set too high, nearly all of the participants were in compliance with speed limit +20%, no matter whether the speed limit is credible or non-credible. The classification method becomes meaningless and none of the road types can be correctly predicted.

In terms of model improvement, further enhancement of the model driving speeding/compliance is required to involve more input factors, including more road layout scenarios, or even more dynamic factors such as inclement weather or traffic flow. It could also develop real-time machine learning techniques that can adapt to the real situation to affect driving behaviour changing for better speed management. Whether in-vehicle real-time alerting can reduce speeding behaviour effectively or bring frustration to vehicle users, and when would be the appropriate moment to alert, need to be investigated after implementation in autonomous driving in the future.

6.7 Model application

By applying the boosted decision tree method with high value of accuracy and recall, the algorithm can establish driving behaviour model based on drivers' credibility perception and risk perception. It introduces drivers' perception of speed limit and risk which models driver compliant/non-compliant behaviour with high accuracy. The classification method offers two contributions. First, a new driver assistant system can be developed. There exists a trend that the sensors in a vehicle understand driver behaviour better. For example, vehicle sensors, IoT (Internet of Things) sensors, emotional indicators and contextual data can provide information to understand the drivers and the applicable responses. By using the model algorithm, a model can be developed for which can be used in a vehicle control system by predicting drivers' speeding/not speeding to achieve a more effective warning system. Predicted driver behaviour can trigger safety alerts, as active safety measurements being helpful for preventing potential hazards. Second, the method is suitable for application to driver training. By classifying the speeding drivers, their perception about speed limit credibility and risk perception can be extracted for investigating the reasons for speeding behaviour. Instructors can provide adequate advice to each speeding driver based on the result from the model.

Chapter 7 Experiment 3- How to convert from credibility to compliance?

7.1 Study rationale

Road layout is an important factor that impacts a driver's perception of a credible speed limit. Consequently, driver behaviour depends, in part, on the decision of whether to comply with the posted speed limit. Experiment 2 reveals that a credible speed limit sign, in itself, does not lead to full compliance with the speed limit, in terms of mean driving speed or the proportion of time spent exceeding the speed limit. The review of speed management found that the 'reasonableness' of a speed limit is one of the most important factors determining the degree of compliance (OECD, 2006).

Various measures can be used to reduce speed to a level that improves compliance with credible speed limits, such as making drivers aware of the road environment on straight roads and the risk environment on curved roads. Speed reduction, using a combination of measures, is one of the main objectives of traffic-calming. For example, rumble strips approaching intersections in rural areas is a physical speed management tool, but is seldom used due to the potential danger (Kallberg et al., 1999).

Previous research shows that signs completely outperform rumble strips at rural junctions. Increasing the number of traffic signs, repeating and anticipating signs and emphasising the contrast, frame and so forth of signs and warning signals placed in areas of potential danger, all evoke desirable driving behaviours and reduce accidents (Smith and Zhang, 2004). They help drivers be ready to accelerate or decelerate when approaching potentially hazardous scenarios.

Experiment 3 investigates whether road warning signs affect perception and driving behaviour on a rural curved road, a rural straight road with a cycle lane and a rural straight road (Figure 7-1). Road warning signs are tested to ascertain whether they change drivers' perceptions of the speed limit's credibility, safety and necessity, and whether they should be different from normal speed limit signs. It can be assumed that the most effective warning signs make drivers more compliant with a credible speed limit.

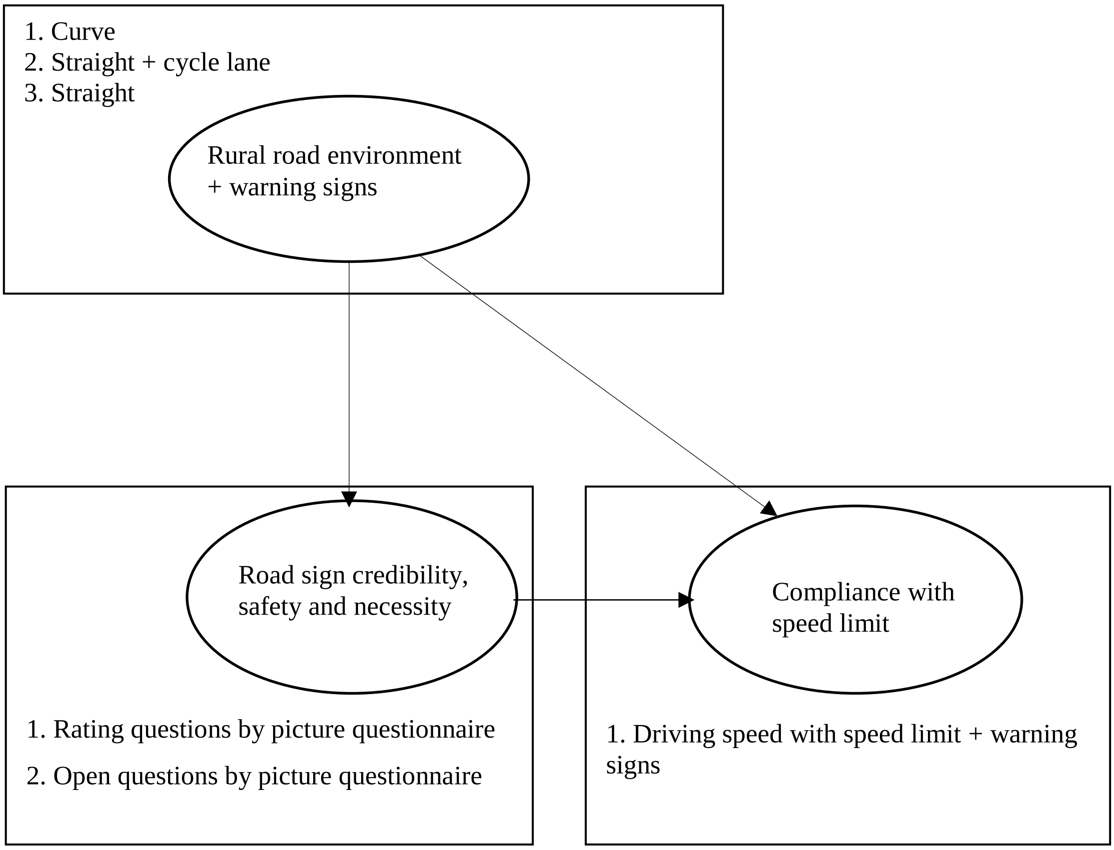


Figure 7-1: Experiment 3 theoretical model

7.2 Study aims

This experiment aims to find the most effective credible speed sign solution to improve compliance with the speed limit on three layouts of a rural single carriageway.

7.3 Experimental hypotheses

Road warning signs are predicted to interfere with perception and behaviour in a given road layout and roadside environment.

- Firstly, it is predicted that road warning signs change drivers' perceptions of the signs' credibility, safety and necessity, which should be different from the normal speed limit sign.
- Secondly, it is predicted that road warning signs interfere with responses to driving speed, specifically by slowing down the driving speed and reducing the proportion of time exceeding the speed limit. The various warning signs are

expected to produce different perceptions of the signs and distinct driving behaviour profiles.

7.4 Method

7.4.1 Experimental design

This experiment uses a repeated measures (within groups) ANOVA design to investigate responses to the different types of road warning signs. In the study, some of the road signs used combine a warning sign and a speed limit sign. This tests whether differences in behaviour are due to differences in the information provided. Participants are randomly assigned to view pictures depicting a driving view and instructed to imagine themselves driving on the road depicted in the picture.

As previous literature mentions, the presence of curves, the presence of cyclists, and the presence of oncoming vehicles are all potential hazards on rural single carriageways. Traffic signs should be placed in areas of potential danger to evoke desirable driving behaviours and reduce accidents. Both the speed limit signs and warning signs come from the UK Highway Code. The following variables are manipulated in the ANOVA design:

- **Types of speed limit sign**

a) The basic speed limit sign is a red circle with a black number contained within it. The limits almost always end in zero.

b) Maximum speed advised signs indicate a suggested maximum speed and are often seen underneath signs showing a bend in the road.

- **Types of warning sign**

Warning signs often take the shape of an equilateral triangle and are used to warn drivers of an impending hazard that might otherwise not be obvious.

a) Bend signs warn drivers of a bend to right (or left if reversed).

b) Two-way traffic straight ahead signs indicate a change from one-way to two-way traffic, and the commencement of any two-way side roads that form a junction with a one-way road. They should be as close as possible to the beginning of two-way working, readily visible to turning traffic, and repeated after 100m.

c) Cyclist warning signs warn traffic of a place where a cycle route crosses or joins a road where it is not controlled by traffic signals. Where cyclists emerge only from the left, the symbol is reversed.

d) Chevron signs with three white chevron arrows pointing left inside a black horizontal rectangle, a striking way to keep drivers safe, show the edge of the road at dangerous curves or other hazards.

Combinations of speed limit signs and warning signs are used in the experimental scenario. The principle in placing the signs is that the triangular warning signs are placed above the speed limit signs. Considering both single road signs and combinations of road signs, the experimental design includes three basic speed limit signs and 16 types of intervention road signs, as listed in Table 7-1.

Table 7-1: Experimental design for road signs

Road signs on curved rural single carriageway (with signs code from Traffic Signal Manual, GOV.UK)						
40 SL	① Warning Sign	② Warning Sign+ Max 40	③ Warning Sign+40 SL	④ Warning Sign+Chevron	⑤ Warning Sign+Max 40+Chevron	⑥ Warning Sign+40 SL+Chevron
						
Road signs on rural single carriageway with a cycle lane (with signs code from Traffic Signal Manual, GOV.UK)						
50 SL	⑦ CycleWarningSign + 50 SL	⑧ OncomingWarningSign + 50 SL	⑨ MaxSpeed50	⑩ CycleWarningSign + MaxSpeed50	⑪ OncomingWarningSign + MaxSpeed50	
						
Road signs on rural single carriageway (with signs code from Traffic Signal Manual, GOV.UK)						
60 SL	⑫ CycleWarningSign+60 SL	⑬ OncomingWarningSign+ 60 SL	⑭ MaxSpeed60	⑮ CycleWarningSign+MaxSpeed60	⑯ OncomingWarningSign+ MaxSpeed60	
						

For the manual driving task, drivers drove on the road with the road signs in a balanced sequence in order to control all other possible factors. Speed limits should not change at less than 600m intervals. The signs were grouped into six as follows:

A--①②③

B--④⑤⑥

C--⑦⑧

D--⑨⑩⑪

E--⑫⑬

F--⑭⑮⑯

The 6 × 6 balanced Latin square of the driving sequence for each participant, with a junction between each, is shown in Table 7-2.

Table 7-2: Counterbalance design for Task 2: Manual driving task

Participant ID	**Driving sequence**						
1,7,13,19,25,31	Normal speed limit sign	A	C	F	B	E	D
2,8,14,20,26,32	Normal speed limit sign	B	C	A	D	F	E
3,9,15,21,27,33	Normal speed limit sign	C	D	B	E	A	F
4,10,16,22,28,34	Normal speed limit sign	D	E	B	F	C	A
5,11,17,23,29,35	Normal speed limit sign	E	F	D	A	C	B
6,12,18,24,30,36	Normal speed limit sign	F	A	E	B	D	C

7.4.2 Apparatus

The study is conducted on a motion-based, high-fidelity University of Leeds Driving Simulator (UoLDS). The simulator vehicle is an adapted cab of a 2005 Jaguar S-type, housed in a 4m spherical projection dome with a 300° field of view projection system. For the questionnaire, the computer monitor was used to present each road scene. The screenshot road scenes were present on the 15” monitor.

7.4.3 Simulated road environment

Road signs on curved rural single carriageway	Road signs on rural single carriageway with a cycle lane	Road signs on rural single carriageway
		
		
		
		
		
		
		

Figure 7-2: Forward view of the road

As shown in Figure 7-2, each road sign stands along the road, 1m from the road curb. For the combinations of signs, the warning sign is located above the speed sign. Chevron boards used on curved roads are spaced along the curve after the point of curve entry, with a distance of 45m between the two boards.

7.4.4 Participants

The participants were selected from the same email list of registered participants as used in Experiment 2. About half the participants overlapped with Experiment 2. The participants consisted of 34 licensed drivers, including 17 males and 17 females, aged from 18 to 57 (mean = 34.5, SD = 13.12), years driving ranged from 0.5 to 40 (mean = 13.74, SD = 12.29).

A road sign intervention effect of 10% or more decrease in speed would be of interest. For the paired group T-test, assuming intervention road sign in the normal speed limit sign group and treatment group of mean 42 (SD = 2.28) and 39.5 (SD = 1.8) respectively, and 0.5 effect size, with a two-sided significance of 0.05 and a power of 0.8, a total of 31 participants was required. The calculation process is shown in Table 7-3, calculated with the sample size calculator (http://www.sample-size.net/sample-size-study-paired-t-test/). The total number of participants was 34, which meets the requirement for before-after study.

Table 7-3: Sample size calculation for before-after study (paired T-test)

α (two-tailed) =	0.050	*Threshold probability for rejecting the null hypothesis. Type I error rate.*
β =	0.200	*Probability of failing to reject the null hypothesis under the alternative hypothesis. Type II error rate.*
E =	0.500	*Effect size*
S(Δ) =	1.000	*Standard Deviation of the CHANGE in the outcome. (If you don't know S(Δ), click here to calculate it.)*

The standard normal deviate for α = $Z\alpha$ = 1.960	The standard normal deviate for β = $Z\beta$ = 0.842	A = 1.000	B = $(Z\alpha+Z\beta)2$ = 7.849	C = $(E/S(\Delta))2$ = 0.250	AB/C = 31.4	**Group size N: 31**

7.4.5 Task procedure

For Task 1, the questionnaire study, intervention road signs were shown on three types of rural road, with each road sign being either a single sign or a combination of a warning sign and a speed limit sign. Each picture showed the road scene from the driver's perspective. The participants were randomly assigned to view the road pictures and instructed to imagine themselves driving on the road. Then they were asked to answer the rating and ranking questions.

For the rating questions, the participants were shown each road scene with a road sign, one by one, on the monitor screen. In total there were 19 road pictures (3 basic speed limit signs and 16 warning signs). As part of the subjective evaluation, the participants were asked to grade each road section in terms of its perceived credibility on a visual analogue scale of 0–100, where 0 meant 'very non-credible' and 100 meant 'very credible', then the same evaluation for perceived safety, and perceived necessity.

For the ranking questions, the participants were shown a group of sign pictures for each road type. Each picture was 14cm × 8cm. Based on the sign information that encouraged changing behaviour, they were requested to rank them in order from lowest speed to highest speed, and from most helpful/useful to least helpful/useful. The order was recorded for further analysis.

The open questions allowed the respondents to express what they thought in their own words based on their driving experience. Rating and ranking questions limit the responses, but open question can find out the reasons why the respondent chose the answers they did.

Task 1- Questionnaire

Show each single picture – rating questions

In your experience, how **credible** is the road sign displayed on this road?

Very Non-credible ———————————————————— Very credible

With regards to the road sign on this road, how **safe** would you feel?

Very Unsafe ———————————————————— Very Safe

How **necessary** do you find the road sign on the approach to road curves?

Not at all necessary ———————————————————— Very necessary

Show all pictures together –ranking questions

Which type of road sign encouraged you to have the driving **speed** below 40mph most?

Please rank the following from lowest speed to highest speed

Which type of road sign do you find most **helpful/useful**? Please rank the following from the most helpful/useful to least helpful/useful **Open questions** Which sign is the most credible and which sign is the least credible on this road? Explain reasons. Which sign make you feel most safety on this road? Explain reasons. Which sign is not appropriate on this road? Explain reasons

Task 2- Manual Driving

In Task 2, the manual driving study, the participants were required to attend the driving simulator. The previous drivers did not need to drive on the road with the basic speed limit sign, but the new drivers did. The participants were present with 16 road signs in a balanced order. For each road sign on the curved road (No.1 to No.6 in Table 7-1), the road section length was 504m straight + 314m curve = 818m. For each road sign on the straight road (No.7 to No.16 in Table 7-1), the road section length was 756m. Filler rural links were used to link the road sections. The task took about 15 minutes.

7.5 Data analysis

7.5.1 Task 1 - Credibility rating

The credibility level was measured separately for rural curved roads with seven road signs. Figure 7-3 shows the mean score of the 34 participants on credibility when presented with seven road signs. A repeated measures ANOVA was conducted for each road sign on the rural curved road. Mauchy's test of sphericity indicates that the assumption of sphericity was violated (χ^2 (20) = 55.583, p < .001), therefore, a Greenhouse-Geisser correction was used. There was a significant effect of road signs on credibility, (F (3.408, 112.462) = 2.768, p < .05, η^2 = .077). Post hoc tests using the Bonferroni correction revealed that Curve Warning Sign + MaxSpeed40 was significantly different from CurveWarningSign + 40SL (p = .015) and WarningSign + 40SL + Chevron (p = .033).

As the speed sign and information sign were both necessary, rather than just the normal speed limit sign, there was a need to detect the main effect of each single independent variable on the dependent variable, as well as the interactions. In addition, there was a need to assess whether the different conditions for the independent variables produced different results depending on the second independent variable. Compared with WarningSign + Max40, WarningSign + 40SL, WarningSign + Max40 + Chevron and WarningSign + 40SL + Chevron, the effects of the two independent variables on perceived credibility were as follows. The main effect of chevron present or absent was not significant ($F(1,132) = 3.058$, $p = .083$) but the main effect of the sign was significant such that the max speed 40 sign had higher credibility scores than the speed limit 40 sign, ($F(1,132) = 4.621$, $p = .033$). There was no significant interaction of road signs and chevrons.

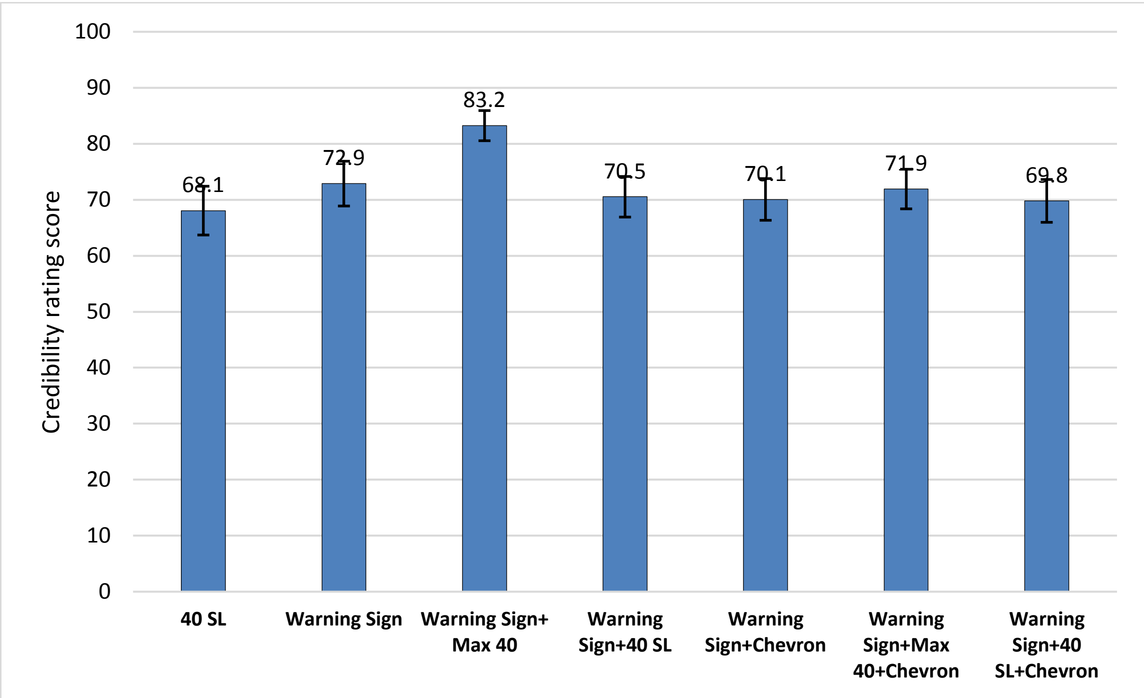


Figure 7-3: Credibility rating for road signs on rural single carriageway with curve

A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean credibility rating score of the signs on the rural single carriageway with a cycle lane differed statistically significantly between road signs ($F(3.216, 106.127) = 7.961$, $p < 0.0005$, $\eta^2 = .194$). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that 50SL was significantly different from MaxSpeed50 ($p = .018$). CycleWarningSign + 50SL was significantly different from OncomingWarningSign + 50SL ($p = .018$), MaxSpeed50 ($p < .001$) and

OncomingWarningSign + MaxSpeed50 (p = .027). MaxSpeed50 was significantly different from CycleWarningSign + MaxSpeed50 ($p < .001$). CycleWarningSign + MaxSpeed50 was significantly different from OncomingWarningSign + MaxSpeed50 (p = .043). Therefore, CycleWarningSign + 50SL elicited a significantly higher credibility than OncomingWarningSign + 50SL, MaxSpeed50 and OncomingWarningSign + MaxSpeed50.

Compared with 50SL, MaxSpeed50, CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50, the main effect of the speed sign was significant ($F(1,132) = 4.499$, p = .036) and the main effect of the warning sign was significant such that the cycle warning sign had higher credibility scores than without the cycle warning sign, ($F(1,132) = 10.335$, p = .002). Therefore, both the speed sign and the warning sign affected credibility level. There was no significant interaction of speed signs and cycle warning signs (see Figure 7-4).

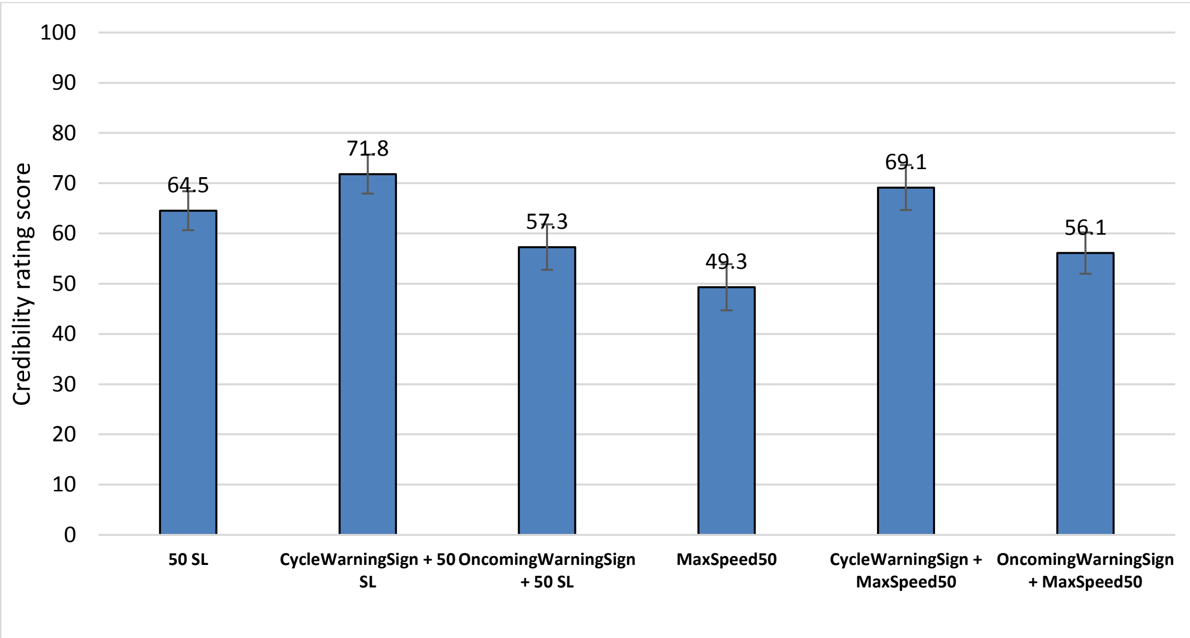


Figure 7-4: Credibility rating for road signs on rural single carriageway with a cycle lane

In terms of the credibility of the signs on a rural single carriageway, a repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean credibility rating score differed statistically significantly between road signs ($F(3.637, 120.017) = 4.301$, p = 0.004, $\eta^2 = .115$). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that the credibility rating for 60SL sign was statistically significantly higher than MaxSpeed60 (p = .009). No other pairwise comparisons were significant. Although 60SL and CycleWarningSign + 60SL were perceived as having higher credibility, they were not statistically different from each other.

Compared with 60SL, MaxSpeed60, CycleWarningSign + 60SL and CycleWarningSign + MaxSpeed60, the main effect of the speed sign was significant (F (1,132) = 6.494, p = .012) but the main effect of the warning sign was not statistically significant. Therefore, the speed sign is the main factor affecting the credibility level. In addition, there was no significant interaction of speed signs and cycle warning signs (see Figure 7-5).

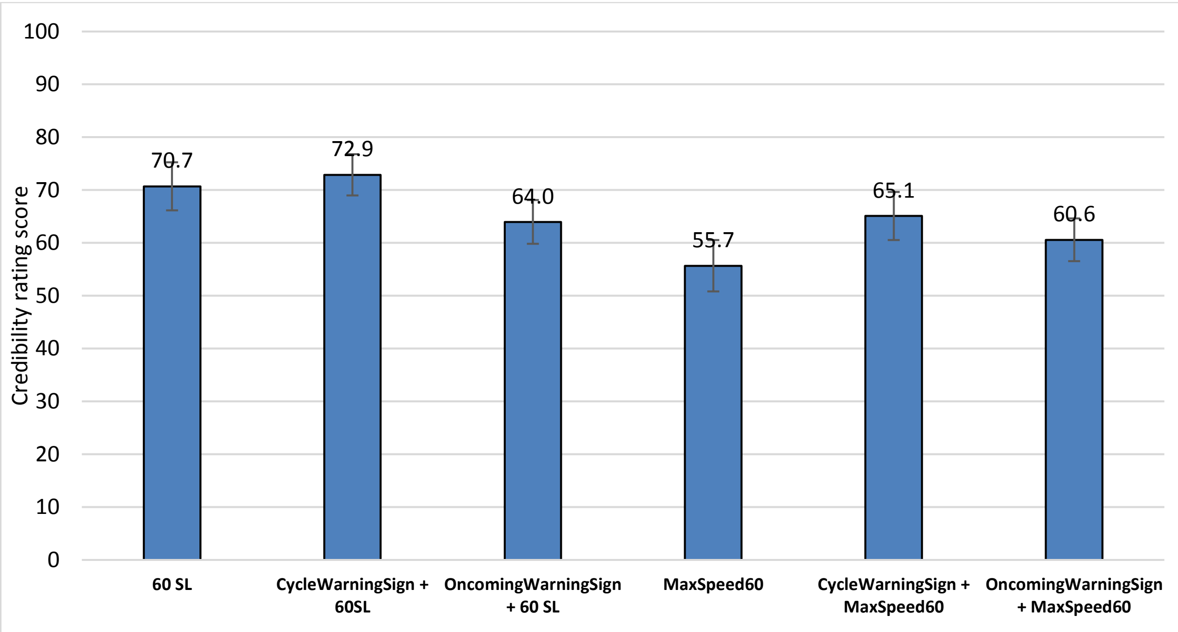


Figure 7-5: Credibility rating for road signs on rural single carriageway

7.5.2 Task 1 - Safety rating

The safety ratings of the signs were analysed separately for rural curved roads with seven different road signs. CurveWarningSign + MaxSpeed40 brought greater safety to the respondents. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean safety rating score differed statistically significantly between road signs (F (2.736, 90.294) = 4.724, p = .005, η^2 = .125). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that the safety rating for WarningSign + Max40 was statistically significantly higher than

40SL (p = .038), WarningSign (p = .002), WarningSign + 40SL (p = .006), and WarningSign + Chevron (p = .003). Safety rating for WarningSign + Max40 + Chevron was statistically significantly higher than WarningSign + Chevron (p = .007).

Compared with WarningSign + Max40, WarningSign + 40SL, WarningSign + Max40 + Chevron, and WarningSign + 40SL + Chevron, the main effect of chevron present or absent was not significant (F (1,132) = .820, p = .367), and the main effect of the sign was not significant either (F (1,132) = 3.825, p = .053). There were no effects for between-subject variables and no interaction effects of road signs and chevrons (see Figure 7-6).

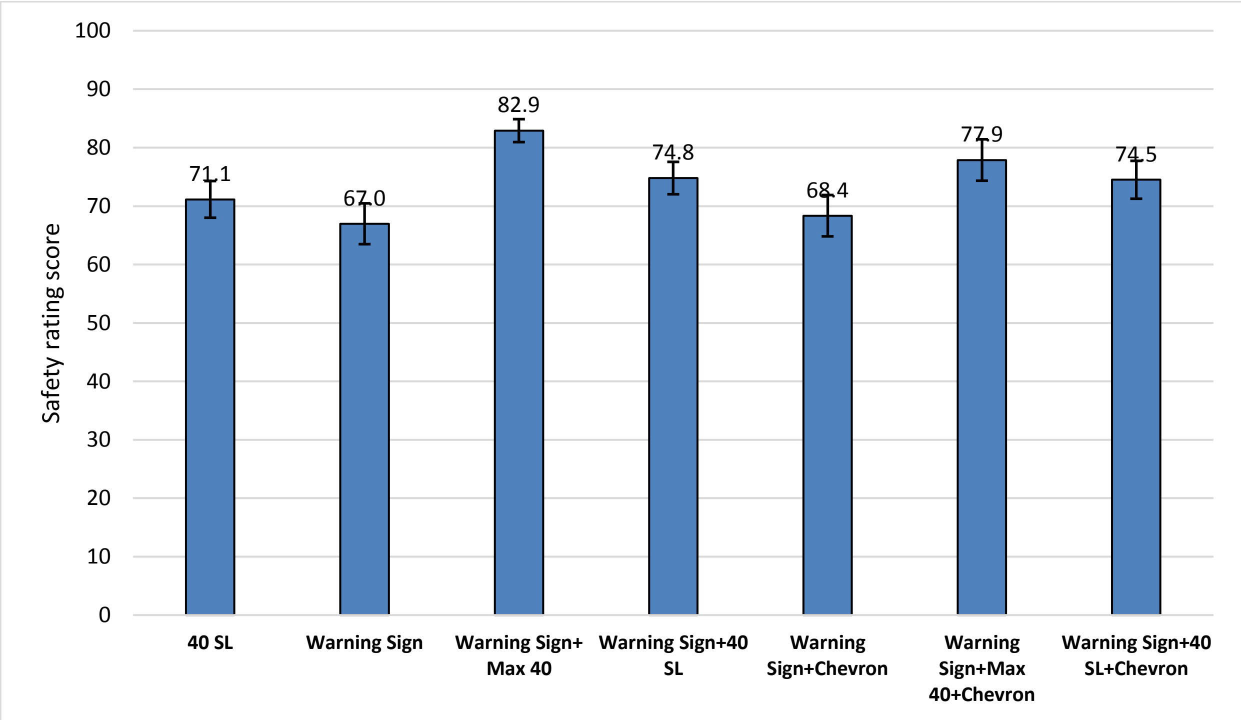


Figure 7-6: Safety rating for road signs on rural single carriageway with curve

In terms of safety ratings of the signs, CycleWarningSign + 50SL brought greater safety to the respondents. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean safety rating score differed statistically significantly between road signs (F (3.241, 106.961) = 4.595, p = .004, η^2 = .122). CycleWarningSign + 50SL encouraged a higher perception of safety than MaxSpeed50 (p = .015). The safety perception for CycleWarningSign + MaxSpeed50 was higher than MaxSpeed50 (p = .020). The safety perception for CycleWarningSign + MaxSpeed50 was higher than OncomingWarningSign + MaxSpeed50 (p = .022).

Compared with 50SL, MaxSpeed50, CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50, the main effect of the cycle warning sign was significant (*F* (1,132) = 10.341, p < .01). However, the main effect of the speed sign was not significant (*F* (1,132) = 1.868, p = .174). Therefore, CycleWarningSign had the main effect on safety issues. There was no significant interaction of speed signs and cycle warning signs (see Figure 7-7).

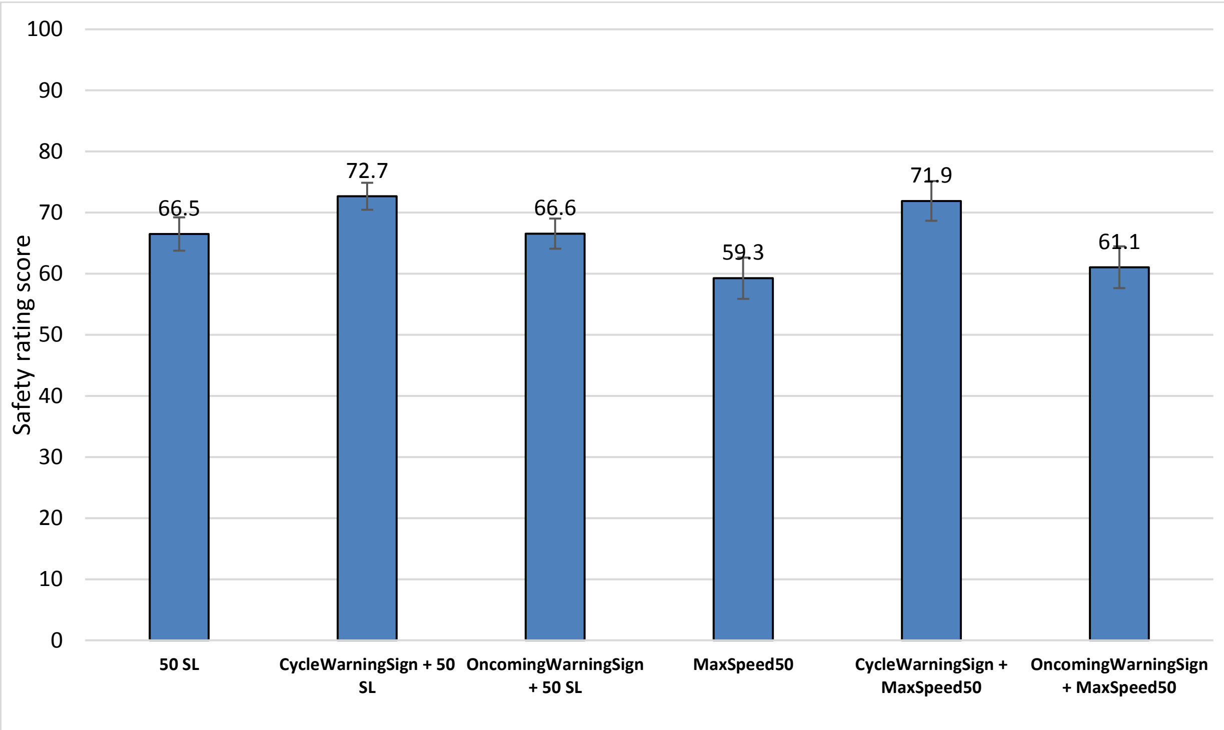


Figure 7-7: Safety rating for road signs on rural single carriageway with a cycle lane

In terms of the safety ratings from the signs on the road without a cycle lane, the 60SL sign brought greater safety to respondents. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean safety rating score differed statistically significantly between road signs (*F* (3.403, 112.285) = 2.964, p = .029, η^2 = .082). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that the safety rating for 60SL was statistically significantly higher than CycleWarningSign + 60SL (p = .045) and OncomingWarningSign + MaxSpeed60 (p = .04).

Compared with 60SL, MaxSpeed60, CycleWarningSign + 60SL and CycleWarningSign + MaxSpeed60, the main effect of the speed sign was significant (F (1,132) = 4.035, p = .047) but the main effect of the warning sign was not statistically significant. Therefore, the speed sign was the main factor affecting safety feeling, especially the national speed limit sign. There was no significant interaction of speed signs and cycle warning signs (see Figure 7-8).

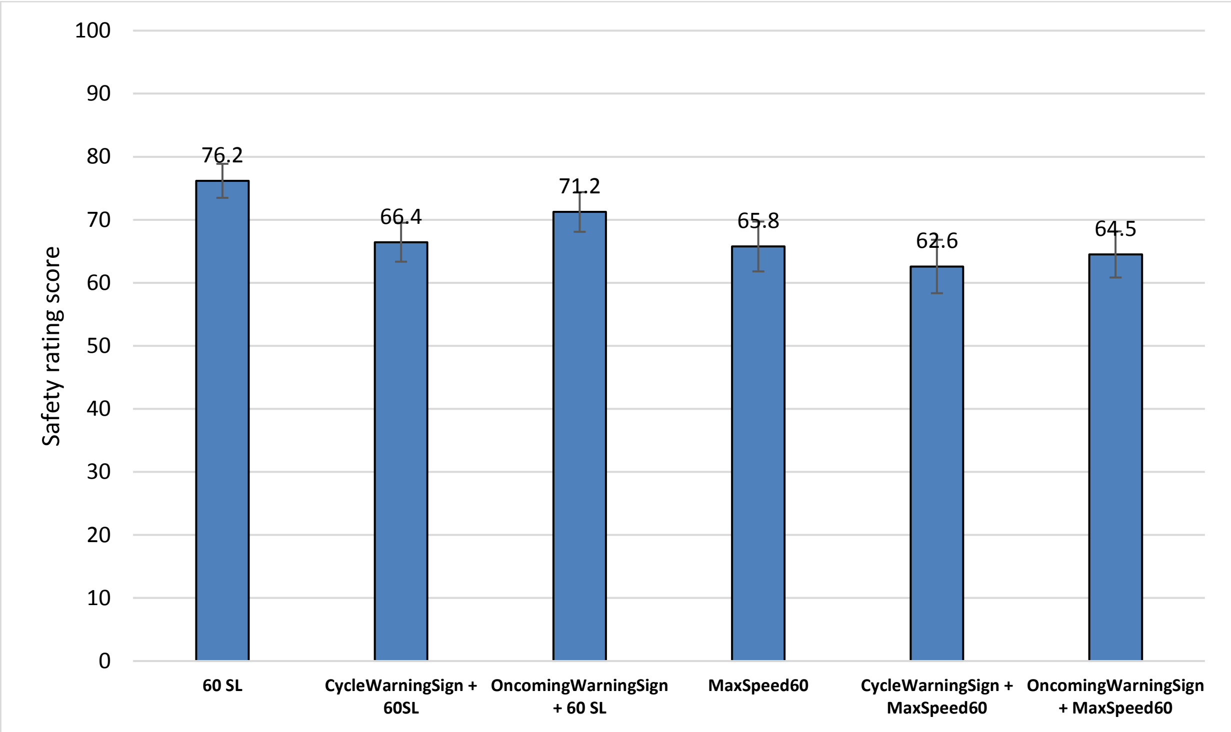


Figure 7-8: Safety rating for road signs on rural single carriageway

7.5.3 Task 1 - Necessity rating

The relative need for the sign rating was analysed separately for rural curved roads with seven road signs. The respondents perceived CurveWarningSign + MaxSpeed40 as more necessary than the other signs. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that he mean necessity rating score differed statistically significantly between seven road signs (F(4.265, 140.756) = 3.952, p = .004, η^2 = .107). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that the necessity rating for CurveWarningSign + MaxSpeed40 was statistically significantly higher than 40SL (p = .004), Warning Sign + Max40 + Chevron (p = .038) and WarningSign + 40SL + Chevron (p = .009).

Compared with WarningSign + Max40, WarningSign + 40SL, WarningSign + Max40 + Chevron and WarningSign + 40SL + Chevron, the main effect of chevron present or absent was significant (F (1,132) = 7.199, p = .008), but the main effect of sign was not significant (F (1,132) = 1.377, p = .243). Thus, chevron was a main factor affecting the necessity level. There were no effects for between-subject variables and no interaction effects of road signs and chevrons (see Figure 7-9).

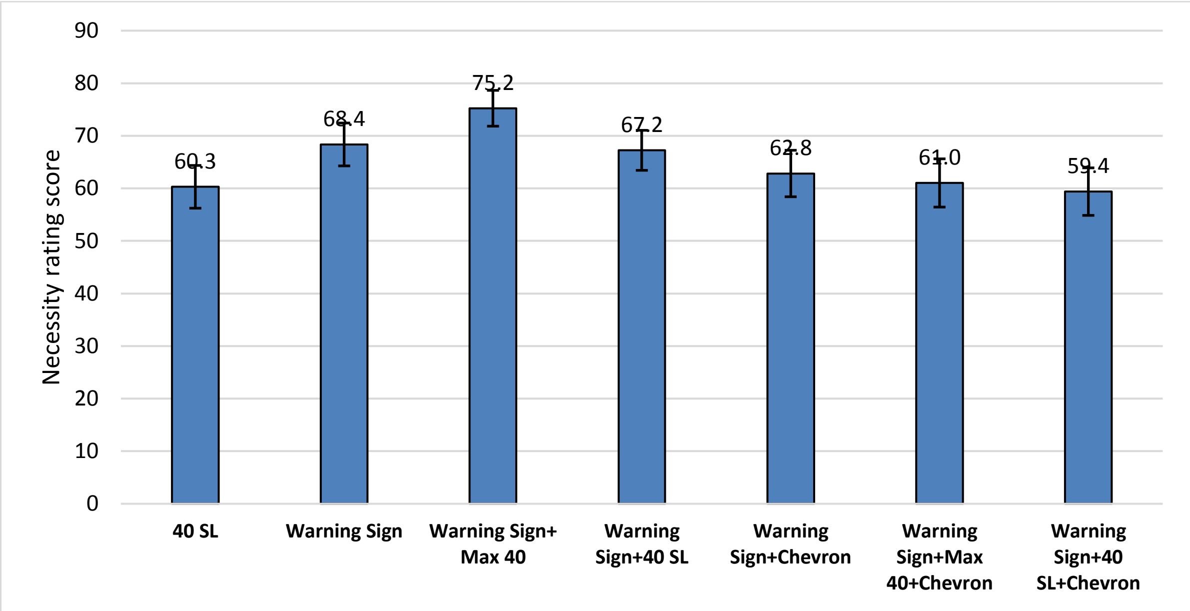


Figure 7-9: Necessity rating for road signs on rural single carriageway with curve

In terms of the necessity of the signs on a rural single carriageway with a cycle lane, the respondents perceived 50SL, CycleWarningSign + MaxSpeed50 and CycleWarningSign + 50SL as more necessary than other signs (Figure 7-10). Signs with oncoming traffic were unnecessary on the rural single carriageway with a cycle lane as the rating score was lower than 50. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean necessity rating score differed statistically significantly between six road signs (F (3.458, 114.106) = 8.715, p = .000, η^2 = .209). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that the necessity rating for 50SL was statistically significantly higher than OncomingWarningSign + 50SL (p = .004), MaxSpeed50 (p = .024), and OncomingWarningSign + MaxSpeed50 (p = .005).

Compared with 50SL, MaxSpeed50, CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50, the effects of both speed signs and cycle warning signs were not significant, at 0.05. However, there was a significant interaction of speed signs and cycle warning signs in terms of necessity level (F (1,132) = 4.243, $p < .05$). As with the necessity, speed sign type correlated with cycle warning sign present/absent. i.e. 50SL, CycleWarningSign + 50SL, CycleWarningSign + MaxSpeed50 were perceived as more necessary. But with the absence of a cycle warning sign, participants perceived MaxSpeed50 not to be a necessity (see Figure 7-10).

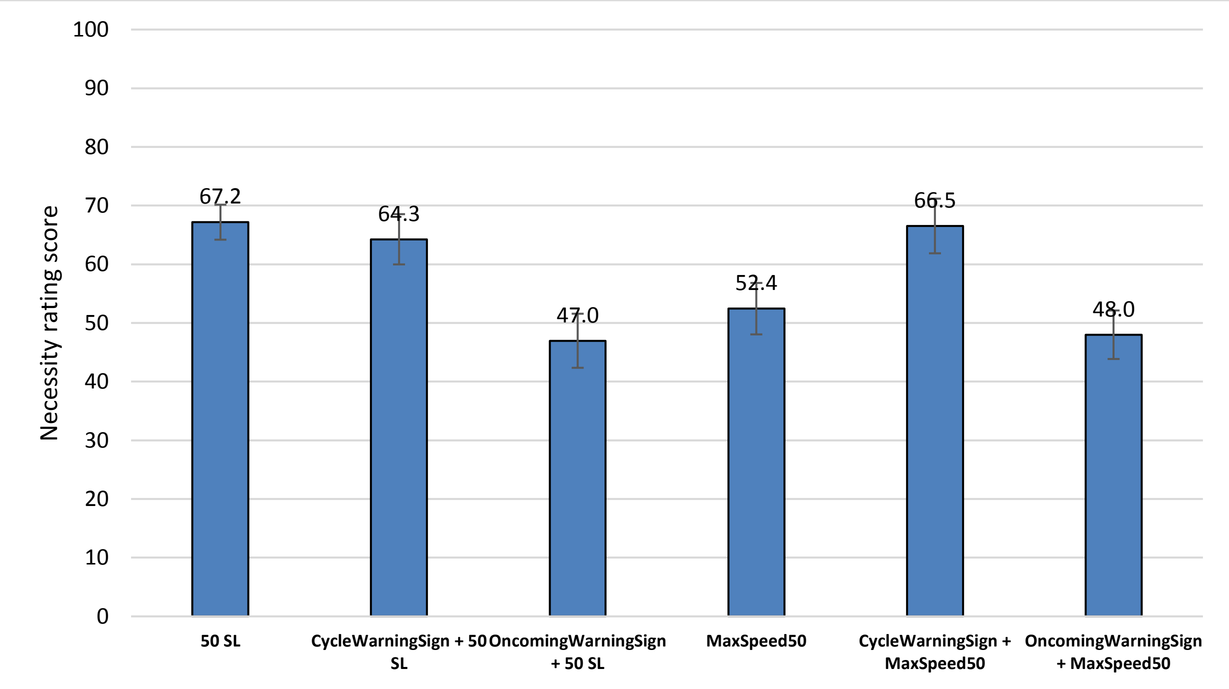


Figure 7-10: Necessity rating for road signs on rural single carriageway with a cycle lane

In terms of the necessity of the signs, the respondents perceived CycleWarningSign + 60SL as more necessary than the other signs (Figure 7-11). OncomingTraffic or MaxSpeed60 were unnecessary on the rural single carriageway. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean necessity rating score differed statistically significantly between six road signs (F (2.725, 89.912) = 7.732, $p = .000$, $\eta^2 = .190$). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that the necessity rating for CycleWarningSign + 60SL was statistically significantly higher than OncomingWarningSign + 60SL ($p = .026$), MaxSpeed60 ($p < .001$) and OncomingWarningSign + MaxSpeed60 ($p = .002$).

Compared with 60SL, MaxSpeed60, CycleWarningSign + 60SL, and CycleWarningSign + MaxSpeed60, the main effect of the speed sign was statistically significant (F (1,132) = 4.012, p = .047) and the main effect of the cycle warning sign was significant, such that CycleWarningSign + 60SL had higher necessity scores than other signs (F (1,132) = 10.518, p = .001). Therefore, both speed signs and warning signs affected the necessity level. There was no significant interaction of speed signs and cycle warning signs (see Figure 7-11).

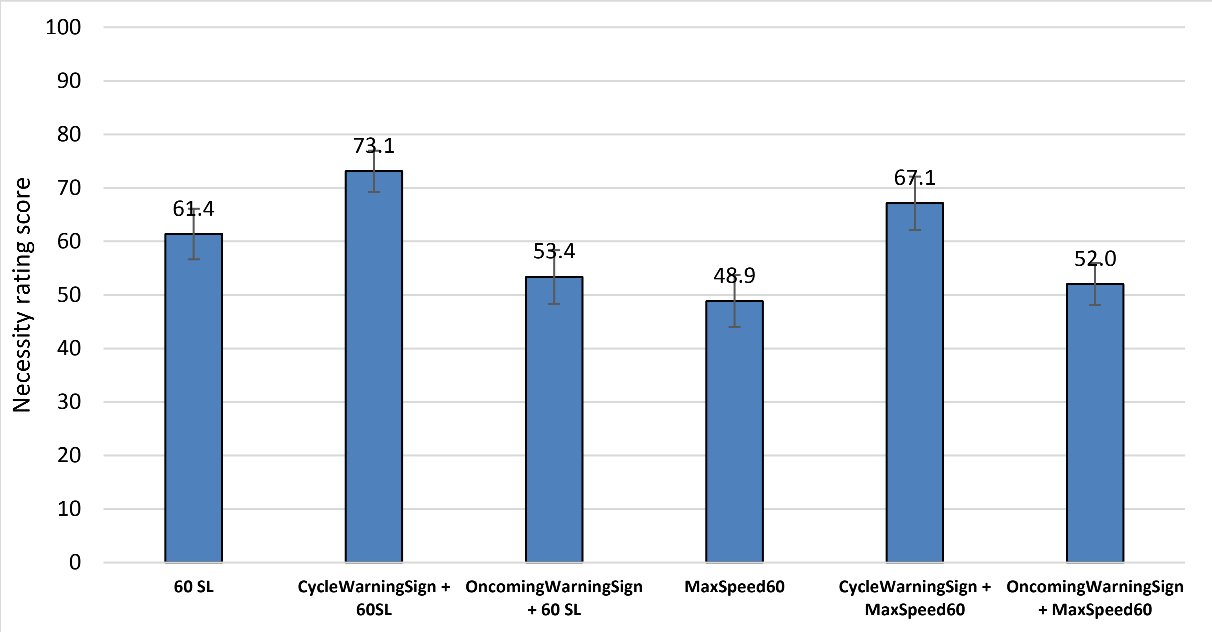


Figure 7-11: Necessity rating for road signs on rural single carriageway

7.5.4 Task 1 - Ranking questions results

The ranking questions were used to evaluate the perception of the lowest speed and whether the road signs for each type of road were helpful/useful. The respondents were shown the picture sequence from the lowest speed to the highest speed, from the most helpful/useful to the least helpful/useful. On the curved road, the mean rank from WarningSign + Max 40 + Chevron was less than mean rank from WarningSign + 40SL + Chevron. This suggests the WarningSign + Max40 + Chevron was perceived as inducing the lowest speed. However, the Mann-Whitney test showed the p-value would be greater than .05, showing that the rank for WarningSign + Max40 had no significant difference from WarningSign + 40SL + Chevron. This result is in accordance with the driving behaviour result and thus confirms that perceptions affect behaviour. A Wilcoxon signed-rank test showed that WarningSign + Max40 +

Chevron was perceived as the most helpful/useful of the seven road signs on curved road (Z = -3.188, p < .01).

On the rural single carriageway with a cycle lane, the mean rank from CycleWarningSign + MaxSpeed50 showed it was perceived as the lowest speed and CycleWarningSign + SL50 was perceived as the most helpful/useful sign of the six. However, the Mann-Whitney test showed the rank for CycleWarningSign + 50SL was not significantly different from CycleWarningSign + MaxSpeed50 in terms of both speed and helpful/useful.

On the rural single carriageway, the mean rank showed that CycleWarningSign + SL60 was perceived as inducing the lowest speed and as the most helpful/useful sign of the six. For the ranking of speed and helpful/useful, the Mann-Whitney test showed the rank for CycleWarningSign + 60SL had no significant difference from CycleWarningSign + MaxSpeed60.

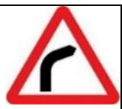
7.5.5 Task 1 - Open questions results

For each group of road signs, respondents were asked the following open questions: which sign is the most credible and which sign is the least credible on this road? Which sign makes you feel most safe on this road? Which sign is not appropriate on this road? Respondents also explained the reasons for each question. The open question results are grouped in a rational way for 40mph road sign in Table 7-4, 50mph road sign in Table 7-5, and 60mph road sign in Table 7-6. The number in the following table shows the number of respondent out of total 34 respondents. For each row, the highest number indicate the common choice of the statement.

- **40mph road sign on rural single carriageway curved road**

Table 7-4: Number of participant opinions' result for road signs on rural single carriageway curved road (Totally 34 participants)

Sign	40 SL	① Warning Sign	② Warning Sign+ Max 40	③ Warning Sign+40 SL	④ Warning Sign+Chevron	⑤ Warning Sign+Max 40+Chevron	⑥ Warning Sign+40 SL+Chevron

							
It is a credible sign	1		11	2	2	16	10
It is not a credible sign	4	10	2	1	2		3
It provides safety feeling	1	1	1	1	1	6	7
It is an appropriate sign	2	1	1	1		1	2
It is not an appropriate sign	5	7	2	4			2
It does not provide enough information	3	6	1	1	1		
Never seen these signs combination before				2			
Too much information/ overload/			1		2	4	6
Uncertainty					1		

Speed limit signs are enforceable:

> "Giving the speed limit on the sign encourages drivers more to obey it. "
>
> "Speed limit in the red circle always more effective for me."
>
> "Credibility depends on what road conditions are coming up after the sign. But I cannot see beyond the curve so I trust to the sign to advise me of what is coming beyond my field of view. Hence they are all credible potentially. No signs are appropriate as this depends on road afterward."
>
> "I am not sure if I listen as much to the "max speed" signs as much as a clear speed limit sign. Normal signs seem more official to me. "

> "40 means max speed 40, but spelling it out could help."

Non-credible:

For the warning sign only, "Feel least credible because curve is obvious and no speed limit."

Safety feeling comes from mandating speed limit sign and the sign does not indicate any hazard ahead, signs not indicate hazard ahead which makes people feel safe. signs indicate hazard ahead which make people feel unsafe.

> "The chevrons make it appear more dangerous so I could be more nervous about taking a corner of 40 with lots of warning signs."

> "I think chevrons can make people feel unsafe and panic a little bit and overthink which could be dangerous."

> "Sign 6 would make me feel the most safe as other drivers would be limited to 40mph too."

> "Sign 0 could be dangerous as drivers might not realise the road had a curve."

Not enough information

> "Simple images such as a curved sign do not encourage drivers to stick to the speed limit but act as a warning instead."

Too much information/ Overload sign

> "It causes distraction even if chevron indicates the severity of the bend, there is no need of duplication for chevrons. "

> "really sharp bends or S sharp bends need that"

> "The others depend on severity of the curve, and conditions of the road: adverse camber, severe drop, other hazards"

> "chevron is helpful especially if the curve is a long one." Chevrons-good for making people want to slow down.

> "The chevrons would indicate to me that the curve is more dangerous due to the condition of the road. If it is just a 200m curve then chevrons are overkill."

- **50mph road sign on rural single carriageway with a cycle lane**

Table 7-5: Number of participant opinions' result for road signs on rural single carriageway with a cycle lane (Totally 34 participants)

Sign	50 SL	⑦ CycleWarningSign + 50 SL	⑧ OncomingWarningSign + 50 SL	⑨ MaxSpeed 50	⑩ CycleWarningSign + MaxSpeed 50	⑪ OncomingWarningSign + MaxSpeed 50
						
It is a credible sign	6	11	3	1	16	2
It is not a credible sign	4		4	7	1	10
It provides safety feeling	3	8	2	1	8	1
It is an appropriate sign	2	1	3			
It is not an appropriate sign	3	2	13	8	1	6
It does not provide enough information	2			2		
Never seen these signs combination before/unusual		1	2	3		
Too much information/ overload/						
Uncertainty		1		1	2	

Credibility evaluation.

Present Cycle warning sign is the most credible road sign from the result. Cycle warning sign provides the reasons that encourages drivers to be aware of cyclists and thus slow down. One respondent raised the opinion that speed limit setting on the road with a cycle lane depends on the roads' history of previous accidents involving cyclists.

Warning of traffic both directions is assumed as non-credible signs (sign 8 and sign 11). There is no need to warn two directions because of obvious oncoming traffic. some driver confused the oncoming sign-directional traffic warning. Other statements about non-credible oncoming warning sign are:

> "the bigger risk is cycles more that oncoming traffic."
>
> "Can see there is a cycle lane marked but nothing on the sign to act as a reminder."
>
> "makes me feel I should look out for oncoming traffic & not cyclists."
>
> "Sign 9 is the least credible as it may result in drivers passing cyclists too quickly. "

More respondents perceived CycleWarningSign + MaxSpeed50 as more credible than CycleWarningSign + 50 SL although max speed 50 is slightly more unusual than the normal 50mph speed limit. However, some respondents raised the opinion that 50 speed limit itself is more important due to safety issues:

> "50 Speed limit most safety, it limits your speed but no warnings, making me feel there is nothing to worry about "
>
> "For cycle lane, inappropriate to have non-enforceable limits."
>
> "I feel safest with signs that express the speed limit in round red signs (0,7,8) because these seem more official"

One respondent raise the opinion that there is no need for the cycle warning sign

> "Cycle warning is unnecessary as the lane is quite clearly painted on the road. Max speed feels like a suggestion rather than the law. It would encourage me to go slower than 50 but I wouldn't necessarily trust that other people would."

Safety evaluation

Safety feeling comes from Cycle warning sign as mentioned mostly in the statements:

> "safest with the limit I would slow down and also know why."
>
> "Provides all information needed to advice drivers of changing conditions that indicates cycle lane use"

“It gives that extra prompt to be aware of cyclists + tells you the max speed.”

“most safe as you know there is 2-way traffic and warning of max speed”

Sign 7, as it should stop drivers passing cyclists too quickly. As then drivers have been sufficiently warned about cyclists.

Not appropriate Signs

“as the warning sign isn’t very helpful.the arrows aren’t necessary as it is obvious to the driver there is two-way traffic on the road.”

“8/11 not appropriate, single carriageway & speed limit. Not the right reason for the speed limit.”

“Sign 11 would be odd to me, as naturally you would always expect cars to be coming the other direction and there is no reason to suggest it is a dual carriageway.”

- **60mph road sign on rural single carriageway**

Table 7-6: Number of participant opinions' result for road signs on rural single carriageway (Totally 34 participants)

Sign	60 SL	⑫ CycleWarningSign+ 60 SL	⑬ OncomingWarningSign+ 60 SL	⑭ MaxSpeed 60	⑮ CycleWarningSign+ MaxSpeed 60	⑯ OncomingWarningSign+MaxSpeed60
						
It is a credible sign	9	12	6	1	12	3
It is not a credible sign	4	3	7	15	3	5
It provides safety feeling	2	6	3		6	1
It is an appropriate sign		1	1	1		
It is not an appropriate sign		1	3	5		4
It does not provide enough information	1		1	1		
Never seen these signs combination before/unusual				1		1
Too much information/ overload/						
Uncertainty			1			

Credibility evaluation. Max speed 60 is evaluated as the most non-credible speed limit by most of the drivers. That might because it is assumed as not familiar sign or uncommon sign on the current road. Familiar signs are easily assumed as a credible sign.

> "I think it was the colour red that alerted me to the fact that I needed to watch my speed here possibly because the limit of 60mph seemed quite high for a single carriageway road."

"Should never see a non-enforceable 60mph limit."

"I would again say that the word max would slow me down most but the sign could be hard to read."

"This depends on what the road is like. If there are a lot of cyclists using this particular road, then option 12 should be used. Otherwise option 0 would suffice."

"The least credible sign is number 14, as I'd only expect to see a max speed sign where drivers temporarily should reduce their speed, such as on a bend in the road."

Useless sign or uncertainty sign may cause distraction during driving

"I generally find having a hazard triangle as in 13 and 16 will get my attention even if it is telling me redundant information."

"The cycle sign confused me as there was no cycle lane. As a driver seeing a cycle above the speed limit didn't make the likelihood of encountering a cyclist obvious to me I would preferred words as well."

For the two warning sign comparison, whether present cyclist warning sign or present oncoming vehicle warning sign is a debatable issue. Some drivers need directional traffic warning while others perceive cyclist need to be considered first.

"If a cycle lane or cycle traffic is part of this, road signage needs to indicate this as drivers often do not see or consider cyclists, especially if they are used to driving at speed without cyclists present."

"I think the most important messages on this road are the cyclists followed by the speed limit and then the approaching traffic."

"You might if going from barrier between the lanes to none then might need the both way signs, otherwise not."

From the result, more respondents perceived cycle warning sign was more credible than oncoming vehicle warning sign. The national speed limit sign was more acceptable than max speed 60 sign. The signs should indicate facts on the road rather than suggestions. On the rural road without a cycle lane, the triangle warning sign should be set based on the real situation such as whether there are many cyclists appeared on the road or whether the single carriageway was located just after the dual carriageway.

In summary, the open question results have given useful information and guidance on how to set credible road signs on newly built roads which might have the same road layout as the tested roads. For 40mph road sign on rural single carriageway curved road, Warning Sign+Max 40+Chevron is the most credible sign among the other road signs. For 50mph road sign on rural single carriageway with a cycle lane, CycleWarningSign + MaxSpeed50 is the most credible sign. For 60mph road sign on rural single carriageway, CycleWarningSign+60 SL is the most credible sign. The open question results provide another evidence for the credible road sign. The results also provide individual perception of each sign although drivers may have different opinions on the same sign. Although the credible road sign could not meet all of the participants' requirement, the common opinions are still useful.

7.5.6 Task 2 - Manual driving results

In the manual driving task, drivers were asked to drive along a rural single carriageway with road signs at the beginning of each road section. The road sections were specific road layouts including rural single carriageway with curve, rural single carriageway with cycle lane and normal rural single carriageway with road signs. The road layout began with a 2-mile rural filler road section (normal rural single carriageway with gentle bend), followed by road sections with normal speed limit signs (40mph, 50mph and 60mph), followed by road sections with intervention road signs. A 252m rural link was set between each road section. In total there were 8 road sections with 7 rural links between.

As there were too many intervention sign scenarios and the normal speed limit was tested at the beginning of the task, the driving order could not be fully counterbalanced. Before testing the manual driving speed, the order effect was tested. The spot speed at the middle of the seven rural links was used, because at that point drivers were unlikely to be influenced by the preceding or subsequent scenarios, as they could not see the next road sign or road layout. Figure 7-12 shows the mean spot speed at the middle point of the seven filler rural links. The paired T-test shows no statistically significant spot speed difference between the first order and the last order, and no consistent order trend. The mean driving speeds on the rural road layouts were tested as follows.

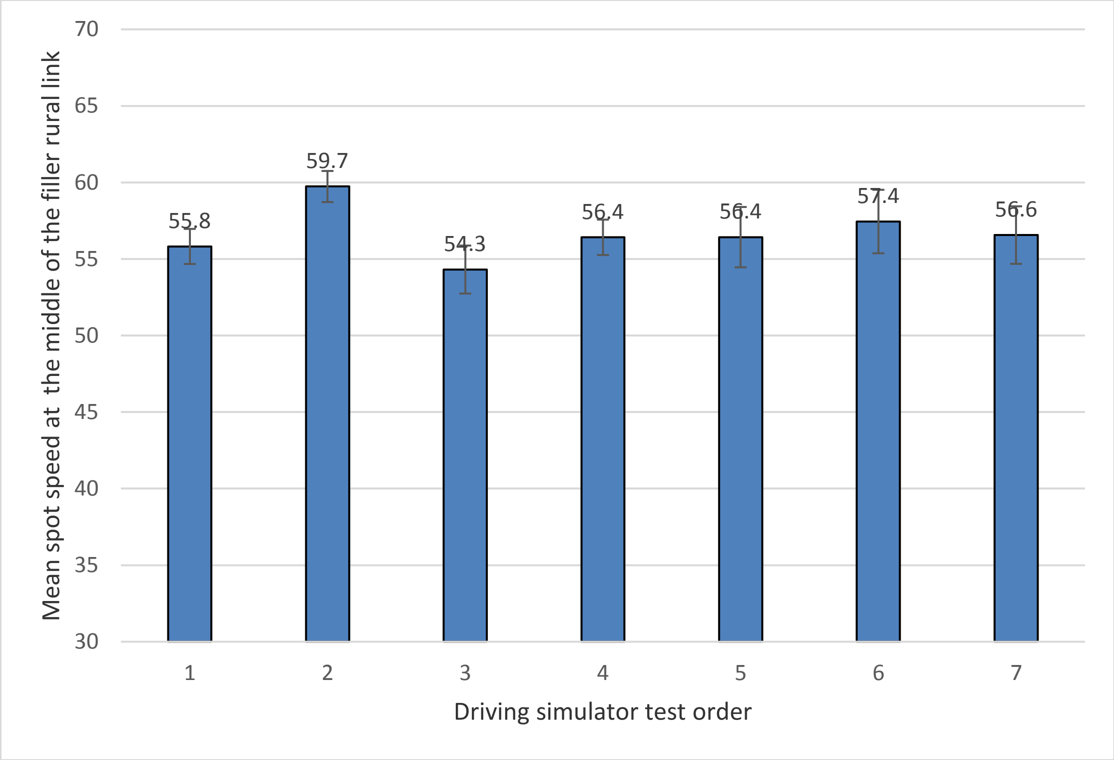


Figure 7-12: Order test for mean spot speed at the middle point of the rural link

Figure 7-13 compares the mean speed during the tested curves after passing each road sign. The tested curve was 504m long. The warning signs and information signs, as an intervention factor, were used to improve the drivers' compliance with the speed limit, evaluated by driving speed. Mauchy's test of sphericity indicated that the assumption of sphericity was violated (χ^2 (20) = 34.448, p = .024), and therefore, a Greenhouse-Geisser correction was used. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that the mean speed during the curved road section differed statistically significantly for seven road signs (*F* (4.322, 142.638) = 6.264, p = .000, η^2 = .160). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that mean speed for CurveWarningSign was statistically significantly higher than 40SL (p = .003), Warning + Max40 (p = .015), Warning + 40SL (p = .013), Warning + Max40 + Chevron (p < .001) and Warning + 40SL + Chevron (p = .001).

Driving speed was the lowest on the curved road with the 40mph speed limit, which was not significantly different from mean driving speed on WarningSign + Max40, WarningSign + 40SL, WarningSign + Chevron, WarningSign + Max40 + Chevron and WarningSign + 40SL + Chevron. Warning sign without speed limit information surprisingly increased drivers' speeds. Signs which involved chevrons did not change the mean speed significantly compared to signs without chevrons.

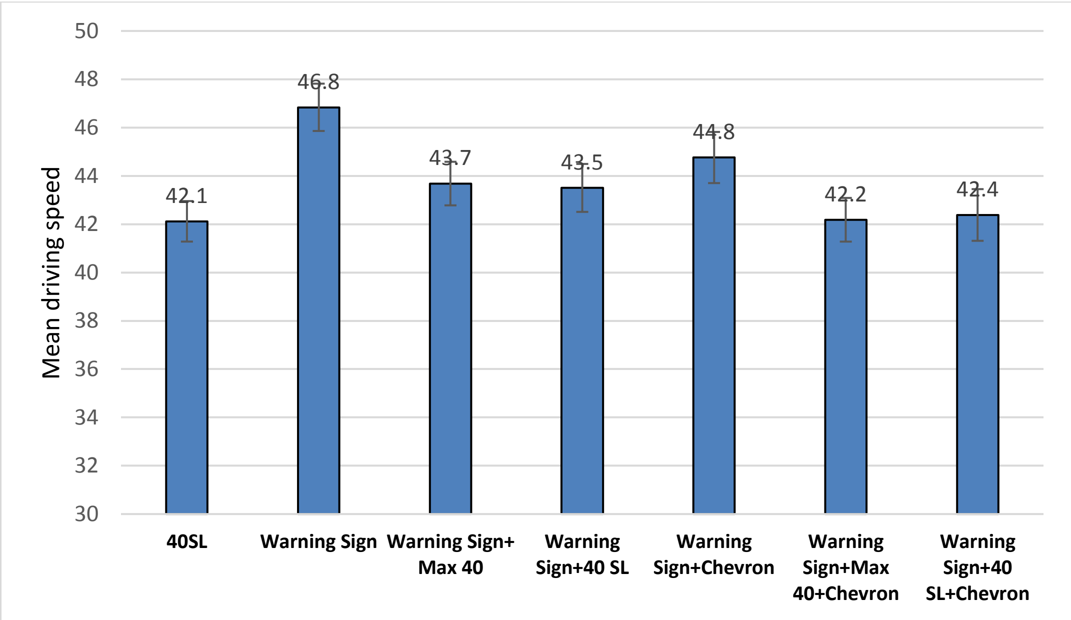


Figure 7-13: Mean driving speed on curved rural road

The percentage of time spent exceeding the speed limit for each road sign tested is presented in Figure 7-14. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that there was a significant difference among the seven road signs in terms of the proportion of time spent exceeding the speed limit (F (4.430, 146.181) = 4.325, p = .002, η^2 = .116). Post-hoc pairwise comparison analysis using the Bonferroni correction revealed that time exceeding speed limit proportion on 40SL was significantly lower than WarningSign (p = .020) but not significantly lower than other signs.

Comparing WarningSign with other signs, the paired T-test shows the proportion of time was significantly lower for WarningSign + 40SL (t (33) = 2.714, p = .010) and significantly lower for WarningSign + Max40 (t(33) = 2.552, p < .01). When chevrons were added, the proportion for WarningSign was significantly higher than WarningSign + Max 40 + Chevron (p < .01) and Warning Sign + 40SL + Chevron (p

< .01). However, there was no significant difference between WarningSign + 40SL and WarningSign + 40SL + Chevron, or between WarningSign + Max40 and WarningSign + Max40 + Chevron.

Comparing 40SL with WarningSign + 40SL + Chevron in terms of proportion of time spent exceeding the 40mph speed limit, the driving time spent exceeding the speed limit percentage generally declined but this was not statistically significant. For the proportion of time spent 10% and 20% over the speed limit, WarningSign + 40SL + Chevron was more effective than 40SL. It is not surprising that WarningSign and WarningSign + Chevron were the least credible, as they did not sufficiently slow people down or warn them about the curvature of the road.

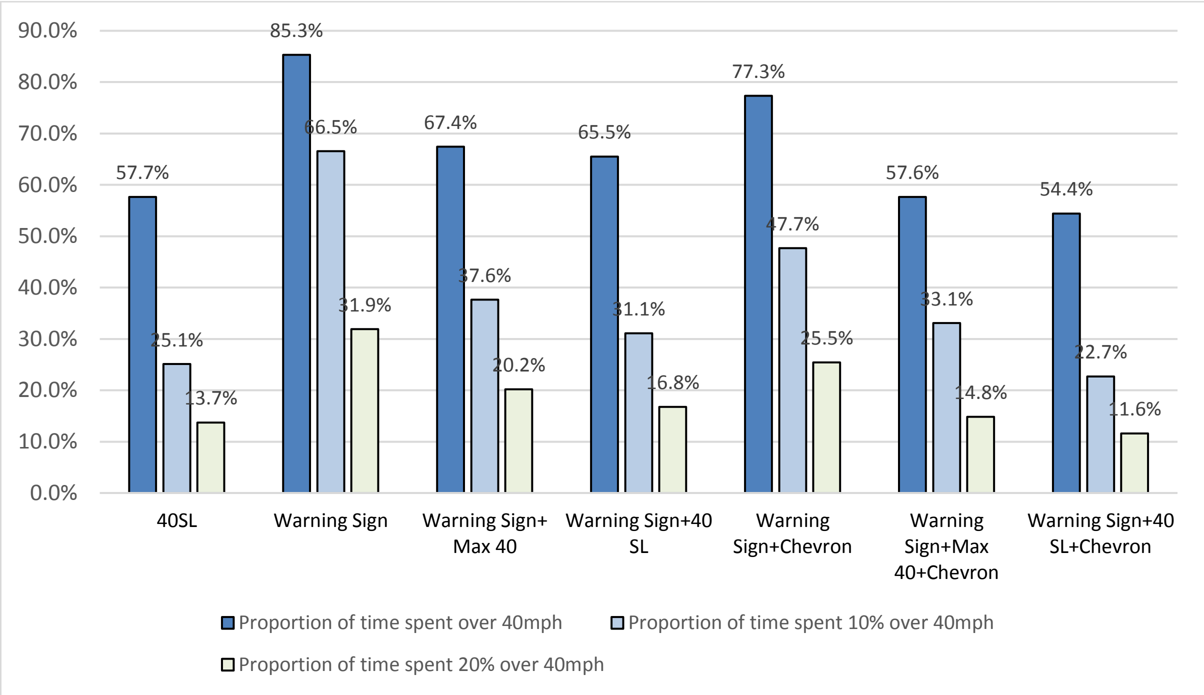


Figure 7-14: Proportion of driving time spent exceeding 40mph on rural curved road

Figure 7-15 compares the mean speed during the tested curves after passing each road sign. The rural straight road with a cycle lane was 756m long. A repeated measures ANOVA with a Greenhouse-Geisser correction determined that there was no significant difference between road sign groups on the rural single carriageway with a cycle lane (F (2.466, 81.374) = 2.584, p = .070, η^2 = .073) (see Figure 7-15).

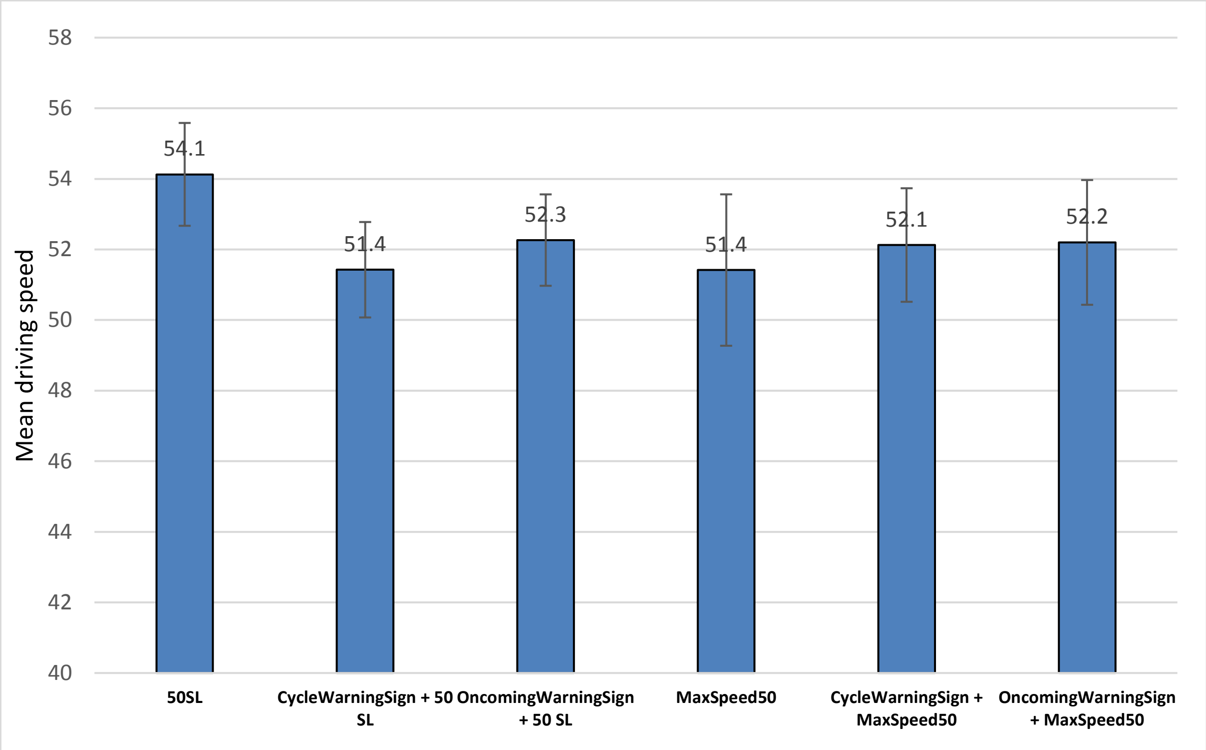


Figure 7-15: Mean driving speed on rural road with a cycle lane

The percentage of time spent exceeding the speed limit for each tested road sign is presented in Figure 7-16. A repeated measures ANOVA with sphericity assumed shows no significant difference between road sign groups for proportion of time exceeding 50mph (F (5, 165) = 0.659, p = .655, η^2 = .020).

Compared with 50SL, the driving time exceeding the speed limit percentage generally declined on CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50. For proportion of time spent 10% and 20% over the speed limit, both CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50 decreased the percentage.

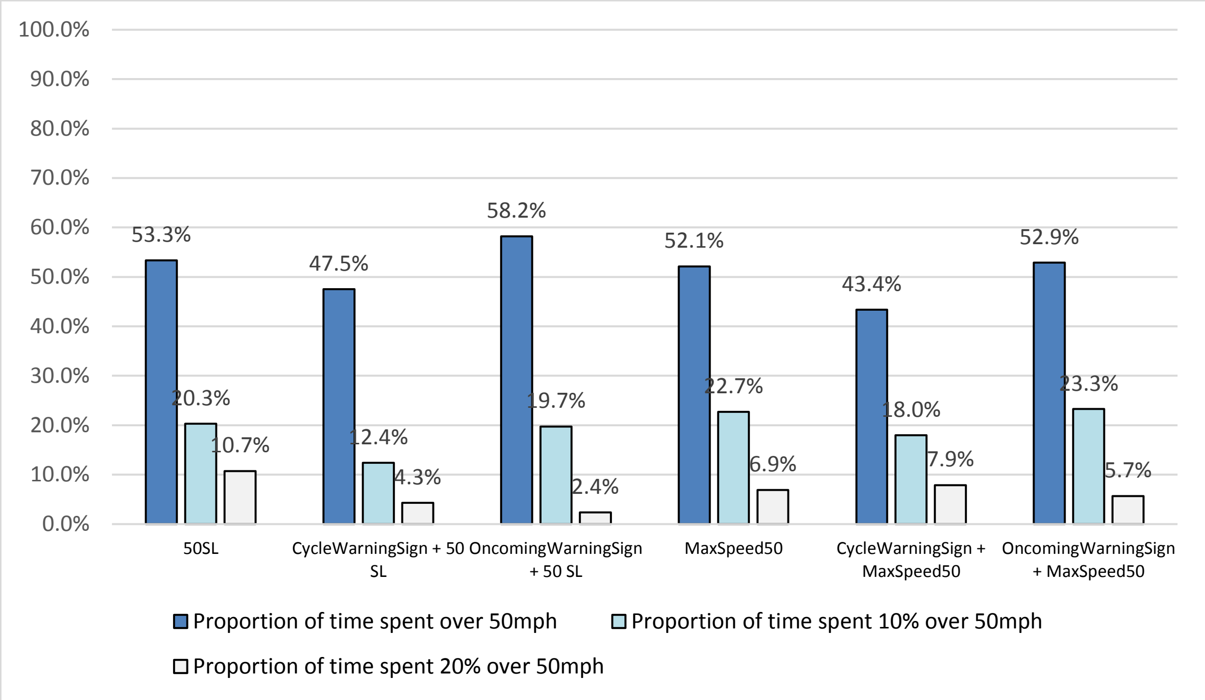


Figure 7-16: Proportion of driving time spent exceeding 50mph on rural road with a cycle lane

A repeated measures ANOVA with a Greenhouse-Geisser correction shows no significant difference between road sign groups on the rural single carriageway (F (2.466,81.374) = 2.584, p = .070). Drivers had the lowest mean speed on MaxSpeed60 but not significantly different from the mean speed with other signs (see Figure 7-17).

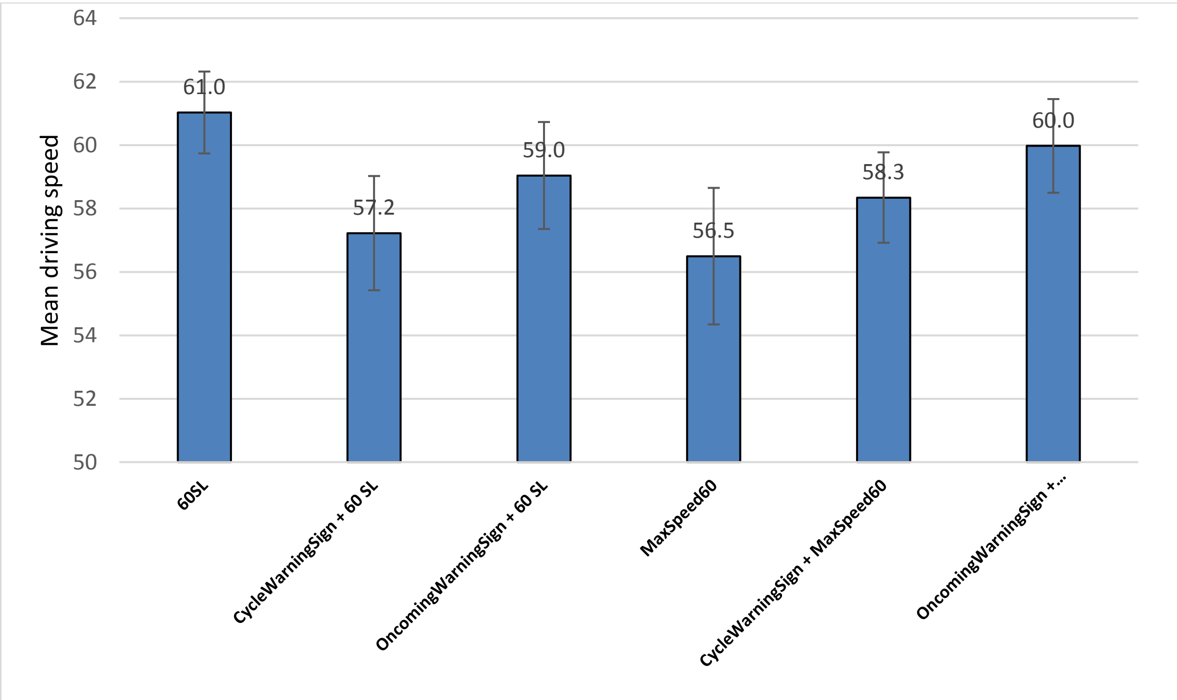


Figure 7-17: Mean driving speed on rural road

The percentage of time exceeding the speed limit for each tested road sign is shown in Figure 7-18. A repeated measures ANOVA with sphericity assumed shows no significant difference between road sign groups for the proportion of time spent exceeding 60mph (F (5, 165) = 0.283, p = .922, η^2 = .008). Driving time exceeding the speed limit generally declined on CycleWarningSign + 60SL. For the proportion of time spend 10% and 20% over the speed limit, all the warning signs worked effectively except OncomingWarningSign + MaxSpeed60.

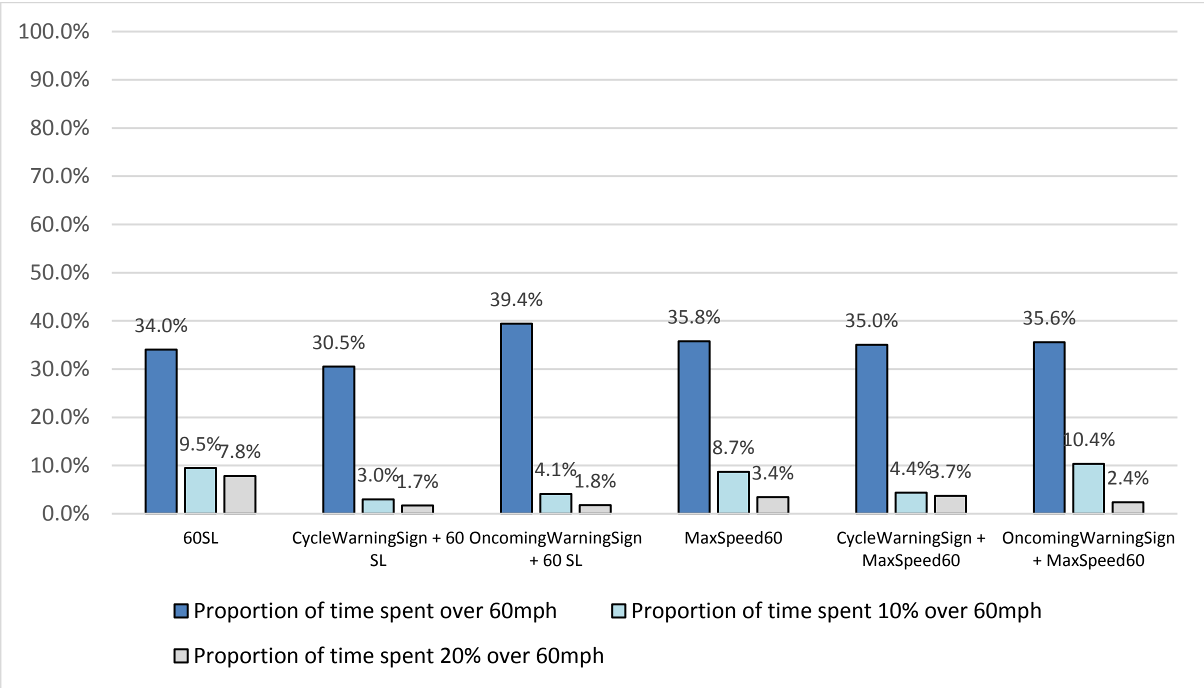


Figure 7-18: Proportion of driving time spent exceeding 60mph on rural road

7.6 Discussion

Generally, warning signs provide two main items of information, enforceable speed and warning of hazard. The use of hazard warning signs enables anticipatory avoidance behaviour in response to the signs rather than the driver's own judgement about possible aversive stimuli. For the three types of rural single carriageway, rural curved road, rural single carriageway with a cycle lane and rural single carriageway, the findings support the hypotheses that warning signs are effective in bringing credibility, safety and necessity perception. The most effective intervention sign which encouraged reducing driving speeds can be identified from the experimental results.

To be specific, signs inform the travelling public of the character of a curve. As drivers approach the curve, they slow down and negotiate the curve safety. On a rural curved road with a credible speed limit of 40mph, CurveWarningSign + Max40 is the most credible, most safe and most necessary road sign. The curve warning sign combined with the speed limit sign has been shown to encourage drivers to approach the bend at a safe speed and better comply with the speed limit. The combination WarningSign + 40SL + Chevron made drivers slow down the most (see Table 7-7).

Table 7-7: Effective treatment on rural curved road

<table>
<tr><td>Most credible sign</td><td>Best safety awareness sign</td><td>Most necessary sign</td><td>Sign encouraging lowest speed</td></tr>
<tr><td colspan="3">

Warning Sign+ Max 40</td><td>

Warning Sign+40 SL+Chevron</td></tr>
</table>

Cycling flows dictate the need for cycle infrastructure. When a cycle lane is provided, motorised traffic speed should be changed using warning signs. On a rural straight road with a cycle lane and a credible speed limit of 50mph, 50SL, CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50 have been shown to be the most credible, most safety inducing and most necessary road signs, respectively. For driving behaviour, CycleWarningSign has been shown to address the problem that cyclists might appear on the rural single carriageway where conventional signing is not effective to warn vehicle drivers. CycleWarningSign + 50SL and CycleWarningSign + MaxSpeed50 made drivers slow down most, particularly faster drivers who had some proportion of their driving time at 10% or 20% over the speed limit (see

Table 7-8).

Table 7-8: Effective treatment on rural straight road with a cycle lane

Most credible sign	Best safety awareness sign	Most necessary sign	Sign encouraging lowest speed
			
CycleWarningSign + 50 SL	CycleWarningSign + 50 SL	CycleWarningSign + MaxSpeed50	CycleWarningSign + 50 SL
			
CycleWarningSign + MaxSpeed50	CycleWarningSign + MaxSpeed50		CycleWarningSign + MaxSpeed50

On the rural straight road with a credible speed limit of 60mph, 60SL, CycleWarningSign + 60SL and CycleWarningSign + MaxSpeed60 have been shown to be the most credible road signs. 60SL is the most safety inducing sign while CycleWarningSign + 60SL is the most necessary road sign. CycleWarningSign + 60SL encouraged drivers to spend the lowest proportion of time over the speed limit compared to the other road signs (see Table 7-9).

Table 7-9: Effective treatment on rural straight road

Most credible sign	Best safety awareness sign	Most necessary sign	Sign encouraging lowest speed
			
CycleWarningSign+60 SL	60 SL	CycleWarningSign+60 SL	CycleWarningSign+60 SL
			
60 SL			

The national speed limit sign and maximum speed signs were perceived differently from other signs. Drivers perceived Max40 as more credible on the curved road while the normal speed sign, 50SL on the straight road with a cycle lane and 60SL on the straight road without a cycle lane, were more credible. Max speed 40 is an advisory speed which can be used on UK roads, but max speed 50 and max speed 60 do not exist in real road situations. This might be one reason for the respondents perceiving them as having low credibility and low safety and being less necessary. Therefore, national speed limit signs are assumed to have higher acceptability than max speed signs on rural single carriageways with cycle lanes and rural single carriageways.

The curve warning sign is shown to be credible on the curved road. On the straight road with a cycle lane, the cyclist warning sign is perceived as more credible. However, on the straight road without a cycle lane, the cyclist warning sign is no longer assumed to be credible. However, if the max speed 50 and max speed 60 signs are combined with the cycle warning sign, the credibility, safety and necessity rating scores all improve.

An interesting finding of this study is the consistency of the credibility, safety and necessity ratings with the intervention of signs. There is a close correlation between credibility, safety and necessity. For example, max speed 50 is shown to have low credibility, low safety and no necessity, as is the oncoming vehicle sign on straight roads. The oncoming vehicle sign is assumed not to be appropriate on the rural straight road unless changing from a dual carriageway to single carriageway. In addition, although the curve warning sign is credible, safe and necessary, it is not suggested that it should be used on its own. The curve warning sign should be combined with a speed sign to maximise its safety effect.

The experimental results show that road warning signs improve road safety. Taylor et al. (2000) state that on rural roads, the accident frequency is directly related to the proportion of drivers exceeding the limit — the higher this proportion, the more accidents occur. The experimental study proves that, by using road warning signs instead of normal speed limit signs, the proportion of exceedance of the speed limit can be reduced, thus, reducing the number of accidents. If drivers still exceed the limit threshold and no other information can be used on the roadside, an in-vehicle speed limit warning system could be used. Speeding drivers' perceptions and the reaction of in-vehicle warning systems on rural single carriageways need to be investigated further. There is a clear need for further development of this type of intervention.

In conclusion, the intervention sign increases traffic safety by decreasing mean speed and the proportion of time spent exceeding the speed limit, exceeding it by 10% and exceeding it by 20%. Careful use of intervention signs at specific sites is recommended. These effects are meaningful, in that small decreases in average speed relate to improved road safety. The result of the experiment can be interpreted as indicating that road warning signs are important and can help road operators reduce traffic accident mortality rates or accident-related injuries by redesigning signs for rural single carriageways at little cost.

Chapter 8 Conclusions

8.1 Summary of research experiments

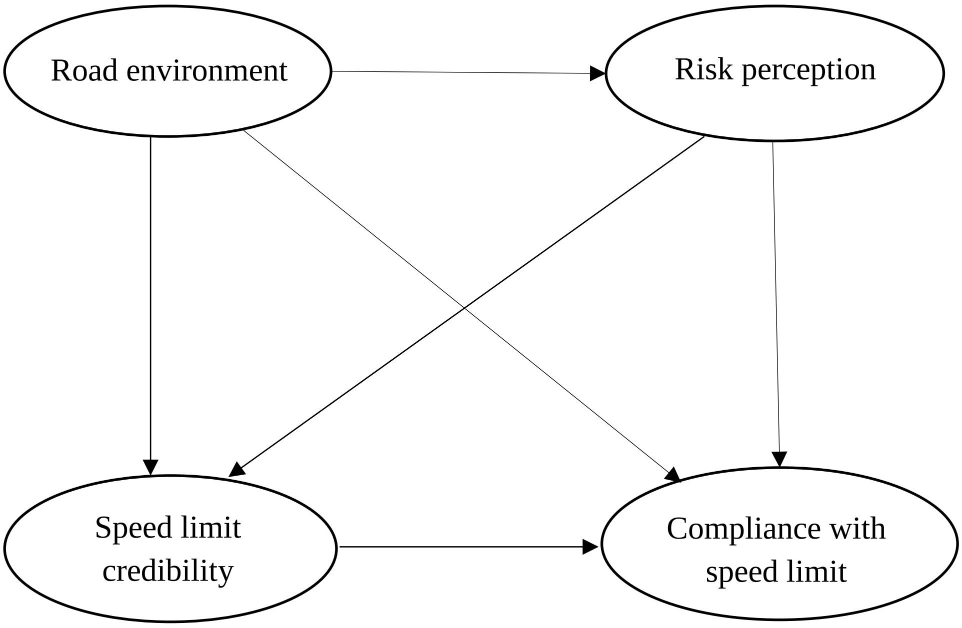


Figure 8-1: Research conceptual model

Overall, this research is a significant achievement, because there are some rather vague notions about the importance of credibility from SWOV (2012d). The research conceptual model has been confirmed and parameterised. A credibility index has been created along with investigating risk perception, which influences compliance.

In order to investigate the factors affecting speed limit credibility, it is necessary first to define what a credible speed limit is, and subsequently how to make drivers more compliant with the speed limit in a given road scenario. To accomplish this, the research conducted here has built an overall conceptual model (Figure 8-1). This model links road environment, risk perception, speed limit credibility and compliance with the speed limit, with each factor measured using both subjective and objective techniques. Credible speed limits are defined as the speed limits which are accepted by most drivers without the need for enforcement for a given road layout. Credibility is different from compliance. The relationships between each factor have been tested by quantitative analysis. The conceptual model is verified and achieved by means of three separate experiments.

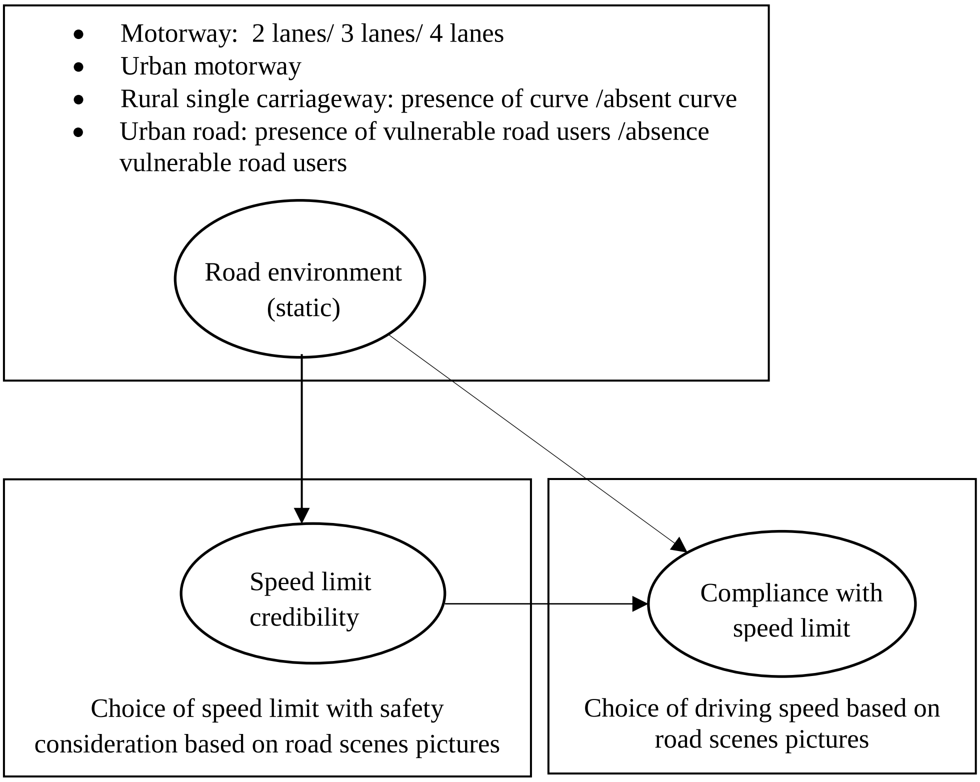


Figure 8-2: Conceptual model for Experiment 1

Experiment 1 investigated three objectives, shown in Figure 8-2: firstly, whether the current national speed limit is credible for current UK road environments (motorway, urban motorway, rural single carriageway and urban road); secondly, how road layout and roadside environment affect speed limit credibility; and thirdly, the difference between the perceived speed limit and choice of driving speed in given road pictures and the effect of demographic characteristics. The research results reveal that, firstly, a difference exists between drivers' perceptions of speed limit and the national speed limit. This illustrates that the national speed limit is not credible in specific road scenes, such as the 40mph national speed limit on an urban motorway such as the A58 (M), or the 60mph national speed limit on curved rural roads. Even on the same road type, road layout and the roadside environment factors are shown to affect the perceived speed limit and speed choice differently. For example, the number of lanes on a motorway affects the perception of speed limit and speed choice. 70mph is shown to be credible, and drivers more compliant on a 2-lane motorway than 3-lane or 4-lane motorways. It is not appropriate to have a 60mph limit in the presence of curves on a rural single carriageway. The 60mph limit lacked credibility and compliance in the presence of various risk factors on a rural single carriageway. A lower speed limit is suggested for curved roads. The presence or absence of VRU on urban roads affects the perceived safe speed limit and speed choice, with 30mph being more credible on urban roads without VRU. Secondly, there is a positive association between speed limit credibility and compliance with the speed limit. The more credible the speed limit, the more compliance. Thirdly, there is a large variation in speed limit choice and speed choice on rural single carriageways due to the presence or absence of curves, which shows that a single speed limit is not credible on rural single carriageways. Because rural single carriageways present greater risks than other road types, the focus of Experiment 2 is the evaluation of speed limit credibility and risk perception on these roads.

This study confirms the suggestion of Goldenbeld and van Schagen (2007), van Nes et al. (2007), and Aarts et al. (2009), based on studies of Dutch roads, that certain specific road and environment combinations influence the credibility of the speed limit and speed choice. Each specific road used in Experiment 1, in a UK context, had a different layout and roadside factors.

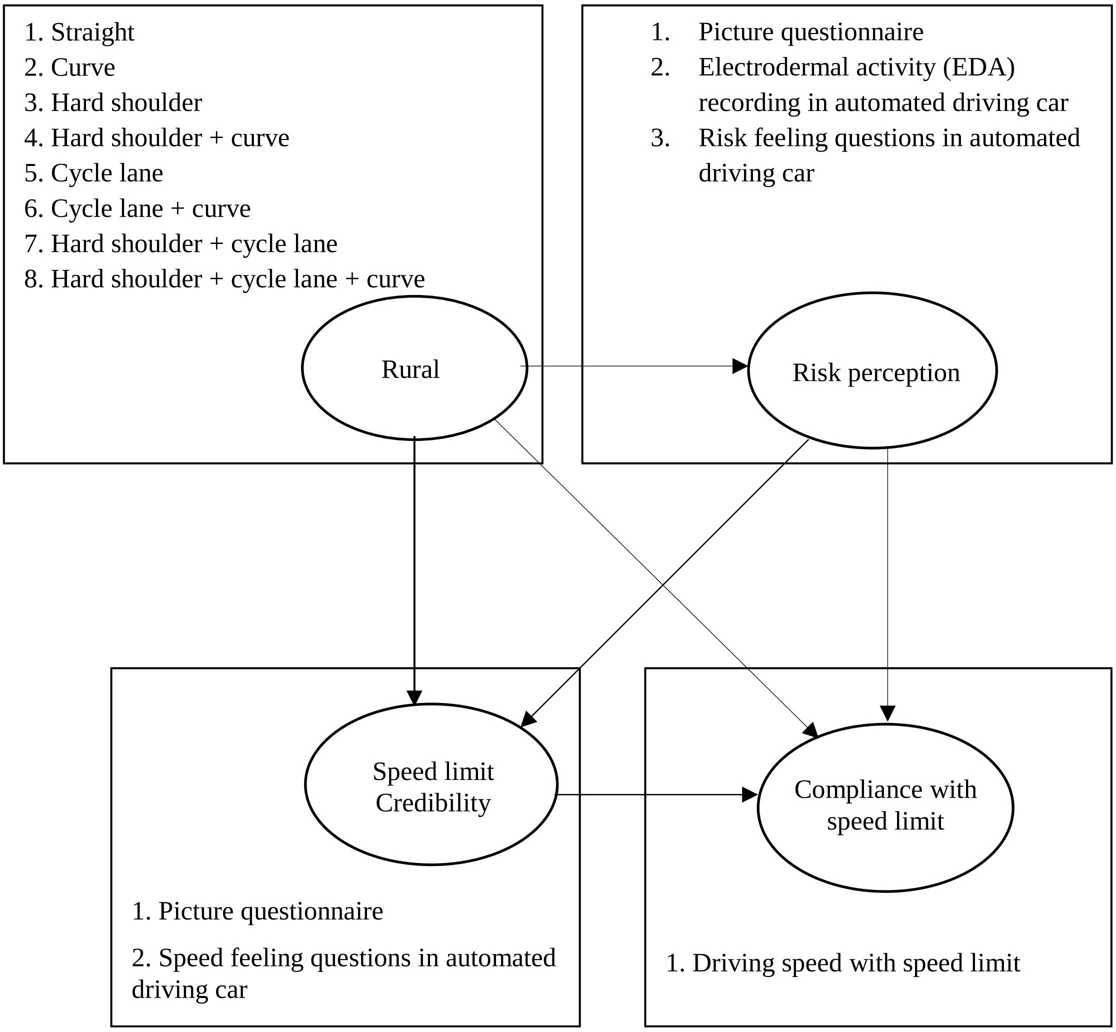


Figure 8-3: Conceptual model of Experiment 2

For Experiment 2, risk perception is added to the conceptual model. Experiment 2 investigated the main objective, focusing on setting a credible speed limit on a rural single carriageway and various measurements of credible speed limit. It investigated how single carriageway road layout and roadside environment factors affect speed limit credibility, subjective risk perception and compliance with speed limits (Figure 8-3). A picture questionnaire, a driving simulator in an automated condition and manual driving were used for the measurements. The speed limit credibility measurements are empirically derived from motorists' subjective perception. From the results, five indicators can be used as a checklist for setting a credible speed limit:

- First, the common choice of speed limit. Subjects have a common agreement on one speed limit which is appropriate and safe for each road scene.

- Second, the highest value of the credibility rating score. Subjects have comparable perceptions of high credibility.
- Third, automated speed rating as appropriate. Subjects have comparable feelings that certain driving speeds match given road situations (neither too fast nor too slow).
- Fourth, risk rating from feeling safe to very safe. Subjects' feelings about driving speed do not include any unsafe feelings.
- Fifth, lower skin conductance arousal. Subjects' have low levels of SCR arousal for each road scenario.

The five indicators together can lead to a credible speed limit for a specific road environment by picking the common choice of speed limit, a value which reflects the socially desired speed limit. A credible speed limit should be the common choice, have a high credibility rating, lead to appropriate speed feelings, lead to a safe feeling, and lead to a lower skin conductance. The results show that a 40mph speed limit is credible on rural curved road (radius 200m), a 50mph speed limit is credible on rural straight road with a cycle lane, and a 60mph speed limit is credible on a normal rural single carriageway. Harmonised speed limits are premised on the belief that road users' expectations are consistent with respect to appropriate speed choices. However, as the skin conductance factor is not directly related to setting credible speed limits, but is related to risk perception, the other four indicators, speed limit choice, credible rating, speed rating and risk rating, can be used as an effective checklist for setting a credible speed limit for a given road layout and roadside environment.

Experiment 2 investigated the relationship between speed limit credibility, risk perception and compliance with speed limit for a given rural single carriageway road layout and roadside environment. Multilevel regression and logistic regression analysis demonstrate that:

- As drivers perceive more risk in a given road environment, they tend to decrease their driving speed and obey the speed limit;
- The risk perception of a given speed has a negative influence on speed limit credibility; a non-credible speed limit is associated with a higher feeling of risk;

- As the speed limit becomes more credible, drivers are more compliant with the speed limit; more credible speed limits can make speeding drivers slow down, especially extreme offenders.

Experiment 2 confirms several issues which are in accordance with SWOV (2012d) research. Firstly, it is possible to choose a speed limit that is more credible for everybody. Secondly, credibility is a sliding scale from very credible to very non-credible. Thirdly, credible speed limits should result in drivers obeying (safe) speed limits better. Fourthly, where a speed limit is non-credible, the limit or the layout of the road or the environment should be changed. This research confirms the statement from ETSC (2010) that credible speed limits are expected to encourage drivers to keep to the limit. If a speed limit is not credible, there are two possibilities, either changing the limit or changing the layout of the road or surroundings.

Experiment 2 confirms that higher speeds in less demanding configurations might be due to lower perceptions of risk. Objective risk perception was measured using skin conductance, is in accordance with Taylor (1964) finding that subjective risk perception affects driving behaviour, also suggested by Fuller (1984), Ulleberg and Rundmo (2003), Rundmo and Iversen (2004), Fuller (2005), and Bella (2008).

Both Experiment 1 and Experiment 2 reveal that speed limit credibility and compliance are not identical. A speed limit can be perceived as too high or too low for a given road layout and roadside environment. The level of compliance is determined by road layout and roadside environment, risk perception and various other factors. When a speed limit is too high, the speed limit can have high compliance but low credibility, such as on a rural single carriageway with curves. Compliance is directly affected by speed limit credibility. Making a speed limit more credible can be achieved by changing the road layout or roadside environment.

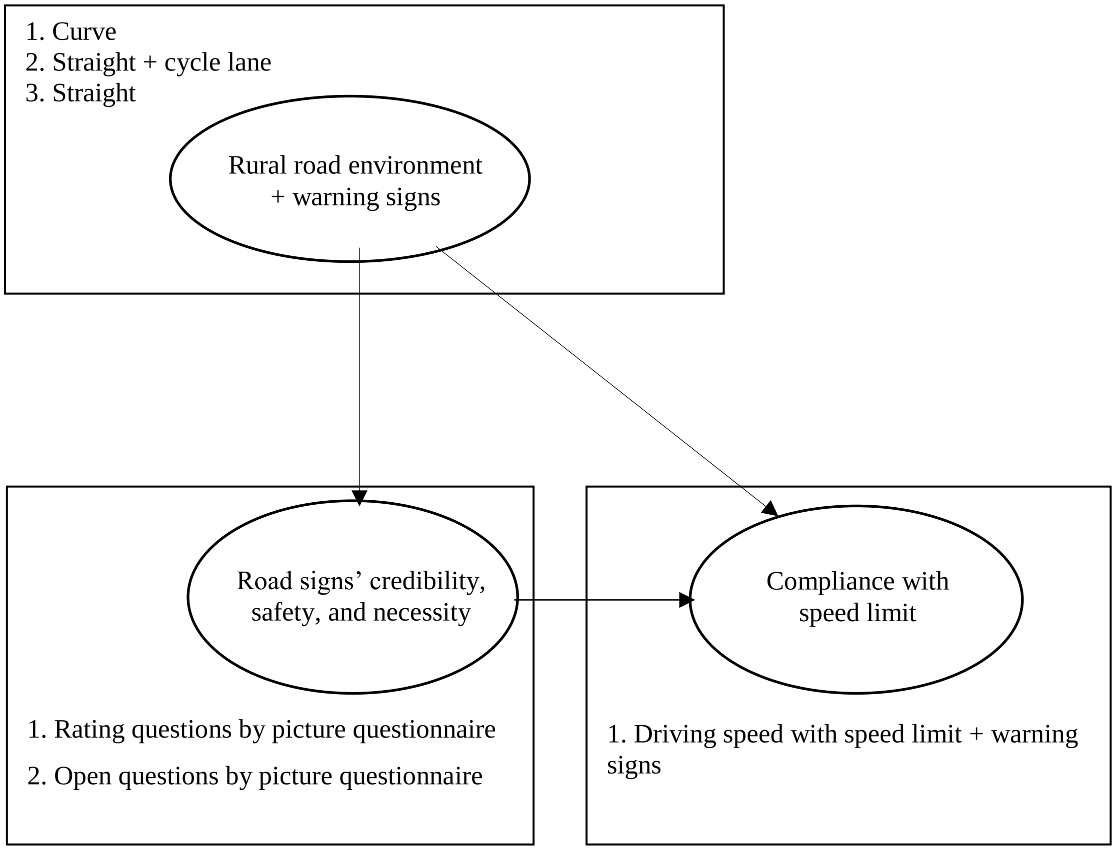


Figure 8-4: Conceptual model for Experiment 3

Experiment 3 investigated whether road warning signs affect perception and driving behaviour for a given road layout and roadside environment (Figure 8-4). It used a list of intervention measurements to improve driver compliance with speed limit, thereby meeting the research objectives. Road warning signs are justified if they change driver perceptions of the speed limit credibility, safety and necessity, and should be different from normal speed limit signs. The study shows that road warning signs do affect driving speeds, specifically by slowing down the driving speed and reducing the proportion of time spent driving in excess of the speed limit. The most effective warning signs make drivers more compliant with a credible speed limit. For example, a 40mph maximum speed limit sign combined with a curve warning sign leads to more credibility, and can therefore be applied to the four types of rural curved roads. An effective cyclist warning sign along with a 50mph speed limit sign is a credible road sign combination for a rural single carriageway with a cycle lane. The default national speed limit sign is the most credible road sign for a rural single carriageway. A cyclist warning sign can be used to warn vehicle drivers where appropriate. Combining the results of the three experiments, a research model is built linking the four factors (Figure 8-1). The findings suggest there exist more credible speed limits for specific types of road than the current national speed limit and it is possible to achieve better speed management by determining a limit that is more credible for most motorists. This research has practical implications for road design and makes recommendations for local highway authorities on matching credible speed limits to rural single carriageway infrastructure in order to provide safe conditions for all road users.

8.2 Guidance for road safety speed management

The results reveal that the most credible speed limit in a given rural layout is often lower than the existing national speed limit. A lower speed limit can meet the requirement of the Safe System by preventing serious or fatal injuries through effective speed management. Credible speed limit research provides evidence local highway agencies can use to achieve better speed management, mainly by changing guidance on speed limit setting to match road layouts and roadside environments. It is possible to determine a limit that is more credible for most motorists in a given road environment. Improving the credibility of the speed limit can improve road safety in the long run. Firstly, uniformity of the speed limit in a given road environment can minimise the standard deviation of speed choice, thus increasing safety and reducing the risk of vehicle collisions. Secondly, as lower speed limits are shown to be credible, the consequences of accidents can be mitigated. Injury can be limited through a forgiving road environment and anticipation of road user behaviour. These findings show a method that can support policy makers in the realisation of safe speeds and credible speed limits.

Speed management needs to target drivers at the top end of the speed distribution. Reducing the speed of the fastest drivers would bring great benefits for road safety. Setting credible speed limits can help achieve this goal. Such speed management would have a significant effect on speeding drivers. Road design integrated with credible speed limits could reduce both the average speed and the spread of speeds and, therefore, prevent intentional and unintentional speeding offences.

8.3 Guidance for road infrastructure

This research gives local councils and highway agencies evidence-based reasons for setting credible speed limits on rural single carriageways. The results suggest that certain road layouts and environmental features influence the speed limit's credibility (40mph, 50 mph or 60 mph). The results provide advice to local highway authorities on matching credible speed limits to rural single carriageway infrastructure, supported by evidence. Changing road infrastructure can improve all road users' safety. Road infrastructure needs to be changed where the roadside environment has enough space to accommodate a painted cycle lane of 2m and hard shoulder of 1m. For example, adding a cycle lane and a warning sign on a straight road is suggested to make a 50mph speed limit credible. For existing UK roads, a 60mph limit is not suggested for roads with a cycle lane or curved roads with a 200m radius. Setting more credible speed limits improves driver compliance. The suggestions for road infrastructure, credible speed limits and road signs for each type of road are listed in Table 8-1. The infrastructure system can affect driving positively, with better speed adaptation to speed limits and conditions. It can be expected to provide safer driving speeds with credible speed limits that improve safety for all road users.

Table 8-1: Road infrastructure suggestion for setting credible speed limits

	Road infrastructure	**Credible speed limit**	**Road signs**
Curve + Shoulder + Cycle Lane	Painted cycle lane 2m and hard shoulder 1m along the track	40mph is a credible speed limit	• 40mph maximum speed limit sign combined with curve warning sign can be applied to the four types of rural curved roads • Chevrons can be used but too many chevron boards may be counter-productive
Curve + Shoulder	Hard shoulder 1m along the track		
Curve + Cycle Lane	Painted cycle lane 2m along the track		
Curve only			

Credible road sign on rural single carriageway with curve

Road sign on rural single carriageway with curve, encouraging speed compliance

Shoulder + Cycle Lane	Painted cycle lane 2m and hard shoulder 1m along the track	50mph is a credible speed limit	• The effective cyclist warning sign and 50mph speed limit sign are a credible combination
Cycle Lane only	Painted cycle lane 2m along the track		

Credible road sign on rural single carriageway with cycle lane

Shoulder only	Hard shoulder 1m along the track	60mph is a credible speed limit	• The default national speed limit sign is the most credible. A cyclist warning sign can be adopted to warn drivers
Straight only			

Credible road sign on rural single carriageway

8.4 Limitations

When using a questionnaire methodology, conscientious responses are expected. However, it cannot be known whether respondents think question through fully before answering. For example, in Experiment 1, one respondent would have liked the driving speed to be 120mph on 3-lane motorway. Respondents skipping questions or making split-second choices may affect the validity of the data. Bias cannot be avoided in any sort of research. Participants in the survey may have had a particular interest in the questions. Such proclivities may lead to inaccuracies in the data which cannot be avoided. Low traffic flow was represented in the driving simulator, which cannot represent the real traffic flow situation on real roads.

The experimental design only investigated a rural single carriageway with three factors, a curve, hard shoulder and cycle lane, making eight road layout combinations in total. Other road layouts were not taken into consideration. In addition, the experiment did not involve cyclists' perceptions of speed limit credibility or behaviour. The interaction between cyclists and car drivers' perceptions and behaviours towards credible and non-credible speed limits might well repay investigation.

The research only focused on four parameters, affecting the model integrity. Other parameters could be tested to expand the existing model. Although compliance with speed limits is a wider topic which is not only affected by road layout and the roadside environment, speed limit credibility and risk perception, the other factors affecting speed choice have not been taken into consideration in this study. Driver personality and attitude and how they affect each of the parameters has not been taken into consideration in this research.

In practical terms, it is insufficient to ask only whether speed limit credibility has an effect on road safety; how imposing a credible speed limit improves road safety is the issue in real traffic situations. For example, when a credible speed limit sign is presented in a real road situation, the mean speed and variation in speed could be collected and compared with the previous situation with a non-credible speed limit sign. The attitude towards and satisfaction with the new sign could be investigated.

8.5 Guidance for further research

This research has justified various measurements of credible speed limit based on experimental evidence. As skin conductance has not been identified as decisive among the five indicators, the other four, speed limit choice, credible rating, speed rating and risk rating can be used as a toolkit for assessing and setting credible speed limits on motorways, urban motorways and urban roads in the future.

For motorways and dual carriageways, the design of new road cross-sections can be tested by applying the same methodology. The test speed limit should be the national speed limit, along with a higher and lower speed limit. For urban motorways, constructed in built-up areas, space constraints should be considered in cross-section design. A speed limit of 40mph is not credible on an urban motorway such as the A58(M). Considering the engineering design standards for urban motorways, if the entry ramp is long enough to accelerate before merging into traffic and there is enough distance between motorway entry and exit to avoid weaving, a higher speed limit e.g. 45mph or 50mph is suggested for testing.

For urban roads, mixed road users are the main factor to be taken into consideration. When motor vehicles, non-motorised vehicles and pedestrians need to use the same type of the road, their perceptions of speed limit credibility may differ from each other. Different speed limits can be proposed for the perception and behaviour tests.

For a rural single carriageway with a cycle lane, there needs to be evaluation of whether lower credible speed limit signs encourage non-cyclists to cycle and existing cyclists to cycle more. Cycle rate can be compared before and after credible speed limit signs are implemented. A cycle lane with a lower speed limit is expected to affect drivers' behaviour.

In order to investigate various road users' interactions, perceptions and behaviours, a driving simulator could be integrated with a bicycle simulator and a pedestrian simulator to test the interaction under various speed limit conditions. Future studies could use eye tracking to investigate what information drivers focus on while making judgements, when presented with various types of road signs. Future work could further validate, calibrate and develop the conceptual research model.

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Appendix

Algorithm of boosted decision tree

Gradient tree boosting is typically used with decision trees (especially CART trees) of a fixed size as base learners. Friedman (2001) proposed a modification to gradient boosting method which improves the quality of fit of each base learner.

Generic gradient boosting at the m-th step would fit a decision tree $h_m(x)$ to pseudo-residuals. Let J_m be the number of its leaves. The tree partitions the input space into J_m disjoint regions $R_{1m}, \ldots, R_{J_m m}$ and predicts a constant value in each region. Using the indicator notation, the output of $h_m(x)$ for input x can be written as the sum:

$$h_m(x) = \sum_{j=1}^{J_m} b_{jm} \mathbf{1}_{R_{jm}}(x),$$

where b_{jm} is the value predicted in the region R_{jm}.

Then the coefficients b_{jm} are multiplied by some value γ_m, chosen using line search so as to minimise the loss function, and the model is updated as follows:

$$F_m(x) = F_{m-1}(x) + \gamma_m h_m(x), \quad \gamma_m = \arg\min_{\gamma} \sum_{i=1}^{n} L(y_i, F_{m-1}(x_i) + \gamma h_m(x_i)).$$

Friedman proposed to modify this algorithm so that it chooses a separate optimal value γ_{jm} for each of the tree's regions, instead of a single γ_m for the whole tree. He calls the modified algorithm "TreeBoost". The coefficients b_{jm} from the tree-fitting procedure can be then simply discarded and the model update rule becomes:

$$F_m(x) = F_{m-1}(x) + \sum_{j=1}^{J_m} \gamma_{jm} \mathbf{1}_{R_{jm}}(x), \quad \gamma_{jm} = \arg\min_{\gamma} \sum_{x_i \in R_{jm}} L(y_i, F_{m-1}(x_i) + \gamma).$$

Experiment 1 Survey Questionnaire

Road and roadside environment Questionnaire

Surveyor: Yao Yao, PhD student from Institute for Transport Studies, University of Leeds.
Contact: ts12yy@leeds.ac.uk, +44 7405640222

- If there was no speed limit, how fast would you drive on the road section shown? Please feel free to enter your speed as an unrounded number (e.g. 62mph or 87mph)_________________
- What speed limit (mph) do you think would be safe here? choose one

10 20 30 40 50 60 70 80

- If there was no speed limit, how fast would you drive on the road section shown? Please feel free to enter your speed as an unrounded number (e.g. 62mph or 87mph) _________________
- What speed limit (mph) do you think would be safe here? choose one

10 20 30 40 50 60 70 80

- If there was no speed limit, how fast would you drive on the road section shown? Please feel free to enter your speed as an unrounded number (e.g. 62mph or 87mph) _________________
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- What speed limit (mph) do you think would be safe here? choose one

10 20 30 40 50 60 70 80

- If there was no speed limit, how fast would you drive on the road section shown? Please feel free to enter your speed as an unrounded number (e.g. 62mph or 87mph) ________________
- What speed limit (mph) do you think would be safe here? choose one

10 20 30 40 50 60 70 80

- If there was no speed limit, how fast would you drive on the road section shown? Please feel free to enter your speed as an unrounded number (e.g. 62mph or 87mph) ________________
- What speed limit (mph) do you think would be safe here? choose one

10 20 30 40 50 60 70 80

- If there was no speed limit, how fast would you drive on the road section shown? Please feel free to enter your speed as an unrounded number (e.g. 62mph or 87mph) ______________
- What speed limit (mph) do you think would be safe here? choose one

10 20 30 40 50 60 70 80

Your gender
☐Male ☐Female

Your age _________

Driving experience since passing the driving test
☐Less than 1 year ☐1 year ☐2 years ☐3 years ☐more than 3 years
___________years

Number of speeding tickets in past 3 years
☐0 ticket ☐1 ticket ☐2 tickets ☐3 tickets ☐more than 3 tickets

Experiment 2

Participant Information Sheet

Research on speed limit credibility.

Contact information for Yao Yao
Email: ts12yy@leeds.ac.uk
Phone: 07405640222
Contact information for Professor Oliver Carsten
Email: O.M.J.Carsten@its.leeds.ac.uk

Please read the following information carefully as it is important that you understand the purpose of this study and what the experiment will involve. Please do not hesitate to contact Yao Yao if you have any questions or concerns.

Please proceed only if you agree with the following statements:
You have to hold UK full driving license

1) **What is the purpose of the study?**

The aim of this study is to investigate how credible speed limit affected by road and roadside environment.
The experiments are carried out in a virtual reality situation in an advanced University of Leeds driving simulator.

2) **Why are you asking me to take part?**

We are looking for 32 participants with valid UK driving license to participate in the study. The total 32 participants' aggregate data will be further analysed.

3) **What will happen if I agree to take part?**

Once you have agreed to take part, we will arrange a mutually convenient date and time for your experiment. You need to come to the lab (University of Leeds Driving simulator Laboratory) in a given time. You have to read the Participant Information Sheet (this one) before the experiment and fill in the Consent form on the day of the experiment. Your personal information and data recording will be highly protected for your privacy.

4) **Do I have to take part?**

No, you should only take part if you wish to do so. Even if you agree to take part, you may change your mind at any time without giving a reason.

5) **What will happen on the day of the experiment?**

On the pre-arranged date you will need to go to the entrance of University of Leeds Driving simulator Laboratory (68 Hillary Place, Leeds, West Yorkshire LS2 3AR), where I will meet you and go through your consent forms.

During the experiment, first, you will look at road scenes pictures and answer questions. Totally there are eight road pictures and you need to answer questions. After a short rest, you will be seated in an automated driving simulator to feel the speed and feel the risk that automated car brings to you. At the same time, your Electrodermal activity for skin conductance will be recorded by BioPac MP35 Electrodermal activity sensor. The data of your skin conductive level and speed level will be recorded.

The total duration of the experiment will be approximately 80 minutes. This will allow for pre-experimental training, briefing, safety checks and the experiment itself. You are free to stop the experiment at any time.

6) What are the possible disadvantages and risks of taking part?

i. Driving simulator safety

There might be a small number of participants feel uncomfortable inside the driving simulator motion, especially driving through the curve. To avoid this, the participants will be observed by the monitor when they are in the task session. If participant feel uncomfortable in the study, the researcher will stop the work immediately.

ii. Electrodermal activity safety

In the experiment, physiological measurements of Electrodermal activity were used a recording system that involved placing electrodes on the fingers. To the index and middle fingers of the participant's non-dominant hand, with the sensor on the bottom of the fingertips. There is no risk involved in this measurement tools. The MP35 satisfies the Medical Safety Test Standards affiliated with IEC60601-1. The MP35 is designated as Class I Type BF medical equipment.

7) What if something goes wrong?

If you are concerned about any aspect of the study please contact Yao Yao, or Professor Oliver Carsten (contact details are provided above), who will do their best to answer your question.

8) Who is organising the study?

Yao Yao is a third year PhD student from Institute for Transport Studies. Professor Oliver Carsten is a Professor of Transport Safety in Institute for Transport Studies and is Yao Yao's supervisor.

9) Can you assure me of anonymisation?

Yes, the University of Leeds staff adheres to the Data Protection Act 1988. Any information that you give us and any data that we collect from you will be after your consent and will remain anonymous. We will store your paper-based consent forms in locked filing cabinets under the charge of University of Leeds and your electronic responses will be stored on the computer provided by University of Leeds and in the specific data storage drive i.e. N:\drive, which is password protected. All the data files will be encrypted and will not be accessible to anyone other than the lead researcher (i.e. me). The identity of each participant will be coded with numbers and original names will not be mentioned anywhere. Only lead researcher (i.e. me) will have access to the data collected by you.

The research do not collect your personal information data, such as your name, date of birth, education or job title etc. If the results of this study are to be presented or published by any conference, then it will be the merged and analysed data, i.e. the aggregation of all 32 participants together which in no case is identifiable for a single respondent. Your driving response' data will not be presented separately anywhere and will be completely anonymised. After finishing the degree, the merged data will be stored in University of Leeds data storage. Other researchers may use the data for further analysis in research and use in teaching, but after going through formal procedures of research ethics under the supervision of Research Ethics & Governance Committee of the University of Leeds (Ref. AREA 16-002), which if satisfied then may allow access to the aggregated data.

10) What if I have any concerns?

Please do not hesitate to contact us if you have any questions or concerns. Contact information is provided at the start of this document.

11) Who has reviewed this study?

This study was approved by the Research Ethics and Governance Committee of the University of Leeds.

12) Will my identity be disclosed?

All information disclosed within the experiment will be kept confidential, except where legal obligations would necessitate disclosure by the researchers to appropriate personnel.

13) What will happen to the information?

All information collected from you during this research will be kept secure and any identifying material, such as names, will be removed in order to ensure anonymity. It is anticipated that the research may, at some point, be published in a journal or report. However, should this happen, your anonymity will be ensured, although it may be necessary to use your words in the presentation of the findings and your permission for this is included in the consent form. You can withdraw you data at any time up till point of analysis and, if you wish to do so, you will need to provide the number that identifies you, as written on your consent form. However it must be noted that you can withdraw your data only up to the point of analysis. After the data has been analysed the withdrawal will not be accepted.

Thank you for reading this document.

Experiment 2 Consent Form

Consent to take part in: The research of speed limit credibility evaluation

	Tick if you agree with
I confirm that I have read and understand the information sheet ____________________ explaining the above research project and I have the opportunity to ask questions about the project.	
I agree for the data collected from me to be stored and used in relevant future research (in an anonymised form).	
I understand that relevant sections of the data collected during the study, may be looked at by researchers from the University of Leeds or from regulatory authorities where it is relevant to my taking part in this research. I give permission for researcher to have access to my records.	

Name of participant	
Participant's signature	
Date	
Name of lead researcher	
Signature	
Date*	

*To be signed and dated in the presence of the participant.

This PhD research project has University of Leeds Research Ethics approval (Ref. AREA 16-002).

Yao Yao

Email: **ts12yy@leeds.ac.uk**

Phone: **07405640222**

Experiment 2 Task 1 Questionnaire

Participant
ID____Time_______________

H-Rural Single Carriageway
What is the lowest speed limit (mph) you think would be **credible** here?
20 30 40 50 60 70 80
How do you perceive a 70mph speed limit on this type of road? Very Non-credible ____ Very credible
How do you perceive a 60mph speed limit on this type of road? Very Non-credible ____ Very credible
How do you perceive a 50mph speed limit on this type of road? Very Non-credible ____ Very credible
How do you perceive a 40mph speed limit on this type of road? Very Non-credible ____ Very credible
How do you perceive a 30mph speed limit on this type of road? Very Non-credible ____ Very credible
What are the reasons that you feel about the speed limit credible/non-credible?
Please evaluate the risk of crashing in the following situations:
What is the risk of your car <u>running off the road here</u>? Extremely low risk ____ Extremely high risk
What is the risk of your car <u>hitting the oncoming vehicle here</u>? Extremely low risk ____ Extremely high risk
What is the risk of your car <u>hitting the cyclist here</u>? Extremely low risk ____ Extremely high risk

Experiment 2 Task 2 Questionnaire

Participant ID__________________

1

How do you feel about the speed, does it feel? Too slow ____ Too fast
With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very Unsafe ____ Very Safe

2

How do you feel about the speed, does it feel? Too slow ____ Too fast
With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very Unsafe ____ Very Safe

3

How do you feel about the speed, does it feel? Too slow ____Too fast
With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very Unsafe ____ Very Safe

4

How do you feel about the speed, does it feel? Too slow ____ Too fast
With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very Unsafe ____ Very Safe

5

How do you feel about the speed, does it feel? Too slow ____ Too fast
With regards to the risk outcome of the current driving speed on this road, how safe would you feel? Very Unsafe ____ Very Safe

Experiment 3

Participant Information Sheet

Research on speed limit credibility and road signs affect your driving speed.

Contact information for Yao Yao
Email: ts12yy@leeds.ac.uk
Phone: 07405640222
Contact information for Professor Oliver Carsten
Email: O.M.J.Carsten@its.leeds.ac.uk

Please read the following information carefully as it is important that you understand the purpose of this study and what the experiment will involve. Please do not hesitate to contact Yao Yao if you have any questions or concerns.

Please proceed only if you agree with the following statements:
You have to hold UK full driving license

14) What is the purpose of the study?
The aim of this study is to investigate which road signs is more credible and how does the road sign affect your driving speed on UK rural single carriageway. The experiments are carried out in a virtual reality situation in an advanced University of Leeds driving simulator.

15) Why are you asking me to take part?
We are looking for 36 participants with valid UK driving license to participate in the study. The total 36 participants' aggregate data will be further analysed.

16) What will happen if I agree to take part?
Once you have agreed to take part, we will arrange a mutually convenient date and time for your experiment. You need to come to the lab (University of Leeds Driving simulator Laboratory) in a given time. You cannot be late. You have to read the Participant Information Sheet (this one) before the experiment and fill in the Consent form on the day of the experiment. Your personal information and data recording will be highly protected for your privacy.

17) What will happen on the day of the experiment?
On the pre-arranged date and time you need to go to the entrance of University of Leeds Driving simulator Laboratory (68 Hillary Place, Leeds, West Yorkshire LS2 3AR), where I will meet you and go through your consent forms.

During the experiment, you have two tasks.
Task 1, you will look at road scenes with road sign pictures and answer questions. The questions include your perception of each road signs in terms of credibility and safety on a given road condition. Totally there are 16 road sign pictures and you need to answer each questions.
Task 2, you need to have a manual driving on a given road. Drive normally, at your own speed.

The total duration of the experiment will be approximately 1 hour (maybe 75 minutes if you have driving practice at the beginning to test in case you have car sickness). This will allow for pre-experimental training, briefing, safety checks and the experiment itself. You are free to stop the experiment at any time. After complete the full experiment, you will receive £10 reward.

18) What are the possible disadvantages and risks of taking part?

iii. Driving simulator safety

There might be a small number of participants feel uncomfortable inside the driving simulator motion, especially driving through the curve. To avoid this, the participants will be observed by the monitor when they are in the task session. If participant feel uncomfortable in the study, the researcher will stop the work immediately.

19) What if something goes wrong?

If you are concerned about any aspect of the study please contact Yao Yao, or Professor Oliver Carsten (contact details are provided above), who will do their best to answer your question.

20) Who is organising the study?

Yao Yao is a fourth year PhD student from Institute for Transport Studies. Professor Oliver Carsten is a Professor of Transport Safety in Institute for Transport Studies and is Yao Yao's supervisor.

21) Can you assure me of anonymisation?

Yes, the University of Leeds staff adheres to the Data Protection Act 1988. Any information that you give us and any data that we collect from you will be after your consent and will remain anonymous. We will store your paper-based consent forms in locked filing cabinets under the charge of University of Leeds and your electronic responses will be stored on the computer provided by University of Leeds and in the specific data storage drive i.e. N:\drive, which is password protected. All the data files will be encrypted and will not be accessible to anyone other than the lead researcher (i.e. me). The identity of each participant will be coded with numbers and original names will not be mentioned anywhere. Only lead researcher (i.e. me) will have access to the data collected by you.

The research do not collect your personal information data, such as your name, date of birth, education or job title etc. If the results of this study are to be presented or published by any conference, then it will be the merged and analysed data, i.e. the aggregation of all 36 participants together which in no case is identifiable for a single respondent. Your driving response' data will not be presented separately anywhere and will be completely anonymised. After finishing the degree, the merged data will be stored in University of Leeds data storage. Other researchers may use the data for further analysis in research and use in teaching, but after going through formal procedures of research ethics under the supervision of Research Ethics & Governance Committee of the University of Leeds (Ref. AREA 16-002), which if satisfied then may allow access to the aggregated data.

22) What if I have any concerns?

Please do not hesitate to contact us if you have any questions or concerns. Contact information is provided at the start of this document.

23) Who has reviewed this study?

This study was approved by the Research Ethics and Governance Committee of the University of Leeds.

24) Will my identity be disclosed?

All information disclosed within the experiment will be kept confidential, except where legal obligations would necessitate disclosure by the researchers to appropriate personnel.

25) What will happen to the information?

All information collected from you during this research will be kept secure and any identifying material, such as names, will be removed in order to ensure anonymity. It is anticipated that the research may, at some point, be published in a journal or report. However, should this happen, your anonymity will be ensured, although it may be necessary to use your words in the presentation of the findings and your permission for this is included in the consent form.

Thank you for reading this document.

Experiment 3 Task 1 Questionnaire

In your experience, how **credible** is the road sign displayed on this road? Very Non-credible ______________________________ Very credible
With regards to the road sign on this road, how **safe** would you feel? Very Unsafe ______________________________ Very Safe
How **necessary** do you find the road sign on this road? Not at all necessary ______________________________ Very necessary

In your experience, how **credible** is the road sign displayed on this road? Very Non-credible ______________________________ Very credible
With regards to the road sign on this road, how **safe** would you feel? Very Unsafe ______________________________ Very Safe
How **necessary** do you find the road sign on this road? Not at all necessary ______________________________ Very necessary

In your experience, how **credible** is the road sign displayed on this road? Very Non-credible ______________________________ Very credible
With regards to the road sign on this road, how **safe** would you feel? Very Unsafe ______________________________ Very Safe
How **necessary** do you find the road sign on this road? Not at all necessary ______________________________ Very necessary

In your experience, how **credible** is the road sign displayed on this road? Very Non-credible ______________________________ Very credible
With regards to the road sign on this road, how **safe** would you feel? Very Unsafe ______________________________ Very Safe
How **necessary** do you find the road sign on this road? Not at all necessary ______________________________ Very necessary

In your experience, how **credible** is the road sign displayed on this road? Very Non-credible ______________________________ Very credible
With regards to the road sign on this road, how **safe** would you feel?

Very Unsafe	______________________	Very Safe
How **necessary** do you find the road sign on this road?		
Not at all necessary	______________________	Very necessary

In your experience, how **credible** is the road sign displayed on this road?		
Very Non-credible	______________________	Very credible
With regards to the road sign on this road, how **safe** would you feel?		
Very Unsafe	______________________	Very Safe
How **necessary** do you find the road sign on this road?		
Not at all necessary	______________________	Very necessary

Open questions:

Which sign is the most credible and which sign is the least credible on this road? Explain reasons.
Which sign make you feel most safety on this road? Explain reasons.

Which sign is not appropriate on this road? Explain reasons.

Which type of road sign encouraged you to have the driving **speed** below 50mph most? Please rank the following from the lowest speed to highest speed
Which type of road sign do you find most **helpful/useful** on these roads? Please rank the following from the most helpful/useful to least helpful/useful