Evaluating cycling infrastructure with large observational data

Caroline Jane Tait

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The following chapters contain jointly authored manuscripts where Caroline Jane Tait is the lead author:

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Abstract

Cycling is an important activity that can improve individual and population health as well as being an important form of active travel. Infrastructure that encourages people to cycle and protects them when cycling is vital to get more people cycling. Evaluating such infrastructure is difficult and there is limited evidence on what infrastructure encourages and protects cyclists. The current evidence base tends to consist of studies that are poor quality, contain limited exposure data, lack adjustment for confounders and utilise coarse outcome measures. They use small amounts of data (e.g. a single cycle lane), provide little information on the type (e.g. cycle lane segregation) and minimal data points before or after interventions.

This thesis addresses these research gaps in infrastructure evaluation by conducting high quality research that: differentiates between the different types of infrastructure; utilises large amounts of data both in terms of infrastructure but also exposure, outcomes and follow-up duration; and adjusts for confounders. It is composed of three papers that evaluate cycling infrastructure using large observational datasets in London, England. The first paper examines the cycling infrastructure that exists in this city whilst the others evaluate the impact of contraflow cycling, where cyclists can travel in both directions on a one-way street, on cyclist safety and participation. To achieve these aims this thesis uses various sources including the new London Cycling Infrastructure Database, road traffic crash datasets and crowd-sourced data.

This thesis demonstrates that there is no evidence that contraflow cycling in unsafe in the UK, contrary to widely-held beliefs, and that contraflow cycling can increase cycling participation. Wide-scale implementation of contraflow cycling may improve cycling routes and networks, cyclist safety and participation at relatively low cost. However, it also shows that cycling infrastructure is not distributed equally across London and may not be of the quality that provides safe space for cycling or that appeals to everyone. Global adoption of lower road speed limits may increase infrastructure compliance with national design standards but may not increase the quality of infrastructure for cycling. These findings have significant policy implications for national and local governments who wish to increase cycling participation. Making large datasets available to researchers could improve infrastructure evaluation but there needs to be awareness of the limitations of such data and analysis methods. Future research should focus on improving cyclist exposure data, examining cyclist infrastructure choices and incorporating qualitative assessments.

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List of Abbreviations

ASL	**A**dvanced **S**top **L**ine
ATE	**A**ctive **T**ravel **E**ngland
CI	**C**onfidence **I**nterval
CID	**C**ycling **I**nfrastructure **D**atabase
DfT	**D**epartment for **T**ransport
GB	**G**reat **B**ritain
OSM	**O**pen **S**treet **M**ap
TRO	**T**raffic **R**egulation **O**rder
TfL	**T**ransport for **L**ondon
UK	**U**nited **K**ingdom
WHO	**W**orld **H**ealth **O**rganisation

Chapter 1

Introduction

This thesis examines the evaluation of cycling infrastructure with large observational data. Part 1 of this introductory chapter explores the background, starting broadly with the history of cycling before narrowing its geographical focus to England and subject focus to cycling infrastructure and the evidence base for its effectiveness in terms of cyclist safety and participation. Part 2 of the Introduction builds on these foundations, developing the research rationale through highlighting the gaps in this evidence base. It describes the importance of data in evaluating such infrastructure and potential for London as a setting for such an evaluation. It then defines the thesis aim and research questions, linking the questions to the research gaps and outlining the principles that have underpinned the research. Finally it describes the research strategy, thesis structure and outputs.

The Introduction is followed by three chapters each containing a discrete piece of research that evaluates cycling infrastructure with large observational data. Chapter 2 (Paper 1) examines what cycling infrastructure exists in London using a new database and evaluates it against design standards. This paper has been published in the Journal of Transport & Health. Chapter 3 (Paper 2) examines the effect of a specific type of cycling infrastructure, contraflow cycling where cyclists can travel against the flow of motor vehicles on one-way streets, on cyclist safety using crash and casualty datasets. This paper has been published in Accident Analysis & Prevention. Chapter 4 (Paper 3) also examines the effect of introducing contraflow cycling but instead looks at cycling volume using crowd-sourced data. This paper is ready to submit to the Journal of Transport & Health.

Chapter 5 is the Discussion that brings the preceding chapters and research together into a coherent evaluation of cycling infrastructure with large observational datasets. It discusses the key findings, strengths, limitations, policy implications and research recommendations. Chapter 6 is the Conclusion.

Part 1: Background

Part 1 of the Introduction provides the background to this thesis. It focuses on cycling as a physical activity and mode of transport and the popularity of cycling in different countries before examining cycling in England, the country studied in this thesis. It considers the importance of cycling and why the English government appears to be keen to encourage participation before discussing approaches to getting more people cycling and their implementation in England. Having identified safety and infrastructure as key barriers for individuals taking up cycling, it discusses infrastructure and the evidence base around its effectiveness on cycling participation and safety, both actual and perceived.

1.1 The bicycle and cycling

1.1.1 History of the bicycle

The exact origins of the bicycle are unknown but it has been suggested that it was invented out of necessity for a horse-less form of transport in the 1800s in Europe (Malizia and Blocken, 2020). During that century, design advancements such as pedals, the indirect drive system, wire wheels and pneumatic tyres meant that the modern bicycle came into existence (Van Nierop et al., 1997; Malizia and Blocken, 2020). This evolution cemented the bicycle for utility and facilitated the popularity of cycling for recreation, touring and racing by individuals and groups (Ritchie, 1999; Oosterhuis, 2016). Cyclists were central to the development of roads suitable for bicycles (and subsequently cars) and improvements in road quality (Reid, 2015). Bicycles have evolved further with specialisations for different types of cycling such a racing or bmxing (Lindsey, 2022); transportation such as cargo bikes (Cox and Rzenwnicki, 2015); and adaptive bicycles that support those who cannot use conventional bicycles (Rodger et al., 2014). More recent innovations include bike sharing schemes (Fishman et al., 2013) and electric bikes (Fishman and Cherry, 2016).

1.1.2 Cycling popularity

Despite wide-spread popularity since its invention, in the latter twentieth century Western European and English-speaking countries have experienced different and diverging relationships with the pedal cycle. Oosterhuis (2016) describes three categories for such countries and argues that historical, social, cultural, political and national contexts are important. In the Netherlands and Denmark, cycling is ingrained into everyday life for people of all ages with collaboration between Government and cycle interest groups to develop pragmatic cycling policies and solutions (Oosterhuis, 2016). This was achieved by conscious decision-making in the 1970s to make cities more people-friendly and less car-friendly through changes to transport and urban planning (Pucher and Buehler, 2008). These decisions resulted in extensive cycling promoting activities including building physical cycling infrastructure (Goeverden et al., 2015). In the Netherlands, 27% of trips are made by pedal cycle (2005 data) and 2.5km cycled per inhabitant per day (2006) with the equivalent figures for Denmark being 18% (2001) and 1.6km (2006) (Pucher and Buehler, 2008). In contrast, in the USA, Britain, Canada and Australia cycling is predominantly recreational and undertaken by children or young-to-middle-aged males (Oosterhuis, 2016). Cycling policies and interventions are frequently opposed and a car versus cycle narrative exists (Oosterhuis, 2016). These governments have not prioritised public or active transport and there are low levels of cycle trips (1-2%) and distance travelled per capita (0.1-0.2 km per day) in these countries (Pucher and Buehler, 2008). Oosterhuis (2016) describes a third cycling culture that is found in France, Italy, Spain and Belgium. These countries have embraced the racing and recreational aspects of cycling, developing Grand Tours that are ingrained within the national psyche but have not necessarily had the infrastructure or policies to develop other types of cycling participation until recently (Oosterhuis, 2016). More information on cycling in Britain can be found in Reid (2015) who describes the development of roads and the important role that the bicycle and cyclists have played; Parkin (2018) who provides an overview of cycling policy, funding, legislation and planning; and Golbuff and Aldred (2011) who narrate a detailed, historical, description of cycling policy.

1.1.3 Epidemiology of cycling in England

In England, pre-COVID data shows that 8% of the population report cycling at least once a week for leisure and 6% for transport (DfT, 2022h). Despite these low overall levels, there are pockets of cycling success. For example, in Cambridge the respective figures are 20% and 51%, in Oxford they are 13% and 35% and in London the Boroughs of Wandsworth and Richmond-upon-Thames report the highest London percentages of 15% for leisure and 18% and 19% (respectively) for transport (DfT, 2022h). However, these figures do not give a picture as to who is cycling in England. There are significant differences in cycling between demographic groups. Being male, younger, white, without a physical disability, more educated or living with a child age 5-15 are predictors of cycling within the last month in England (Goodman and Aldred, 2018). Women, non-whites and those with a physical disability are half as likely to cycle, whilst women and older people are less likely to cycle for utility as opposed to recreational purposes (Goodman and Aldred, 2018). These demographic differences are not seen everywhere - there is evidence that there can be greater age and gender equity in areas of higher cycling prevalence (Goodman and Aldred, 2018).

1.1.4 Contemporary cycling policy in England

Prior to the COVID-19 pandemic, national policies had moved towards promoting cycling alongside walking as the preferred method of transport i.e. active travel (DfT, 2017) but these policies had been accused of being rhetorical, advisory and dependent on local government and individual change rather than forceful, directive and central government-led (Bloyce and White, 2018). The pandemic profoundly impacted transport, leisure and exercise and disrupted historical patterns of cycling and motor vehicle use (e.g. Hong, McArthur and Raturi, 2020; De Vos, 2020; Hadjidemetriou et al., 2020; Li et al., 2021). This presented new opportunities to challenge and change the status quo with the potential to embed active travel and increase greater cycling participation (Tirachini and Cats, 2020; Budd and Ison, 2020; Laverty et al., 2020; Musselwhite et al., 2021).

During the pandemic, England, in common with many countries across the world (Nikitas et al., 2021), introduced measures to make cycling safer and easier. These included funding for cycle repair vouchers, pop-up bike lanes, use of 'school streets', reducing speed limits, restricting access to motor vehicles, introducing modal filters, changing junction design and providing additional cycle parking (DfT, 2020f; DfT, 2020a). This was supplemented with new cycling infrastructure design standards (DfT, 2020d), policy documents (DfT, 2020c) and the establishment of Active Travel England, a government body charged with promoting active travel (DfT, 2021a; ATE, 2023a). In most countries a supportive government approach resulted in increased cycling (Kraus and Koch, 2021; Buehler and Pucher, 2022), predominantly in recreational rather than utility cycling (Buehler and Pucher, 2022). England saw large-scale pandemic cycling uptake with increases in the number of trips, individuals and average distance (DfT, 2021b). Recent data (2021) suggests that cycling in England has fallen back to pre-pandemic levels (DfT, 2022e).

Despite this recent set-back, the new policy ambition in England is to increase the percentage of short journeys that are cycled or walked to 50% by 2030 (DfT, 2020c) and to 55% by 2035 (DfT, 2023b). This represents a substantial challenge as currently around 27% of trips are walked and 2% of trips are cycled (DfT, 2020c). In addition to the measures and changes introduced during the pandemic, it is proposed that this will be achieved by: making better streets for cycling and people; enabling people to cycle and protecting them to do so; putting cycling at the centre of transport decision-making; and enabling, empowering and encouraging local highway authorities, as the organisations that own the majority of roads, to make this happen. The proposed funding to implement this policy was £3.6 billion (DfT, 2020c). This represents a fraction of the total transport expenditure (HM Treasury, 2021). However, the National Active Travel Commissioner has suggested that between £9 and £18 billion is required to reach these targets (Boardman, 2022). This funding has been recently cut to £3 billion (Reid, 2023; Norman, 2023).

1.1.5 Summary

The bicycle and its descendants have been used for centuries as a mode of transport and for leisure. However, the popularity of cycling varies by country influenced by historical, social, cultural, political and national contexts. Cycling in England is lower than other countries and predominantly undertaken by able-bodied, younger males. However, there are places where it is more popular, demographic differences are reduced and utility cycling is common. Opportunities seized during the pandemic increased cycling but this has not been sustained. Ambitions to increase cycling in England may be in jeopardy due to underinvestment despite new policies, standards and a standalone agency. It is essential that steps taken to achieve these ambitions are evaluated to understand effectiveness, ensure value for money and prioritise further investment.

1.2 The importance of cycling

But why is cycling considered to be important? Why did governments seek to take advantage of opportunities that the pandemic offered to promote and fund measures to increase cycling? This section examines why cycling is considered so important by organisations such as the World Health Organisation (WHO), what the benefits of increasing cycling can be and whether there are any pitfalls of promoting cycling.

1.2.1 Physical inactivity

Physical inactivity is directly attributable for up to 8% of worldwide non-communicable diseases such as heart disease, stroke, breast cancer, colon cancer and dementia and accounts for around 9% of premature deaths (Lee et al., 2012). It also contributes to disease risk factors such as high blood pressure and obesity. Worldwide, 1 in 4 adults do not meet current physical activity guidelines (WHO, 2018). In England, the figure is much higher with 34% of adults not meeting physical activity guidelines (2020/2021 data) (OHID, 2023). The higher prevalence in England is unsurprising as inactivity increases with economic development due to changing patterns of transportation (e.g. more people can afford to own cars), urbanisation (e.g. services and businesses are more accessible) and technological developments (e.g. less reliance on physical labour) (WHO, 2018).

In 2018, WHO published a global action plan to increase physical activity by creating active: societies, environments, people and systems (WHO, 2018). Cycling is specifically identified as being a core physical activity that is central to the plan. The plan states it must be prioritised through urban and transport planning policies, improved infrastructure, and improved road and cyclist safety; in addition to the cultural and societal changes required to ensure cycling can be chosen by all to increase their physical activity (WHO, 2018).

1.2.2 Individual benefits of cycling

Regular physical activity, such as cycling, is essential to maintain physical health and to prevent and manage non-communicable diseases. It promotes mental well-being and cognitive function and can improve confidence and self-esteem. It has been shown to enhance employment opportunities and reduce social isolation (DHSC, 2019). In addition to indirectly benefiting health as a form of physical activity, there is evidence that cycling *in itself* has direct beneficial impacts on health. These include reductions in all cause mortality, cardiovascular disease and type 2 diabetes plus improvements in cardio-respiratory fitness and disease risk factors such as obesity, high blood pressure and abnormal lipid profiles (Laird et al., 2018).

1.2.3 Population benefits of cycling

Beyond these individual health benefits, there are health, environmental, social and economic benefits to the wider population when people cycle (WHO, 2022). Firstly, there are reduced healthcare costs from physical inactivity. These are estimated to be £1 billion in direct costs (2007 prices) and £8.2 billion in indirect costs (2002 prices) to the National Health Services in the UK (Davies, 2014).

Secondly, economic benefits can accrue from increased cycling such as improved employee productivity in those who commute by cycle (Ma and Ye, 2019) and reductions in road congestion (estimated to cost $25 million per year to the UK) (CEBR, 2014), whilst improvements in street design result in positive value to retailers and businesses without negative impact on residential value (Carmona et al., 2018).

Thirdly, if people reduce their car use because they are cycling more, there are a number of environmental benefits. There are reductions in air and noise pollution that improve people's health (Laird et al., 2018). There are reductions in carbon dioxide emissions (Woodcock et al., 2009; CCC, 2018; Brand et al., 2021) which is particularly important as the transport sector (predominantly road) accounts for 35% of all UK emissions and has remained relatively static since 1990 (DfES & NZ, 2023). Another benefit is that the urban environment is more efficient and pleasant because cycling is a more space-efficient mode of transport in terms of road space and parking (WHO, 2022). Reductions in car use also have societal and health benefits such as improved social cohesion, reduced social isolation and improved quality of life (Hart and Parkhurst, 2011; PHE, 2016).

Fourthly, cycling is potentially the most equitable form of transport (Pereira et al., 2017). Transport is strongly linked to inequalities in society (Gates et al., 2019), where resources and opportunities are unequally and unjustly distributed (Koh, 2020), and socio-economic disadvantage (Gates et al., 2019). For example, employment, education and leisure are distributed geographically and frequently co-located with transport links whilst the transport system itself can be inaccessible due to cost, geography, unreliability or slowness. Furthermore, people living in disadvantaged areas are exposed to more health-related externalities of transport such as air pollution, fast moving traffic and on street parking (Lucas et al., 2019). Therefore greater cycling and fewer cars could reduce the transport inequalities and health-related externalities which will in turn reduce socio-economic inequalities. Reducing these inequalities and externalities will then reduce health inequalities. The consequence of such changes will be an improvement in population health (Laird et al., 2018).

Finally, the majority of car journeys undertaken in England are short and can easily be replaced by bicycle. Around 72% of all trips are under 5 miles in distance - a figure that has remained fairly constant over time (DfT, 2022c). However, whilst walking is the preferred mode of transport for journeys under 1 mile (82% of these trips are walked), cars are the preferred mode for journeys between 1 and 5 miles (67% of trips are in cars) (DfT, 2022b). With cycling speeds of between 11 and 22mph (Parkin and Rotheram,

2010) these journeys could be achieved in under 30 minutes and potentially as fast as 5 minutes if cycled.

1.2.4 Risks of cycling

There are some negative effects of cycling. The first is exposure to air pollution due to cycling in close proximity to motor vehicles and the increased ventilation that physical activity entails (Cepeda et al., 2017). However it has been demonstrated that the benefits of the physical activity outweigh the air pollution risks (Tainio et al., 2016) and that such risks can be reduced by cyclist separation from motor vehicles and traffic-free routes (Mitsakou et al., 2021).

The second risk is injuries and crashes. These can be injuries related to overuse such as knee pain or from contact with the pedal cycle such as saddle sores; or traumatic injuries from falling off or crashes (Silberman, 2013). Single pedal cycle crashes involve just the cyclist and occur when they collide with an obstacle or fall off their bike (Schepers et al., 2015). They are usually due to factors related to the cyclist, physical infrastructure, cycle malfunction or the external environment and tend to involve skidding or loss of control (Schepers and Wolt, 2012; Utriainen et al., 2022). Whilst the proportion of single pedal cycle crashes in injured cyclists could range from 17 to 85% depending on study type and size (Utriainen et al., 2022), these types of crashes are known to be under-reported to the police and therefore under-reported in crash statistics (Davidson, 2005; Jeffrey et al., 2009; Juhra et al., 2012). In Great Britain (GB) [1], single pedal cycle crashes account for around 4.6% of cyclist casualties. The overwhelming majority of cyclist casualties are from crashes involving motor vehicles (94.5%)(DfT, 2022e). Despite air pollution, injuries and crashes, the benefits of physical activity from cycling far outweigh the risks (Woodcock et al., 2014).

1.2.5 Pedal cycle crashes in Great Britain

In GB crashes involving pedal cyclists are relatively rare (DfT, 2020e). However, there was on average two pedal cyclists killed and 84 seriously injured each week between 2016 and 2021 (DfT, 2022e). Cyclists have a much higher casualty rate per mile travelled (along with pedestrians and motorcyclists) than motor vehicle drivers or passengers. The 2019 casualty rate for cyclists was 4,891 per billion miles travelled compared to 5,051 for motorcyclists and 195 for car users with a fatality rate of 29 per billion miles travelled compared to 104.6 and 1.6 (DfT, 2020e).

Pedal cyclist casualties are predominantly younger males who experience crashes in urban environments at or near junctions or roundabouts. However, the majority of cyclist fatalities occur on rural roads despite these having only 29% of traffic (DfT, 2022e). Factors that are associated with fatal and seriously injured cyclist casualties include male

[1] Aggregated road crash statistical reports are provided at Great Britain rather than England level.

gender, increasing age, increasing road speed limit, involvement of heavy goods vehicles and proximity to junctions or roundabouts (Knowles et al., 2009; DfT, 2022e; Mason-Jones et al., 2022).

Since 2014, the number of pedal cyclist casualties has a fallen (apart from 2020), driven mainly by reductions in slight and severely injured cyclists (DfT, 2022e). These casualty trends are occurring despite an increase in the volume of pedal cyclist traffic during this time period (DfT, 2022e). This may be explained by the 'safety in numbers' effect where the risk to the individual is less as the size of the group increases (Collins English Dictionary, 2023). This has been observed when the volume of cycling increases as a reduction in risk of cyclists being: involved in crashes (Elvik and Bjørnskau, 2017; Elvik and Goel, 2019); injured (Aldred et al., 2018); or killed (Jacobsen, 2003). However, the exact causal mechanism is unknown with many studies being cross-sectional in study design. It is presumed to be related to changing interactions between motor vehicles and cyclists as cycling becomes more prevalent. However, it is possible that the reverse, 'numbers-in-safety' where as cycling becomes safer the number of people cycling increases, is true (Elvik and Goel, 2019).

1.2.6 Summary

Increasing cycling is important as it is one of the healthiest, safest and potentially most equitable forms of transport, leisure and exercise. Cycling generates numerous benefits for individuals and society representing one of the simplest and most effective solutions to crises ranging from climate change to obesity. The physical and mental health benefits of cycling outweigh the risks. Increased cycling can reduce motor vehicle usage, congestion, air and noise pollution; reduce health and economic costs; and reduce inequalities. The more people cycle, the safer cycling becomes. Therefore, interventions that encourage more people to cycle and increase safety are very important. This means that interventions need to be evaluated to understand what works, when, where and why.

1.3 How do we get more people cycling?

We have established that cycling is important for governments, society and people. This next section considers what is required to increase cycling and then focusses on the barriers that prevent such changes in England at a national, local and individual level.

1.3.1 Approaches that can increase cycling

Experience from Europe suggests that the following physical measures are required to increase levels of cycling: an extensive network of cycling facilities separated from motor vehicles; junction modifications and traffic signal prioritisation for cyclist safety and journey facilitation; traffic calming; quality bike parking; and cycling integration with transport interchanges (Pucher and Buehler, 2008). To be successful these measures need to be part of a comprehensive approach that includes wider policy and societal changes such as addressing legislative issues e.g. introducing traffic laws that protect cyclists and ensure motorist responsibility; raising awareness and providing traffic education and training for all; and creating a ‘cycling culture’ (Pucher and Buehler, 2008; Pucher et al., 2010; Urban Movement, 2014). These measures need to be delivered with good governance and long-term commitment by quality leadership (Urban Movement, 2014).

1.3.2 Implementing such approaches in England

Such a comprehensive approach has not been delivered across England. It requires aligned central and local government action. Central government has the legislative power; financial power; and ability to set national policy, guidance and influence culture. Issues regarding this have been discussed in the previous sections and documented in Parkin (2018) and Golbuff and Aldred (2011). Local governments are autonomous political and highway entities. They are responsible for highways, traffic management, road safety, transport planning, air and noise pollution (LGA, 2010) and public health (Anon, 2013). As autonomous entities their politics, policies and investment can differ and influence their approach towards increasing cycling (Lumsdon and Tolley, 2001; Gaffron, 2003; Deegan and Parkin, 2011; Deegan, 2016).

Barriers to investing in cycling at a regional or local level can be categorised as resources, politics, institutional and attitudes/opposition. Specific issues include finance or funding; lack of political leadership; lack of support within the organisations; lack of awareness of the benefits of cycling; difficult funding and planning processes; cultural car dominance and lobbying; lack of road space to implement cycling infrastructure; perceived negative impact on other transport modes or users; and opposition by the public, businesses and the media (Aldred et al., 2019).

Examples of differences between local governments in cycling approaches are not hard to find. There is considerable variation in cycling spending between such organisations ranging from £0.03 to £8.58 per head of population (averaged over 5 years) and political affiliation appears to influence this spending (Allison and Allison, 2020). There are also differences in the capability of local governments to deliver such interventions. Recent capability analysis (graded 0-4, London not included) shows that only five out of 79 local governments have a level 3 rating (described as very strong local leadership with comprehensive plans and a significant network in place that is resulting in greater active travel) whilst four have a level 0 rating (no obvious leadership, no significant plans and limited previous delivery) (ATE, 2023c). Of the remaining local governments, 40 have a level 1 and 30 a level 2 (ATE, 2023c).

However, evidence suggests that ‘whole town’ approaches such as those that can be delivered by local government can increase cycling prevalence (Goodman et al., 2013). But these whole town approaches require leadership, strategy and funding that deliver programmes of cycling to workplaces and stations, promoting cycling in schools and colleges, physical infrastructure improvements and targeting of specific neighbourhoods and groups (Goodman et al., 2013).

1.3.3 Devolved transport - London and beyond

London has been identified as a 'special case' (Parkin, 2018). In 2000 it became the first area in England to elect a Mayor to represent its interests (GLA, 2023). Transport for London (TfL) is the integrated transport authority that is responsible for delivering the Mayor's Transport Strategy (TfL, 2023a). A key part of that role is encouraging more people to cycle. Successive Mayors have championed cycling in their Transport Strategies and Cycling Actions Plans and invested to make this happen resulting in visible outputs such as the London Cycle Hire Scheme and strategic cycling infrastructure (Golbuff and Aldred, 2011; Di Gregorio and Palmieri, 2016; Parkin, 2018). Additional transport-related measures and strategies that can increase the attractiveness of cycling and discourage car use have been introduced in London. These include the congestion charge zone to reduce traffic congestion in 2003 (TfL, 2003), the low emission zone that charges the most polluting vehicles in order to improve air quality in 2008 (TfL, 2008) (and subsequent ultra low emission zone in 2019 (GLA, 2019)) and Vision Zero that seeks to eliminate all deaths and serious injuries from road crashes by 2041 (TfL, 2018b) .

Since 2000, the volume of cycling has increased in London. Between 2000 and 2019 trips that had cycling as the main mode increased by 137 percent with the average number of such trips increasing from 0.3 million to 0.7 million per day (TfL, 2022a). Cycle counts across strategic cordons demonstrated an increase from 51,000 (2001) to 168,000 cycles (2019) in or out of central London and 25,000 (2002) to 70,000 cycles (2018) in or out of inner London (TfL, 2022b). TfL reports that the risk of being killed or seriously injured whilst cycling in London has more than halved between 2000 and 2017 (TfL, 2018a).

However, there are 33 local governments in London (known as Boroughs) that manage 95% of the roads. TfL have certain powers and control funding for Boroughs to improve transport that includes cycle networks, parking and training (TfL, 2023b). TfL are a mandatory consultee for various work that Boroughs perform related to planning and transport. Therefore close working relationships need to exist between TfL and the Boroughs (e.g. London Borough of Islington, 2009; London Borough of Wandsworth, 2022). However, the Boroughs do not necessarily agree with the Mayor's Transport Strategy and can oppose initiatives to increase cycling (e.g. Macmichael, 2019; London Borough of Hillingdon, 2023).

In other English locations, devolution of transport from central government has begun. It can involve combined authorities that bring together different local governments (LGA, 2023) or regional transport bodies that bring together local government, businesses and transport organisations such as rail or airports (TAN, 2023). Many of these bodies have ambitious targets to achieve more cycling such as West Yorkshire that wants to increase the number of cycling trips by 300% by 2027 (WYCA, 2017) and Greater Manchester who aim to quadruple the volume of cycling (Boardman, 2017). Three of the five organisations that achieved an active travel capability rating level of 3, the second highest rating and the highest achieved by any organisation outside of London, are combined authorities (ATE, 2023c).

1.3.4 Barriers for individuals participating in cycling

Whilst we have identified what needs to happen at a national and local level to encourage more cycling, there are barriers at an individual level that are important. An international systematic review of quantitative and qualitative research identified 34 barriers across eight themes for utility cycling that are outlined below (Pearson et al., 2022). Safety encompassed fears around motorist aggression and risk of injury, crime or theft in addition to general feelings of lack of safety and concerns about high traffic density. Infrastructure related to a lack of dedicated bike lanes; the minimal connectivity, poor quality and condition of dedicated bike lanes when they exist; and the quality and condition of roads in general. Trip factors included long distance and long travel time plus the need to transport goods or children. Aspects such as no bike, high cost of bikes or mandatory helmet laws were categorised under 'access' whilst lack of showers, lockers or bike parking were considered as 'end of trip facilities'. Another theme was personal factors such as no desire, too much effort, lack of fitness, lack of comfort, inability to ride a bike or lack of knowledge about cycling or the need to change or shower. The final categories were negative social perceptions and environmental factors such as bad weather, air pollution exposure and hills.

The most commonly reported barriers were bad weather, perceived lack of safety, high motor vehicle density and long travel time. However, safety and infrastructure barriers were reported by the most participants (Pearson et al., 2022). These particular barriers are consistently found in the UK. For example, participants interviewed by Pooley et al. (2013) consider it unsafe to cycle on most urban roads due to motor vehicles, particularly for children. This was echoed in a systematic review focussing on barriers for children participating in active travel along with lack of infrastructure and parental concerns about being responsible for safety (Lorenc et al., 2008). National survey data has found that most adults (66%) believe it is too dangerous to cycle on English roads with a higher proportion of women (71%) compared to men (61%) and a higher proportion of non-cyclists (70%) compared to cyclists (57%) (DfT, 2020g). London cyclist survey data has shown that route choice is strongly influenced by safety, for example, actively choosing to travel on roads with less and slower traffic and cycling further to avoid motor vehicles (Steer Davies Gleave, 2012). Fear of crashes or too much traffic are significant deterrents for the majority of Londoners (TfL, 2017).

1.3.5 Summary

A comprehensive approach encompassing leadership, dedicated funding, policy, infrastructure, legislation, training, education and societal changes are required to increase cycling. Implementing such an approach requires aligned governmental (central and local) and devolved transport authority action. Many barriers exist in England at national, regional and local levels that have hindered such unified approaches. Furthermore, barriers exist that discourage individuals from cycling. In particular, negative perceptions of the safety of cycling and a lack of or poor quality infrastructure prevent many people from cycling. Interventions that include high-quality cycling infrastructure could be effective at encouraging more people to cycle, particularly if they make people feel safer, but such interventions need to be evaluated to ensure that achieve the desired effect.

1.4 Cycling infrastructure

A lack of or poor quality infrastructure can deter people from cycling and thus prevent the participation required to reap the benefits of increased cycling. Implementing quality cycling infrastructure is central to any programme to promote cycling. This section considers what constitutes good cycling infrastructure, how it is perceived and whether it is effective at increasing cycling safety and participation.

1.4.1 Quality cycling infrastructure

There does not appear to be an agreed definition of cycling infrastructure. However, it could be defined as infrastructure that is provided for and used by all cyclists where the assets have certain physical characteristics (e.g. segregated cycle lanes, traffic signs) or perform certain functions beneficial to cyclists such as reduce motor vehicle speed or offer priority for cyclists at junctions. Examples of cycling infrastructure include: on and off-road cycle lanes and tracks; shared use spaces; cycling in bus and tram lanes; reducing use by motor traffic (e.g. through mode filtering, one way streets); reducing motor traffic speed enforced by physical measures; transitions on and off cycle tracks; junctions and crossings (including signals that prioritise cyclists); cycle parking; and traffic signs, road markings and wayfinding (DfT, 2020d).

Whilst there is no agreed definition, there is consensus on the design principles that underpin any high-quality cycling infrastructure (TfL, 2016; CROW, 2017; Parkin, 2018; DfT, 2020d; European Commission, 2023). It should be safe, coherent, direct, comfortable and attractive. Other aspects considered important include accessibility so that anyone can cycle and vulnerable pedestrians are protected (DfT, 2020d); adaptability so that it can accommodate increasing numbers over time (TfL, 2016); recognition that pedal cycles are vehicles not pedestrians thus their speed and shape should be considered (Parkin, 2018); protection from motor vehicles on high speed, high volume roads (DfT, 2020d); and the use of appropriate construction materials and subsequent maintenance (Parkin, 2018; DfT, 2020d).

To be effective at increasing cycling and popularising cycling as a form of transport for shorter journeys, infrastructure should form routes and networks that link people to places they wish to go. These routes and networks must also be safe, coherent, direct, comfortable and attractive (CROW, 2017; Parkin, 2018; DfT, 2020d).

Updated cycle infrastructure design standards for England were published in 2020 (DfT, 2020d). In order to be eligible for central government funding via Active Travel England, any new cycling infrastructure needs to meet these design standards (DfT, 2020c; DfT and ATE, 2023; ATE, 2023b). The cost of constructing such quality cycling infrastructure can vary and be substantial. In 2017, two-way physically segregated cycle lanes cost £1.15-1.45 million per km whilst comprehensive cycle route signage or a 20mph zone with traffic calming measures cost around £12,000 per km. Cycle crossings vary from £0.14-0.41 million and cycle-specific major junction redesigns from £0.24-1.61 million (Taylor and Hiblin, 2017). However, contraflow cycling, where pedal cycles can travel against the flow of motor vehicles on one-way streets, can cost as little as £8,500 per road (Steer Davies Gleave, 2016).

1.4.2 Cycle lanes and tracks in England

Terminology used to describe infrastructure such as cycle lanes, tracks and paths differs around the world (Schröter et al., 2021). In England, terms such as lanes and tracks have legal significance regarding their construction, who can use them and how usage can be enforced (Parkin, 2018). Such infrastructure can be motor vehicle-free, for example, along waterways or through parks; or on, adjacent to or distinct from roads. The London Cycling Design Standards provide a useful visualisation that describe the English types of on or adjacent to road cycling facilities and their degree of separation or segregation from motor vehicles (see Figure 1.1). It should be noted that Mandatory and Advisory cycle lanes, where separation is demarcated by white paint, are widespread in England but offer no protection and are frequently misused by motor vehicles (e.g. CCC, 2012; Geffen, 2019).

1.4.3 Perceptions of cycling infrastructure

Cycling infrastructure has been identified as a factor that could encourage more cycling by reducing barriers to individuals and improving safety perceptions (e.g. Lorenc et al., 2008; DfT, 2020g). In particular, off-road cycle tracks and quality on-road cycle lanes seem to be important in the literature. In English household travel surveys, the most frequently identified cycling encouragements are safer roads (28%), safe cycle lanes (21%) and segregated cycle paths (19%) (DfT, 2020g). A survey of London residents

FIGURE 1.1: Description of cycle lanes and tracks and their separation from motor vehicles (Source: TfL 2016, Chapter 4, page 5)

report infrastructure improvements are a key factor behind their increased cycling with 68% reporting that strategic on-road cycle lanes have encouraged them to cycle more. They associate these strategic cycle lanes with safety, separation from motor vehicles and dedicated cycling infrastructure (TfL, 2017). London cyclists report a preference for dedicated cycle lanes with 51% stating they would change their route to use such infrastructure and 12% stating they would take a much longer route in order to use these cycle lanes (Steer Davies Gleave, 2012).

Whilst overall, all types of cyclists prefer dedicated cycling facilities (Misra et al., 2015), females express a greater survey preference for segregated infrastructure compared to males (Steer Davies Gleave, 2012; Aldred et al., 2017) as do those who cycle less frequently (Steer Davies Gleave, 2012).

Certain characteristics of cycle lanes and tracks are associated with higher perceptions of safety. A large survey in Berlin, Germany (n = 13,735) found preferences for off-road cycle tracks and wider, coloured on-road cycle lanes on low speed roads that are segregated by obstacles from moving traffic and do not have on-road parking (von Stülpnagel and Binnig, 2022).

1.4.4 Does cycling infrastructure increase safety and participation?

Whilst the presence of infrastructure is associated with increased subjective perceptions of safety and likelihood of cycling, does infrastructure *objectively* increases safety and participation? This has been explored by systematic reviews that have examined the effectiveness of cycling infrastructure on measures such as cyclist crash rates or counts using high-quality primary studies. The following sections discuss some of the key systematic reviews that examine these issues, each addressing slightly different research questions.

1.4.4.1 Effect of cycling infrastructure on actual cyclist safety and participation

Mulvaney et al. (2015) performed a Cochrane Collaboration[2] systematic review with meta-analysis that sought to examine the effect of different types of cycling infrastructure on cycling injuries (primary outcome), cyclist crash rates and cycle counts (secondary outcomes). They only considered studies that were randomised controlled trials, controlled before and after studies or interrupted time series studies in order to ensure the included study designs were of the highest quality and reduced the risk of bias. The interventions of interest were cycling infrastructure that separates cyclists from motor vehicles; or that aimed to manage shared space between motor vehicles and cyclists such as on-road cycle lanes, bus lanes and advanced stop lines (ASL, an area by traffic lights that allows cyclists to stop ahead of motor vehicles); or transport network management such as cycle phases at traffic lights, speed management and separation of traffic movements.

Using their comprehensive search strategy of both published and grey literature, they identified 21 studies for inclusion; one was an interrupted time series study and the others were controlled before and after studies as no randomised controlled trials were found. Only 5 studies were conducted outside of Europe: 3 in the USA and 2 in New Zealand.

None of the included studies examined the primary outcome of cycling injuries. For infrastructure that separates cyclists from motor vehicles by either being totally separate from the road or using a kerb (or other physical barrier) there was no statistical evidence of change in cyclist crashes or counts. On-road cycle lanes with no separation were not associated with any significant change in crashes before and after implementation. Other infrastructure such as ASL or coloured tarmac had no evidence of impact on crashes or counts. However, the introduction of 20mph zones did appear to reduce cyclist crashes significantly as did speed reduction engineering. Cycle routes that contained multiple types of infrastructure did not appear to reduce crash risk when adjusted for cycle flow.

Regarding the effectiveness of cycling infrastructure, the authors concluded that there was a lack of evidence in terms of reducing injuries and limited evidence of its impact on cyclist crashes and counts. They also state that the evidence that exists is not high quality.

They identified three key issues that meant the evidence was not considered high quality. Firstly, there was limited information about and a lack of matching of intervention and control sites. This meant that the sites were potentially dissimilar and thus unable to provide a fair comparison. Secondly, confounders, such as cycle volume, traffic mix, weather, time of year, population and changes in the reporting, were not always addressed.

[2]Cochrane is a global independent network that gathers and summarises the best research evidence on the effectiveness of health care and is internationally recognised as the benchmark for such syntheses (Cochrane, 2021).

In particular, crash rates were not always adjusted for changes in cycling flow. Thirdly, for many studies the number of crashes were very small and the duration of follow up was short. This meant that statistical significance could be not assessed and that aspects such as seasonal variation and regression to the mean could have influenced the findings.

1.4.4.2 Effect of cycling infrastructure on actual and perceived cyclist safety

Phillips et al. (2018) performed a wide, rapid evidence review for the national government in England that included using experimental, quasi-experimental and quantitative studies plus evidence reviews to examine the effectiveness of interventions on reducing actual and perceived safety for cyclists in Europe, North America or Australasia. They identified 23 cycling infrastructure studies (11 quantitative primary studies and 12 evidence reviews (one of which was Mulvaney et al. (2015))). Interestingly, there is no overlap between the studies identified by Phillips et al. (2018) and Mulvaney et al. (2015). Of the 23 studies, the most common infrastructure examined was cycle tracks and lanes (8), signal control (6) and traffic calming measures (5).

They found that physical traffic calming infrastructure such as chicanes and refuges increased cycling, reduced cyclist casualties and reduced speeds whilst speed cameras and cyclist signals reduced the number of injured cyclists. Regarding cycle lanes and tracks, the evidence is reported as inconclusive but if segregated or well designed, with infrastructure such as ASL, speed humps, cyclist signals, they seem more likely to reduce cyclist crashes and injuries. ASL may reduce cyclists' perceived risk but no studies examined the impact of cycle lanes or tracks on perceived risk. The evidence suggests that conversion of junctions to roundabouts can improve safety but only if designed appropriately.

Key issues that Phillips et al. (2018) highlight is that many studies do not differentiate between the degree of segregation or provide enough information on the types of cycle lanes, tracks or paths. They also identify that the primary studies and the evidence reviews are often poor in quality. Finally, they highlight the issue of confounding and failure of the studies to address confounding in study design or analysis.

1.4.4.3 Effect of cycling infrastructure on cycling participation

Panter et al. (2019) performed a systematic review to examine the effectiveness of physical environment interventions in promoting cycling and to understand how and why these changes may or may not have increased cycling. They focused on interventions that changed the natural or built environment but excluded those that related to the existing environment e.g. new signage, public transport links and composite interventions (e.g. environmental with education). Studies had to be on the general population and assess the impact on cycling through self-reports, objective measures or observation. The study designs included were randomised controlled trials, comparison trials, quasi-experimental and had to have control/comparison groups or graded exposure groups.

They identified five studies that examined the implementation of new on or off-road cycle lanes or tracks, one with a new cycling/walking route and one with a new pedestrian/cycle bridge, all of which were undertaken Europe, the USA or Australia. Their findings were that three of the five cycle lane/tracks and the cycle/walking route reported significant positive effects on cycling participation, one showed positive effects of uncertain significance (as did the new bridge) and one was inconclusive or had no effect.

Looking at potential mechanisms for these intervention effects, they describe three key explanations: improved accessibility and/or connectivity; improved traffic or personal safety; and improved cycling experience. They identified that these can occur in 'supportive' or 'unsupportive' contexts e.g. 'unsupportive' could be a car-dominated area. Looking specifically at the safety explanation, they found in 'unsupportive' contexts where there is busy, fast, car dominance segregating cyclists from motor vehicles reduces conflict between users and improves perceptions of safety. But this effect is not seen in every context. The authors postulate this could be related to not feeling safe for the whole route as opposed to part of the route. In supportive contexts they found that infrastructure increased cycling but they expressed concern that this may be due to route substitution (e.g. moving from a less supportive cycle route to a much better one). In summary, they found that both supportive and unsupportive contexts can result in the same outcomes but mediated through different mechanisms whilst the same context can bring about very different outcomes. Unsupportive contexts can mean that mechanisms are not triggered and no outcomes achieved.

The authors identified various issues with the studies in the systematic review. These included multiple methodological issues such as short duration of follow up, delays in intervention implementation, coarse or unspecific outcomes and insufficient intervention exposure. They noted that most studies scored poorly on quality when their randomisation, study group representativeness, comparability between the intervention and control groups, measurement of outcomes and use of statistical tests was assessed. Most studies contained little detail on the intervention context and potential mechanisms.

1.4.4.4 Strengthening causal inference from observational data on the effect of infrastructure interventions

Molenberg et al. (2019) chose to examine the effects of infrastructure interventions on cycling and whether these effects varied by study design, data collection methods or statistical analysis. They wanted to improve understanding of the strengths and limitations of different methods used for infrastructure evaluation to aid interpretation of research.

A variety of study designs (controlled and uncontrolled) were included along with infrastructure interventions to promote cycling (e.g. cycle lanes, networks, improvements to existing infrastructure). The infrastructure interventions could occur with other environmental infrastructure changes to promote cycling e.g. new bike parking but not with interventions to target individuals such as training or education. Cycling behaviour (e.g. frequency or duration, mainly measured by survey data) or use of infrastructure (quantified by e.g. direct observation, automatic counters) had to be assessed before and after the intervention.

31 studies were identified, all conducted in high-income countries, of which 16 examined cycling infrastructure usage and 20 examined cycling behaviour. Of the 20 measuring cycling behaviour, 18 found an increase in cycling with the median relative change being 22% (range -21% to 262%). All the studies measuring infrastructure usage reported positive effects (median relative change: 62%, range 4 to 438%).

The authors recommend causal association can be strengthened by using controlled designs in multiple locations, multiple cycling outcomes (potentially both objective and subjective measures), collecting data around the clock, using a long follow up period and testing for statistical significance. Uncontrolled designs can be improved if they consider the effect of underlying time trends in cycling. For infrastructure usage it is important to consider displacement of existing riders on to the new infrastructure and thus include measures of the wider area.

1.4.5 Summary

High-quality cycling infrastructure, routes and networks must be safe, coherent, direct, comfortable and attractive. In particular, they must protect cyclists from motor vehicles on high speed, high volume roads. Infrastructure that increases road safety and separates cyclists from motor vehicles are associated with perceptions of cyclist safety and increased cycling participation. However, the evidence suggesting such infrastructure objectively or subjectively increases cycling safety and participation is limited and hindered by a 'lack of high-quality rigorous evaluation' (Mulvaney et al. (2015), page 2).

Part 2: The Research

To summarise Part 1, cycling in England is not universal and there are spatial and demographic variations. There is a drive to increase the amount of cycling to realise the extensive individual and population benefits. Increasing the amount of cycling requires a comprehensive approach with alignment of central and local government but barriers exist to achieving this aim. High-quality cycling infrastructure is core to any such approach as the biggest barriers to cycling uptake are related to concerns about safety and a lack of quality cycling infrastructure. Design standards exist for such infrastructure, guided by the key principles of safety, coherence, directness, comfort and attractiveness. However, the evidence base concerning the effectiveness of such infrastructure on objective and subjective cyclist safety and cycling participation is limited.

Part 2 builds on Part 1. It develops the research rationale by highlighting the research gaps in this evidence base, identifying data as key to evaluating such infrastructure and the potential of London as a setting for such an evaluation. It then describes the thesis aim and research questions and links these to the research gaps before outlining principles that have underpinned the research. Finally it describes the research strategy, thesis structure and outputs beyond the publications included in this thesis.

1.5 Research rationale: evaluating the effectiveness of cycling infrastructure on cyclist safety and participation

Multiple evidence reviews have concluded that there is a 'lack of high-quality rigorous evaluation' (Mulvaney et al. (2015), page 2) of cycling infrastructure (Reynolds et al., 2009; Reid and Ada, 2010; Mulvaney et al., 2015; Phillips et al., 2018; Stappers et al., 2018; Panter et al., 2019; Molenberg et al., 2019). This deficit in the literature hinders our understanding of what infrastructure is effective at improving both subjective and objective cyclist safety and participation. Such understanding is vital as it is essential to know what works in order for such evidence to inform cycling policy and funding (Evaluation Task Force, 2023a; Evaluation Task Force, 2023b). This section develops further the research rationale for the thesis by examining the research gaps in the current evidence base for the effectiveness of cycling infrastructure on safety and participation. It then examines a factor that is consistently lacking or limiting the evidence base, namely, data and information, before describing why London is an important location for infrastructure evaluation.

1.5.1 Research gap - the lack of high-quality rigorous evaluation of cycling infrastructure

Having established that there is consensus that the current evidence base is limited, this section uses three categories to describe the reasons for this lack of high-quality rigorous evaluation of cycling infrastructure: infrastructural, methodological and contextual.

Firstly, there are issues with the infrastructure. In many studies the infrastructure is partial, sporadic and contains a fraction of infrastructure available (for example, a few kilometres) (Reid and Ada, 2010). It is complicated by differences or inconsistency in infrastructure design (Reynolds et al., 2009) and failure to describe infrastructure in the studies. This can be compounded by difficulties in obtaining accurate detailed infrastructure information as much of it is held locally by planners and not accessible to researchers (e.g. Schoner and Levinson, 2014; Hong, McArthur and Livingston, 2020).

Secondly, there are multiple challenges in evaluating the effectiveness of infrastructure on safety and perceptions (Molenberg et al., 2019). There are difficulties in quantifying cyclist exposure to such infrastructure (Vanparijs et al., 2015), for example, cycle counters are relatively cheap but they tend to be used for short time periods in limited locations (NACTO, 2022). There are also difficulties in defining and measuring outcomes; for example, how 'safety' is defined (Santacreu, 2018). Furthermore, objective outcomes such as crashes involving cyclists are rare events. To draw strong conclusions, exposure and outcome data should be collected multiple times before and after infrastructure introduction. These time periods should be of sufficient duration to ensure adequate exposure to infrastructure and that any effects are true and not due to natural variability. However, longer studies are usually more expensive and hindered by a lack of exposure or outcome data. Confounding factors should be considered in the study design and analysis (e.g. Harris et al., 2011). A wide variety of confounders should be examined including weather, season, time of day, traffic volume, traffic mix, cyclist volume and change in cycling routes as infrastructure develops (Mulvaney et al., 2015) but such data may be hard to obtain at a granular level. Statistical analysis can strengthen evaluation but measuring uncertainty requires sufficient data points.

Finally, there is usually a lack of information about the context in which the infrastructure is introduced. For example, the wider social environment, the law and the behaviour of all road users (Reid and Ada, 2010; Panter et al., 2019). We have already explored how important national, regional and local contexts are in determining approaches to increase cycling and the impact that politics, policies and funding have on implementations. However, information about such aspects can be hard to obtain. Whilst national government documents including websites are archived (The National Archives, 2023) and tend to be easier to obtain remotely via the internet, local government documents are harder to access. Their documents are dependent on good record management (Shepherd et al., 2010; Shepherd et al., 2011), something that is complex due to outsourcing of such services (Waugh and Hodkinson, 2021), and whether the documents are likely to have been published and retained (Lawson et al., 2007). This lack of context can limit the representativeness and generalisability of findings.

Therefore, there are significant opportunities to develop and perform original research that addresses gaps and improves the current evidence base in relation to the effectiveness of cycling infrastructure on safety and participation.

1.5.2 Addressing the research gaps - data and information

Data and information are vital for effective infrastructure evaluation and, as discussed above, issues with data and information commonly hinder the quality of evaluation. To summarise the key problems: firstly, such data and information needs to exist; then it must be: accessible to researchers, sufficient in volume and detail, and extensive in spatial and temporal coverage; and finally it must have all the characteristics of high quality data (accurate, complete, reliable, relevant and timely) (Wand and Wang, 1996).

There is a wide variety of data and information sources that can be used to evaluate the effectiveness of cycling infrastructure on safety and participation (see Table 1.1). Some have been used for many years such as counts and surveys whilst others are examples that have emerged from technological advances and can be crowd-sourced (Nelson et al., 2021). In England, some data and information is freely available to researchers as open data, for example, road traffic collision and casualty datasets (DfT, 2022g), London Bike Hire Scheme (TfL, 2023e) and OpenStreetMap (OpenStreetMap contributors, 2023) or on application as aggregated data, for example, the National Travel Survey (DfT, 2022a). Access to certain data, for example, individual record data, is carefully controlled and can only be accessed by authorised researchers in limited and secure conditions (UK Data Service, 2023; NHS Digital, 2023b). Other data is owned by private companies and can be made available to researchers (e.g. Strava Metro) (Strava Metro, 2023). Some privately-owned data is only available in aggregated form (e.g. motor insurance claims data (ABI, 2023)). Other data and information may be available but difficult to access as it can be on paper, held locally or the researcher may not know it exists. This is a particular challenge when infrastructure is implemented by local government - for example, local surveys, counts and implementation approaches.

Data can be small in size and limited in granularity. For example, manual counts can be resource intense if undertaken by humans but even if automatic counters are used they can only be deployed in a certain number of locations and for a certain time period (NACTO, 2022). This means such data can lack spatio-temporal coverage and granularity limiting its usefulness when evaluating infrastructure. Emerging data sources could be used to fill this void as they can offer much greater spatio-temporal coverage and granularity (Alattar et al., 2021; Nelson et al., 2021), if accessible. The data generated from the emerging sources is usually large in volume potentially making it 'big data' - an "information asset characterized by such a high volume, velocity and variety to require specific technology and analytical methods for its transformation into value" (De Mauro et al., 2016, 122). Therefore, using such data for evaluation and research requires data science expertise (Keller et al., 2020).

Traditional sources such as counts, surveys and crash datasets have been used extensively for evaluation and their strengths and limitations are usually well-known and studied (Keller et al., 2017; NACTO, 2022). This means there are often objective assessments or, at a minimum, transparency about its data quality. In contrast, data from emerging sources can be classified as opportunity data, where the data is continuously generated through societal interactions with technology (Keller et al., 2017). This data is less well-known or studied and thus considerable research gaps exist around the use of this data. Furthermore, the quality of such data can be variable or unknown and there can be a lack of transparency about data processing by providers (e.g. Lee and Sener, 2021).

Therefore, using traditional and emerging sources and triangulating such data and information could bridge this research gap and improve the evidence base of the effectiveness of cycling infrastructure on safety and participation.

Table 1.1: Examples of cycling data and information sources available in England for infrastructure evaluation (adapted and enhanced from the following: NACTO (2022); Nelson et al. (2021); Griffin et al. (2020); Handy et al. (2014); Parkin (2018); Alattar et al. (2021))

Cycling theme	Traditional sources	Emerging sources
Volume	• Manual cycle counts: e.g. on-site counts, manual counts of video images • Automatic cycle counts: e.g. pneumatic tubes, infrared sensors, CCTV • Surveys: e.g. Intercept surveys, travel diaries	• Bike sharing scheme data e.g. London (TfL, 2023e) • Fitness app datasets e.g. Strava Metro (Strava Metro, 2023) • Automated image processing e.g Telraam (Telraam, 2023) • GPS-enabled devices e.g. See.Sense(See.Sense, 2023)
Safety	• Road traffic collision and casualty data sets (DfT, 2022g) • Healthcare data (hospital episode statistics) (NHS Digital, 2023a) • Compensation Recovery Unit data (CRU, 2022) • Motor insurance claims statistics (ABI, 2023) • National Travel Survey road safety questions (DfT, 2022d)	• Participatory mapping e.g. BikeMaps.org (Nelson et al., 2015), Collideoscope (mySociety, 2023)

Cycling theme	Traditional sources	Emerging sources
Infrastructure	• Records of Traffic Regulation Orders made by Highway Authorities (British Parking Association, 2019) • Reports and publications • Design standards e.g. DfT (DfT, 2020d), TfL (TfL, 2016)	• Participatory mapping e.g. OpenStreetMap (OpenStreetMap contributors, 2023) • Imagery e.g. Google Maps and Google Street View (Google, 2023) • Collated datasets e.g. Bikedata (CycleStreets, 2023)
Attitudes	• National Travel Attitudes Survey (DfT, 2023a) • Local travel attitude surveys e.g. TfL cycling attitudes survey (TfL, 2017)	• Social media e.g. Twitter (Twitter, 2023)
General	• National Travel Survey - cycle ownership, trips, journey purpose, socio-demographics (DfT, 2022d)	

1.5.3 Addressing the research gaps - the special case of London

London has already been highlighted a unusual case by virtue of transportation being devolved and strong Mayoral leadership that promotes cycling and discourages car use. There has been considerable investment in cycling infrastructure in London with around £101 million spent in 2016/2017 (London Assembly Transport Committee, 2018) and an average of £150 million per year proposed until 2026 for active travel schemes (TfL, 2023c). There are 325 kilometres of strategic cycle routes in London (personal analysis of data from TfL (2023e)) that are considered high quality and data has shown that the percentage of Londoners living within 400m of these cycle routes has increased from 12% in 2019 to 22% in 2022 (TfL, 2022a). Cycling participation has grown since 2000 with the biggest growth on the strategic cycle routes (TfL, 2019a). Compared to other regions, London has the highest number of cyclist casualties from road traffic crashes and the joint highest number of killed or seriously injured cyclist casualties (DfT, 2022f).

These characteristics of London as a cycling region make it an ideal location to conduct infrastructure evaluation. It has a significant amount of high-quality cycling infrastructure; such infrastructure is being used and used extensively i.e. a large number of people are being exposed to the infrastructure; it has a high number of crashes involving pedal cyclists so safety can be examined without being compromised by small numbers; and the infrastructure has been introduced for many years thus enabling a before and after comparison. Whilst other areas may have higher participation or a stronger cycling culture, none have all these important characteristics for infrastructure evaluation, unlike London. Furthermore, TfL has extensive open data including the bicycle sharing scheme, cycling infrastructure database, cycle routes, cycle counts and other transport related data (TfL, 2023e; TfL, 2023d).

1.5.4 Summary

Reasons for the lack of high-quality rigorous evaluation of cycling infrastructure can be considered as infrastructural, methodological and contextual. Issues with data and information underpin many reasons and are centred around its existence, accessibility, sufficiency, detail, spatio-temporal coverage and quality. There are many traditional and emerging sources for such data that have strengths and limitations. Therefore, there are significant opportunities to develop and perform original research, in particular using large datasets, that addresses research gaps and improves the evidence base on effectiveness of cycling infrastructure on safety and participation. London has a number of characteristics that makes it ideally placed as a location for such research.

1.6 Research aim and questions

The overall aim of this thesis is to contribute original research evaluating the effect of cycling infrastructure on cyclist safety and participation. It seeks to generate high-quality research using large observational datasets that can influence policy and have a real-world impact on building cycling infrastructure that makes people want to cycle and protects them when they do so. This aim leads to three research questions (RQ1, RQ2 and RQ3) that are each answered by three papers (Chapters 2-4). Each research question and paper aims to address issues with the evidence base outlined in previous sections by: differentiating between different types of infrastructure; using large volume of data both in terms of infrastructure but also exposure, outcomes and follow up duration; adjusting for confounders and using a method that enables effects to be detected.

Whilst RQ1 examines cycling infrastructure as a whole, both RQ2 and RQ3 focus on a particular form of infrastructure - contraflow cycling where cyclists can travel against the flow of motor vehicles on one-way streets. The idea for this focus came from discussions with a cycling advocate. They described issues faced locally to persuade local government that they should allow cycling on all one-way streets as there were still some one-way streets in Cambridge (a location with very high cycling participation) where cyclists were not allowed to cycle against the flow of traffic. Safety was cited as a key concern preventing implementation despite national guidance recommending the use of contraflow cycling on most one-way streets (DfT, 2020d). Exploration of the literature demonstrated that there was limited evaluation of such infrastructure on safety and participation but that it was deemed safe and popular in Europe (e.g. Alrutz et al., 2002; Bjørnskau et al., 2012; Vandenbulcke et al., 2014; Pritchard et al., 2019). This highlighted a further evidence gap - that there is a need for high-quality, UK-based research on contraflow cycling and safety that can inform and support cycle campaigners and local government.

It should be mentioned at this point that this thesis was funded by the Economic Social Research Council (ESRC) through the Data Analytics and Society Centre for Doctoral Training. Research from the Centre is focused on: "promoting the creation and analysis of new longitudinal and streamed data resources for socio-economic investigations, creating new methods, investigating social processes and facilitating interventions" (DataCDT, 2023). Therefore, the research presented aligns with the Centre's focus.

1.6.1 RQ1: What cycling infrastructure exists in London?

This question is explored in Chapter 2 in the paper *"Is cycling infrastructure in London safe and equitable? Evidence from the cycling infrastructure database"*. It presents the first analysis of the new, traditionally-surveyed London Cycling Infrastructure Database (CID). It describes the database in detail and compares the variation in cycling infrastructure provision across London adjusted for factors such as population, geographical size and cycle commuting. Finally, it evaluates on-road cycle lane separation from motor vehicles and estimates compliance with cycle infrastructure design guidance.

This research question and paper address a number of research gaps in the evaluation of cycling infrastructure. It presents a data source that contains a large volume of infrastructure data of different types. This can inform subsequent research, including that in this thesis, by identifying where infrastructure is located and the volume, type and subtype of such infrastructure. Researchers will then be able to identify locations of similar infrastructure, use large volumes of infrastructure or use detailed infrastructure data for their evaluations.

1.6.2 RQ2: What is the impact of introducing contraflow cycling on one-way streets on cyclist safety in London?

This question is explored in Chapter 3 in the paper *"Contraflows and cycling safety: Evidence from 22 years of data involving 508 one-way streets"*. It constructs a primary database of all roads with contraflow cycling implemented in inner London between 1998 and 2019. After identifying road traffic crashes involving pedal cyclists on or near those roads, it analyses the crashes and casualties to identify whether the crash or cyclist casualty rates changed after implementation of the contraflows and provides an estimate of the uncertainty around these rates

This research question and paper address a key research gap - the lack of evidence on actual contraflow safety in the UK. It also addresses issues with evaluation of such infrastructure by: using a very specific type of described infrastructure; using large volumes of infrastructure, crash and casualty data; having a total follow up period of 22 years; using a before and after method at each infrastructure location; and by estimating uncertainty around rates. It also adjusts for change in cycling volume.

1.6.3 RQ3: What is the impact of introducing contraflow cycling on one-way streets on cycling participation in London?

This question is explored in Chapter 4 in the paper *"Build it but will they come? Exploring the impact of introducing contraflow cycling on cycling volumes with crowd-sourced data"*. Using the primary database of roads with contraflow cycling in inner London developed for RQ2, it explores whether the volume of pedal cyclists alters when contraflow cycling is introduced. The observed pedal cyclist data used is Strava Metro counts. An expected count is generated based on the overall change in Strava Metro counts in inner London during the study period. Having quantitatively examined whether there are any changes, it then qualitatively assesses characteristics of successful and unsuccessful implementations where success is defined as an increase in cycling volume after contraflow implementation.

This research question and paper address the important research gap on contraflow cycling in the UK and its impact on cycling participation. It also contributes to the assessment of the impact of contraflow cycling on perceived safety by using cycling volumes as a indirect measure of safety perception. Again, the approach of this paper seeks to provide high-quality evaluation by using: a very specific type of described infrastructure; large amounts of infrastructure and cycling volume data; cycling volume data that has a very high level of spatio-temporal coverage and granularity; and a before and after method at each infrastructure location. It also adjusts for change in the number of cycling trips, Strava Metro users and seasonality.

1.6.4 Principles underpinning the research

There are several key principles that have underpinned the research. The first is that the research should be of high quality and conducted in a way that directly addresses research gaps that have been identified in the literature and thus contributes to the evidence base on cycling infrastructure. The second builds on the first, such a contribution should be policy relevant i.e. address an important policy area within cycling infrastructure. The third is to make all code and datasets openly available. The reasons for this are transparency, reproducibility and to facilitate further research. The final principle is that all research should be published and disseminated. This is to ensure that the research findings (positive, negative or indifferent) were made available to researchers, national government, local government, cycle campaigners and others in order that everyone can use this evidence to inform best practice in implementing cycling infrastructure. This final principle was the reason for pursuing the alternative format thesis.

1.7 Research design

All chapters (papers) use quantitative methods. Whilst Chapter 2 (Paper 1) generates a primary dataset, all other datasets used are secondary and anonymised (when individual level data is available). With the exception of the Strava Metro data, all datasets are open datasets. The data, their sources and the chapter (paper) that the data is used in is described in Table 1.2. Chapter 4 (Paper 3) uses qualitative methods in addition to quantitative methods.

TABLE 1.2: Data and its sources used in thesis

Data	Source	Chapter (Paper)
London Cycling Infrastructure database (CID)	TFL (TfL, 2023e)	2, 3 (P1, P2)
Geographical boundaries of London Boroughs (2020)	Office for National Statistics (ONS) (ONS, 2020)	2, 3, 4 (P1, P2, P3)
Geographical areas of London Boroughs (2020)	ONS (ONS, 2020)	2 (P1)
Population of London Boroughs (Mid-2019)	ONS (ONS, 2019)	2 (P1)
Commuting cycling volume (2011 census data)	Propensity to Cycle Tool (Lovelace et al., 2017)	2 (P1)
Historical road speed limits (2019)	OSM (OpenStreetMap contributors, 2023)	2 (P1)
Cycling infrastructure (various years)	OSM (OpenStreetMap contributors, 2023)	3, 4 (P2, P3)
Road layout and direction of motor vehicle flow (various years)	OSM (OpenStreetMap contributors, 2023)	3, 4 (P2, P3)
Specifications for cyclist segregation from motor vehicles and contraflows	LTN 1/20: Cycle Infrastructure Design (DfT, 2020d)	2, 4 (P1, P3)
Code and data for visualisation of London Boroughs	After the Flood (After the Flood, 2019b; After the Flood, 2019a)	2 (P1)
London contraflow Traffic Regulation Orders (1998-2019)	The Gazette (the national public record) (TSO, 2022)	3, 4 (P2, P3)

Data	Source	Chapter (Paper)
UK Road traffic collision data (vehicles, crashes and casualties, 1998-2019)	DfT (DfT, 2022g)	3 (P2)
Adjustment factors for change in pedal cyclist casualty severity reporting	DfT (DfT, 2020b)	3 (P2)
Inner London manual cordon cycle counts (1998-2019)	TfL (TfL, 2019b; TfL, 2021)	3 (P2)
Inner London Strava Metro cycle counts (2018-2019)	Strava Metro (Strava Metro, 2023)	4 (P4)
Historical street view images of roads	Google Maps Street View (Google, 2023)	4 (P4)
Inner London cycle routes and networks	OSM (OpenStreetMap contributors, 2023)	4 (P4)
Historical weather data	The Met Office (Met Office, 2020a; Met Office, 2020b)	4 (P4)

Chapter 2 (Paper 1) uses data from the London CID that contains observations of all cycle lanes, tracks, parking, crossings, signals, signage and ASL in addition to on-road traffic calming measures and cycle restrictions (on routes or at points) (TfL, 2023e). These observations were obtained by on-site physical surveying and made available as open datasets. For the infrastructure most commonly associated with providing safe space for cycling: ASL, crossing, cycle lane and tracks, signals and traffic calming; descriptive statistics and visualisations were created showing the provision by borough. The amount of infrastructure was adjusted using official statistics on population, area and commuter cycling with chloropleths constructed that illustrated how infrastructure alters at a borough level when such factors are considered (Lovelace et al., 2017; ONS, 2019; ONS, 2020). Using variables in the CID, the degree of on-road cycle lane segregation from motor vehicles was calculated. Combining the infrastructure data with design guidance and road speed limit data from OSM led to estimations of borough-level compliance with national design guidance (DfT, 2020d; OpenStreetMap contributors, 2023) .

Chapter 3 (Paper 2) constructs a dataset of all one-way streets that had contraflow cycling introduced between 1998 and 2019 in inner London and populated it with multiple variables including borough, road name, spatial extent of contraflow and contraflow start date (and/or stop date). The data comes from searching The Gazette to identify all Traffic Regulation Orders (TRO) that were published in this time period for inner London boroughs (TSO, 2022). These TRO provide the legal exemption for cyclists to cycle against the flow of motor vehicles on one-way streets. Spatial data for the contraflows was obtained from either the London CID, OpenStreetMap(OSM) or constructed using data from the TRO. UK road traffic crash data was obtained for the study years and crashes involving pedal cyclists occurring with 10m of a contraflow segment were identified (DfT, 2022g). The crashes were spatially associated with the nearest contraflow segment and classified as pre-contraflow, contraflow or contraflow removed based on whether the crash occurred before or after contraflow implementation or removal.

The crash rate for pedal cyclists was estimated from the total number of crashes that occurred during the 22 year study period before, during or after the contraflow was removed (numerator) and divided by the total time exposed by each contraflow segment in that status during the 22 year period (denominator) (see Chapter 3 for equations) giving a crash rate per 100 years of exposure. As the volume of cyclists had changed during the study period, manual cordon counts for cyclists travelling into central, inner and outer London were used to generate indices of cycling volume base-lined to 1998 (TfL, 2019b; TfL, 2021). The annual number of crashes occurring in each cordon were adjusted by the cordon-specific cycling volume index for that year and an adjusted crash rate calculated (see Chapter 3 for equations). Pedal cycle casualty rates were calculated using the same approach as the crash rates but the data was limited to the years 2005-2019 as changes were made to injury reporting in 2005. Adjustment factors to take this change into account are only available for subsequent years (DfT, 2020b). Raw casualty rates and rates adjusted for injury severity and change in cordon cycling volume were calculated. Uncertainty of all these rates were estimated using the bootstrapping method. One thousand random re-sampled with replacement datasets were generated from our crash and casualty datasets (Efron and Tibshirani, 1986). Raw and adjusted crash and casualty rates were calculated for each bootstrapped dataset. 95% confidence intervals was calculated from the bootstrapped dataset rates.

Chapter 4 (Paper 3) uses monthly Strava Metro cycle count data for the earliest years available (2018 and 2019) in inner London (Strava Metro, 2023). From the primary dataset created for Chapter 3 (the dataset of all contraflows introduced on one-way streets between 1999 and 2019 in inner London), the roads that had a contraflow introduced in 2018 or 2019 were extracted. The observed monthly cycle counts before and after contraflow implementation were compared to that expected if the monthly change in Strava Metro cycling volume across inner London as a whole occurred on each road. Contraflows that appeared to have a large increase in counts after contraflow cycling was allowed were compared to those that did not see an increase using Google Maps Street View images to understand how the infrastructure varied (Google, 2023). The infrastructure was assessed using the five key design principles of coherence, directness, safety, comfort and attractiveness as well as accessibility and proximity to local cycling routes/networks (DfT, 2020d).

Ethical approval was not required for any of the research. Open source software, R and RStudio, were used for data analysis (RStudio Team, 2023; R Core Team, 2023).

1.8 Thesis structure

This thesis is an alternative format thesis and is composed of six chapters (see Figure 1.2). The first chapter is the Introduction which is divided into two parts. Part 1 sets the scene for the thesis by starting with the history of the bicycle and cycling before focussing geographically to England, specifically on cycling infrastructure and then the evidence base on its effectiveness in terms of cyclist safety and participation. Part 2 builds on these foundations and develops the research rationale by identifying the key research gaps in this evidence base, highlighting the importance of data in evaluating such interventions and the suitability of London as a setting for such evaluation. It then describes the thesis aim and research questions, drawing the links between the questions and the research gaps and outlining key principles that have underpinned the research. Finally it describes the research strategy.

Chapters 2 and 3 are papers that have been published in the Journal of Transport & Health and Accident Analysis & Prevention (respectively). Chapter 4 is a paper that is formatted in the style ready for submission to the Journal of Transport & Health. Citations for these papers and the contributions made by the candidate and co-authors can be found in the Intellectual Property and Publications section after the main title page.

Chapters 5 and 6 are the Discussion and Conclusion chapters. Appendix A is the published supplementary material that accompanies Chapter 2 (Paper 1), Appendix B is the supplementary material for Chapter 4 (Paper 3) and Appendix C contains figures referenced in the Discussion.

1.9 Wider thesis outputs

The research for this thesis generated more outputs beyond that presented within this thesis. To facilitate easy access to and analysis of the London CID, an R package was created by the candidate (Tait and Lovelace, 2019). This package, known as *CycleInfraLnd* is available for others to use via github (https://github.com/PublicHealthDataGeek/CycleInfraLnd). This package was used to access the CID data for Paper 1 (see Chapter 2) but it was also used to access the CID data for another paper that the candidate co-authored, *Connected bikeability in London: Which localities are better connected by bike and does this matter?* (Beecham et al., 2023). This published paper examines the connected bikeability of cycle routes and the CID contributed to the assessment of bikeability across three components: safety, attractiveness and coherence. The candidate contributed to the paper in the following ways: conceptualisation, data extraction, data analysis, writing and visualisation.

The candidate also co-authored a second paper, *Severe and Fatal Cycling Crash Injury in Britain: Time to Make Urban Cycling Safer*, that used UK road traffic crash data to examine the individual, social and environmental predictors associated with fatal or severe

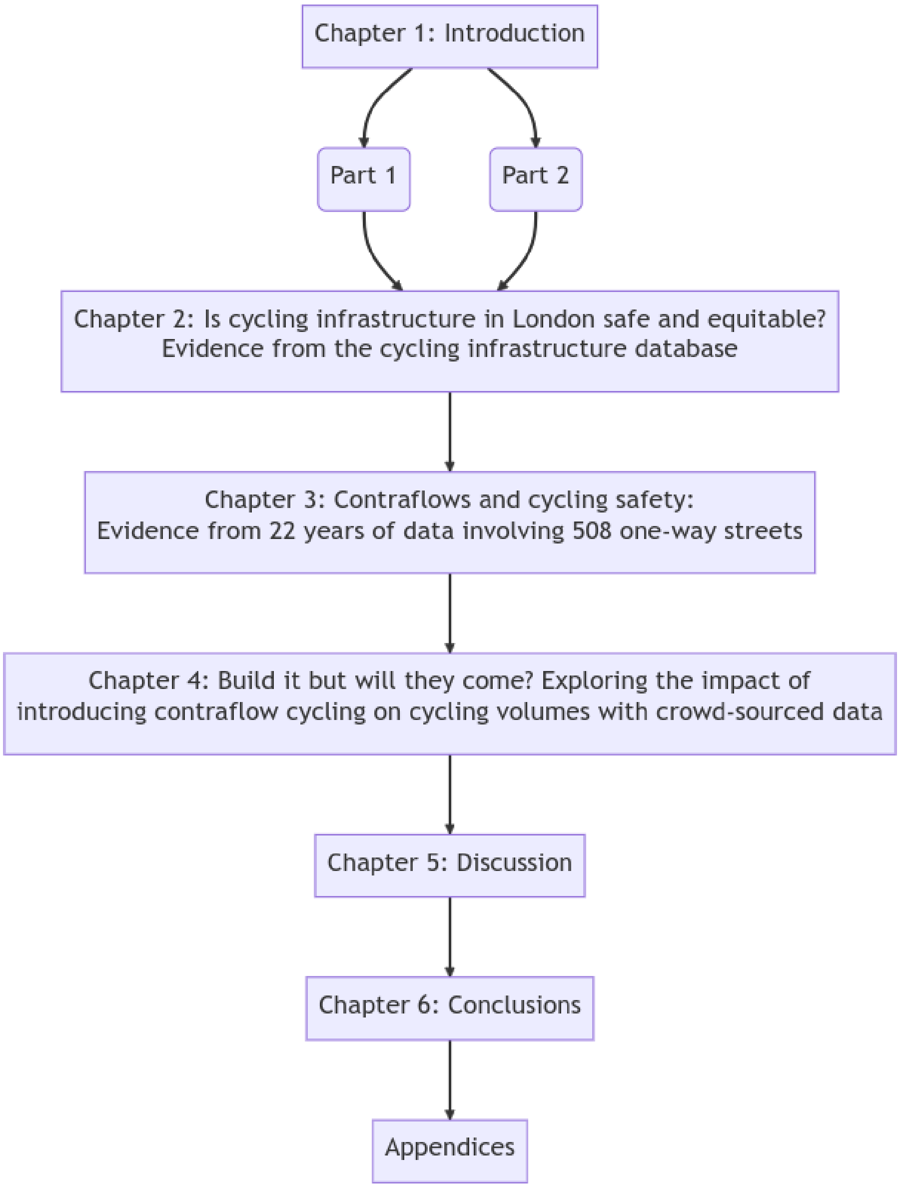

FIGURE 1.2: Thesis structure

cyclist casualties (Mason-Jones et al., 2022). The candidate contributed to the paper's conceptualisation, extracted the road traffic crash data and contributed to the writing of the article.

Key principles driving the research is that it should contribute to the evidence base and be policy relevant. The findings of Paper 2 (Chapter 3) regarding the safety of contraflow cycling, namely that introducing contraflow cycling had no change on the pedal cyclist crash or casualty rate, was a significant finding in terms of being policy relevant as implementing such infrastructure is relatively cheap and there are many one-way streets in England. As such it was important to disseminate this research. As part of this dissemination, a thread was constructed on Twitter to communicate the publication and its findings. This reached many readers through re-tweets including in Finland, Sweden, France, USA and Belgium who ranged from transport planners, cycle campaigners, academics to members of the public. This research was presented to the Department for Transport as part of their regular seminars with the Leeds Social Science Institute at the University of Leeds (a recording is available Tait (2022)). It has also been presented to Active Travel England, the Cycling & Walking Commissioner at West Midlands Combined Authority, the Urban Transport Group (the UK network of city region transport authorities), Road Safety GB members (a national road safety organisation that includes local government road safety teams) and the Public Health and Sustainable Transport Partnership Group convened by Public Health Scotland.

1.10 Summary of Introduction

Cycling in England is not universal with spatial and demographic variations. It generates numerous benefits for the individual and society across health, environment, society and economy. The benefits of cycling far outweigh the risk of injury, crashes and air pollution and it is one of the most equitable forms of transport. The more people who cycle, the safer cycling becomes.

To encourage more people to cycle, there must be a multi-pronged, multi-agency approach encompassing policy, legislation, awareness, training, societal change, leadership and physical cycling infrastructure. High-quality cycling infrastructure should be coherent, direct, comfortable, attractive and safe. Implementing such wide-ranging approaches in England has been variable as it requires aligned central and local government action. Particular barriers at local level include resources, politics, institutions and attitudes. Perceptions of being unsafe and a lack of infrastructure are particular barriers for individuals, discouraging many from cycling. Introducing safe infrastructure has been identified as part of the solution to increase cycling as it can address these personal barriers. However, the evidence base around the effectiveness of cycling infrastructure to objectively or subjectively increase cyclist safety and participation is limited.

There are significant research gaps in the evidence base on cycling infrastructure. These are related to the infrastructure, methods and implementation context. Most studies use very little data, provide little detail, use substandard methods and have short duration of follow up. Issues around data and information are significant. The use of 'big data' such as large observational datasets on infrastructure, crashes or participation could help to address some of these issues.

The aim of this thesis to is generate high-quality research evaluating the effect of cycling infrastructure on safety and participation using large observational datasets that addresses some of the current issues with the evidence base. It focusses on London and examines what cycling infrastructure exists in this city (Chapter 2, Paper 1) before examining an under-researched infrastructure type - that of contraflow cycling, cycling against the flow of motor vehicle traffic on one-way streets. Firstly, it examines the safety of such infrastructure by looking at cyclist crashes and casualties over 22 years using a before and after approach on 508 one-way streets (Chapter 3, Paper 2). Secondly it examines the effect of the infrastructure on these same streets on cycling participation measured using new crowd-sourced datasets (Chapter 4, Paper 3). These chapters and paper following the introduction with both Chapters 2 and 3 being published in peer-reviewed journals and Chapter 4 about to be submitted for publication.

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Chapter 2

Paper 1: Is cycling infrastructure in London safe and equitable? Evidence from the cycling infrastructure database

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Is cycling infrastructure in London safe and equitable? Evidence from the cycling infrastructure database

Caroline Tait [a,*], Roger Beecham [b], Robin Lovelace [a,c], Stuart Barber [d]

[a] Leeds Institute for Data Analytics, University of Leeds, Leeds, UK
[b] School of Geography, University of Leeds, Leeds, UK
[c] Institute for Transport Studies, University of Leeds, Leeds, UK
[d] School of Mathematics, University of Leeds, Leeds, UK

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A B S T R A C T

Introduction: We describe and analyse a new, open dataset of surveyed cycling infrastructure in London UK. We demonstrate its potential to contribute to research and evidence-based policy development through a spatial analysis of infrastructure provision in London, before evaluating administrative boroughs on their infrastructure mix and compliance with UK Cycle Infrastructure Design Standards.
Methods: We processed and cleaned the 233,596 records in the London Cycling Infrastructure Database (CID) that contains nine infrastructure types. To support comparison between London boroughs, infrastructure provision was normalised to borough area, population size and level of commuter cycling. We generated variables capturing cyclist separation from motor vehicles and estimated cycle lane compliance for such segregation against design standards.
Results: Each CID record contains the infrastructure survey date, spatial location, infrastructure-specific variables and accompanying photographs. Traffic calming assets are numerous and distributed throughout London. Cyclist signals, crossings, Advanced Stop Lanes and cycle lanes and tracks are less numerous and more commonly seen in inner rather than outer London. Normalisation by area and population did not change these spatial patterns. Six percent of on-road cycle lane length is physically segregated from vehicles. Estimated compliance with UK design standards was notably higher for inner London boroughs with 66% exceeding mean compliance compared to just 24% of outer London boroughs.
Conclusions: In this first systematic description and analysis of the CID we have demonstrated its potential to quantitively and qualitatively compare infrastructure and a method to estimate compliance against design standards. We found that cycling infrastructure is not distributed equally across London and may not be of the quality that provides safe space for cycling. Such datasets are critical assets to evaluate infrastructure and guide health and transport policies.

1. Introduction

Enabling more cycling is important as it is one of the healthiest, safest (Khreis et al., 2016; Woodcock et al., 2014) and potentially

* Corresponding author. Leeds Institute for Data Analytics, Level 11 Worsley Building, Clarendon Way, Leeds, LS2 9NL, UK.
E-mail addresses: ugm4cjt@leeds.ac.uk (C. Tait), r.j.beecham@leeds.ac.uk (R. Beecham), r.lovelace@leeds.ac.uk (R. Lovelace), s.barber@leeds.ac.uk (S. Barber).

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most equitable (Pereira et al., 2017) forms of transport, leisure and exercise. Cycling generates numerous benefits for individuals and society, representing one of the simplest and most effective solutions to crises ranging from climate change (Woodcock et al., 2009) to the obesity epidemic (Rasmussen et al., 2018). Increased physical activity associated with cycling uptake can improve physical and mental health, reduce motor vehicle usage, congestion, air and noise pollution and health costs (Götschi et al., 2020; Laird et al., 2018). The COVID-19 pandemic has profoundly impacted transport, leisure and exercise and disrupted historical patterns of cycling and motor vehicle use (De Vos, 2020; Hadjidemetriou et al., 2020; Hong et al., 2020a; Li et al., 2021). Some pandemic impacts may become sustained societal shifts, presenting new opportunities to embed active travel and greater cycling participation (Budd and Ison, 2020; Laverty et al., 2020; Musselwhite et al., 2021; Tirachini and Cats, 2020).

To enable more cycling, cycling networks and routes must be safe, coherent, direct, comfortable and attractive (DfT, 2020a). Dedicated cycling infrastructure has a central role to play in delivering these key principles. Cycle lanes and segregated cycle paths are cited by people as factors that would encourage them to cycle (DfT, 2020b) and dedicated infrastructure may address the significant perceived and actual safety concerns that deter many from cycling (e.g. DfT, 2020c; Félix et al., 2019; Lorenc et al., 2008; Pooley et al., 2013). However, evaluating infrastructure, to determine whether it is safe, coherent, direct, comfortable and attractive, is hindered by a lack of high-quality infrastructure data (Reid and Ada, 2010). In many studies this data is partial, sporadic and contains a fraction of the infrastructure available (e.g. a few kilometres) (Reid and Ada, 2010). It is complicated by differences or inconsistency in infrastructure design (Reynolds et al., 2009) and failure to describe infrastructure characteristics (Mulvaney et al., 2015). This can be compounded by the fact that much infrastructure data is held locally by planners and not publicly accessible (Hong et al., 2020b; Schoner and Levinson, 2014).

High-quality, complete, open, infrastructure datasets such as the London Cycling Infrastructure Database (CID) could improve the quality of evaluation and thus the evidence base for infrastructure effectiveness. Cycling infrastructure in London has developed over many years influenced by geography, politics, priorities and investment (Golbuff and Aldred, 2011; Di Gregorio and Palmieri, 2016). Ninety-five percent of London roads are managed by local government (33 London boroughs). Transport for London (TfL) manages most main roads and is responsible for delivering the Mayor of London's Transport Strategy including the implementation of strategic schemes such as Cycle Superhighways, which aim to provide direct, quality cycling highways connecting key parts of the city (TfL, 2022). The CID surveys all physical cycling infrastructure in London. Created by TfL in 2019, its ambition is to 'address barriers to cycling by providing Londoners with clear and accurate information about cycling infrastructure, helping them plan cycle journeys with confidence' and to 'help TfL and the boroughs to plan future cycling investment' (TfL, 2019a). This data was systematically collected and coded through on-site surveying and provided complete, contemporary, coverage (TfL, 2019b, 2020a). The CID is available as open data (TfL, 2019c) and collaboration with OpenStreetMap aims to ensure that it becomes a dynamic dataset (OSM Wiki contributors, 2020). We believe this new, open dataset is a highly valuable cycling infrastructure resource.

This paper explores this new cycling infrastructure database for the first time and demonstrates its potential to support research and influence policy and planning. After describing the database in detail, we present a data analysis comparing variation in cycling infrastructure provision across London's boroughs. We compare boroughs according to the distribution, type, quantity and quality of infrastructure, adjusting for factors such as geographical area, population size and amount of cycle commuting. We also evaluate on-road cycle lane separation from motor vehicles and estimate compliance of this separation with new UK Cycle Infrastructure Design Guidance (DfT, 2020a).

2. Methods

2.1. Data

The London CID contains cycling infrastructure data derived from systematic physical surveys conducted between 2017 and 2019 (TfL, 2019a). The CID data were accessed via the TfL cycling open data portal (TfL, 2019c). We created an R package named CycleInfraLnd (Tait and Lovelace, 2019) to import the data into R in the standard simple features class (Pebesma, 2018). The CycleInfraLnd package presents the cycling infrastructure as a data frame, with latitude and longitude coordinates represented in a 'geometry' column for each of the 233,596 cycling infrastructure observations in the CID.

The 2019 Greater London boundary was used to spatially limit all datasets to within London to coincide with the final year of CID survey. Inner and outer London boroughs were defined by the London Plan (GLA, 2021). To support borough-level comparison when characterising infrastructure provision, we adjusted for geographical area, population size and level of commuter cycling. The population estimates (mid-2019) (ONS, 2020a), geographical boundaries and areas (ONS, 2020b) for each of the 33 London boroughs were obtained from the Office for National Statistics. The Propensity to Cycle Tool uses individuals' home origin and employment destinations from the 2011 Census and a cycling routing algorithm to estimate the number of commuter cycling trips using each segment on the route network (Lovelace et al., 2017). We took these route network level data and split it by borough boundaries. Where the network crossed a boundary, we created two segments. We calculated the total distance cycled by commuters per working day on each borough segment by multiplying the segment length by the number of commuter cyclists using that segment per working day. Finally, we calculated the estimated annual total distance cycled by commuters by multiplying the previous figure by 400 (one outbound and one inbound trip for 200 working days of the year). Historical road speed limit data, required to assess compliance of cycle lanes with UK design standards, was obtained from OpenStreetMap for January 2019 (Geofabrik, 2019; OSM contributors, 2017).

2.2. Analysis of the cycling infrastructure database

We examined all CID datasets for errors and missing values. Minor spelling mistakes were corrected and missing infrastructure values were examined and corrected manually where possible, for example by using a combination of google maps and CID infrastructure images.

We spatially joined all CID observations with borough boundaries to ensure they were labelled with the correct borough (ONS, 2020c). Where an observation did not have a pre-existing borough label or there was a mismatch between the pre-existing and spatially-joined borough, these were corrected. Observations were examined to ensure they contained a single infrastructure item per row of data. Where a single row represented more than one infrastructure item, for example, multiple cycle crossings at a junction, it was replaced by multiple, new, single observations. We calculated the dimension of those CID observations that have linear spatial data. We performed a detailed analysis of the five CID datasets most obviously related to providing safe space for cycling. These are: Advanced Stop Lines (ASL) that provide protective space at traffic signals, crossings for cyclists, signals for cyclists, physical traffic calming and cycle lanes and tracks. Observations were aggregated to borough level and joined to datasets containing geographical area, estimated population and estimated total annual commuter cycle distance. To support borough-level comparison we calculated counts (length for cycle lanes and tracks) by area (square kilometre), per 100,000 head of population and per 100,000 km estimated total annual commuter cycling.

2.3. Determining on-road cycle lane separation from motor vehicles

On-road cycle lanes in the CID have multiple variables that define their separation from motor vehicles. Each on-road cycle lane observation was assigned the ‘highest’ level of separation ordered as follows: full segregation, stepped, partial segregation, mandatory cycle lane, advisory cycle lane and no separation (Fig. 1). We categorised the cycle lanes by whether they were shared bus lanes, contraflow cycle lanes or general cycle lanes.

2.4. Estimating on-road cycle lane compliance with UK Cycle Infrastructure Design Guidance (LTN 1/20)

The UK Cycle Infrastructure Design Guidance (LTN 1/20) provides clear recommendations for designing cycle lanes to protect cyclists from motor vehicles on highways (DfT, 2020a). Full segregation is considered suitable in most road conditions whilst stepped or part segregation is appropriate when the road speed limit is 30 mph or less (see Fig. 1 depictions). Mandatory and advisory cycle

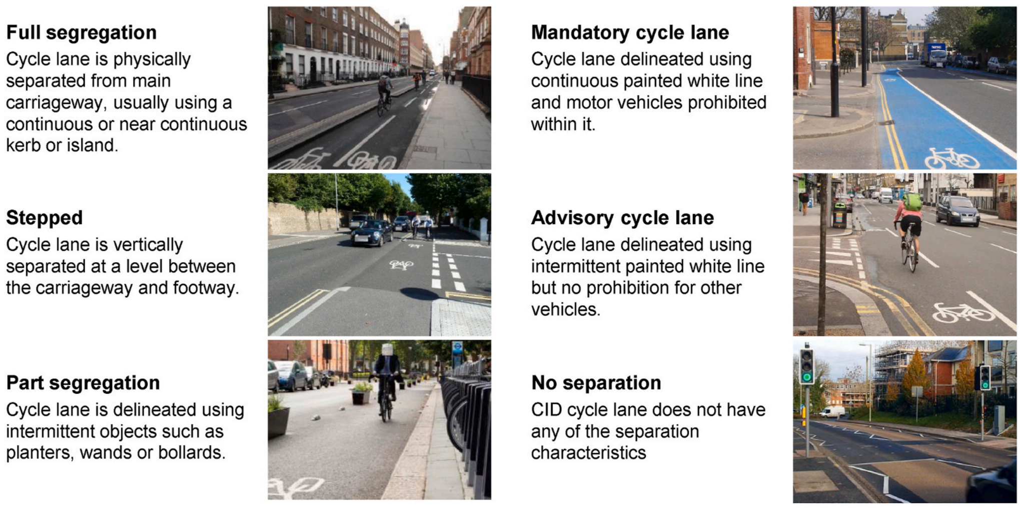


Fig. 1. Categorisation of CID on-road cycle lane separation from motor vehicles (images taken from TfL, 2019b).

lanes are considered better than no cycle lane but only under certain circumstances: the road speed limit is 20 mph or less, exceedance of this speed limit is minimal and traffic volumes are below a certain threshold (DfT, 2020a). Data on traffic volumes and speed limit exceedance is not available for most roads in London so for this analysis we assumed that these thresholds were not breached.

To associate cycle lane separation with the speed limit of that road, we needed to join the CID to OpenStreetMap speed limit data. As OpenStreetMap speed limit data is represented as a single line, we enlarged this to a road 'zone' allowing 3.65 m for lane width (Highways England, 2020) and 6 m for potential OpenStreetMap positional inaccuracy (Haklay, 2010) each side of the line. Cycle lanes that were within (67%) or touching (13%) a road zone were allocated that road zone speed limit (facilitated by spatial joins). All cycle lane segments were then tested for compliance with LTN 1/20 level of protection standards and judged as being compliant if they met the criteria in Table S1. This identified 2738 (18%) cycle lanes where it was unknown as to whether the cycle lane was compliant (actual number of cycle lanes with unknown speed limits was 3158). These 2738 cycle lanes were visually inspected with OpenStreetMap data to establish whether a speed limit could be attributed to the cycle lane. Where it could, speed limit data was attributed and where it could not it was left as "Unknown". This approach resulted in 2335 (15%) observations where it was unknown as to whether the separation was appropriate.

More details about all the methods described above can be found in the Supplementary materials.

3. Results

3.1. Description of the cycling infrastructure database

The CID consists of nine datasets each containing a different type of linear or point physical cycling infrastructure (Fig. 2). There are seven variables present in every dataset: a unique identifier, survey date, borough location, two URLs for photographs of the infrastructure and coordinates of the location. Each dataset contains further variables that are unique and relevant to the infrastructure type and these are detailed in Table S2.

In total the CID datasets contained 234,251 observations, each representing an individual infrastructure object, after applying the processing steps outlined in the previous section. The majority are signage (51%) or traffic calming (25%) whilst restricted points

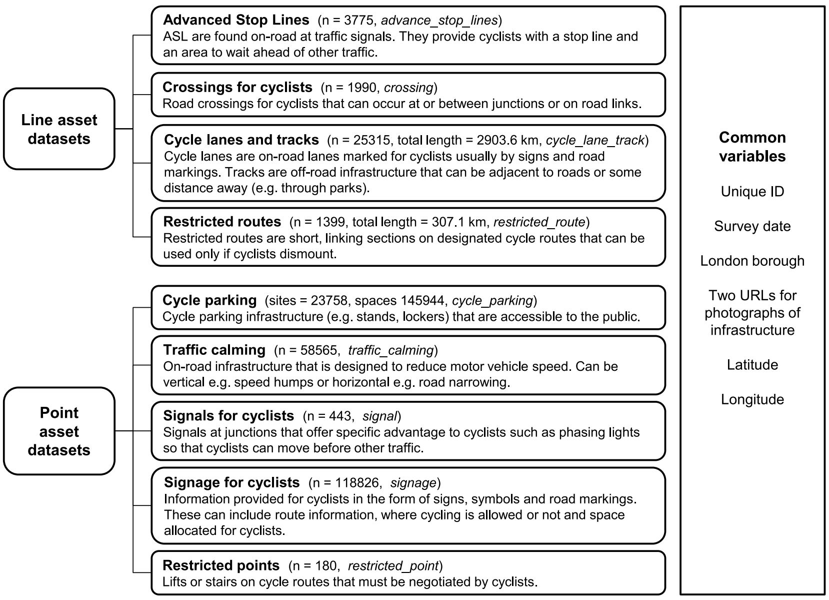
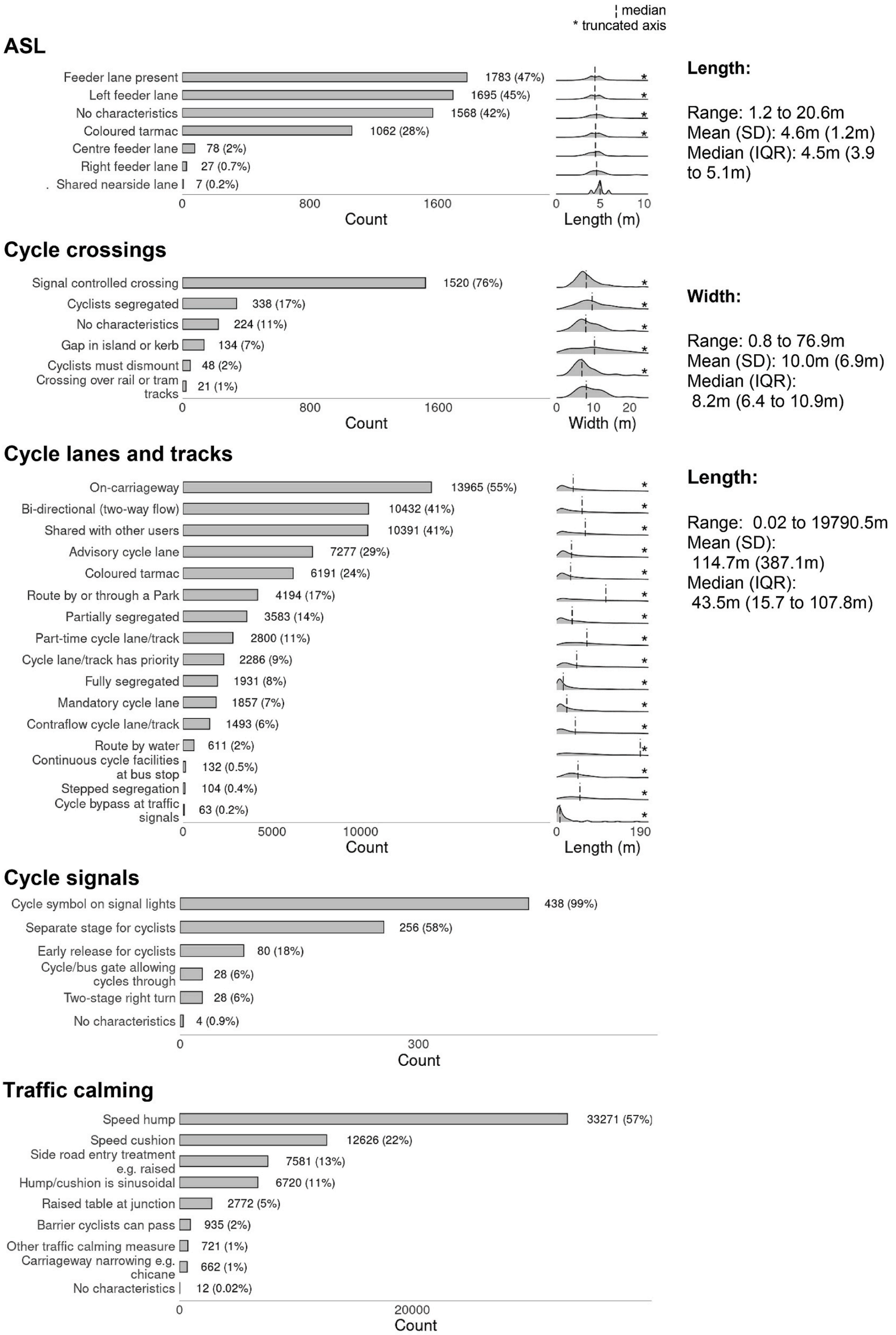


Fig. 2. An overview of the nine CID datasets (number of observations and *dataset name*) and their common variables [a].
[a] Descriptions sourced from TfL (2019b). Number of observations reflects the count following data cleansing described in the Methods section. On-carriageway line asset spatial data is aligned to the kerb except for crossings, which run perpendicular to the kerb, and cycle lanes that continue through a junction. It represents where the infrastructure starts and ends according to road markings. Off-carriageway line asset spatial data is aligned to actual position where possible and represents the central location on the footway or path. Point assets are spatially located as close as possible to their physical location. Co-located assets, e.g. multiple signs on a single signpost, are recorded as separate assets.

Table 1
Characterisation of infrastructure data by variables: bar charts of counts (%), and smoothed histograms with summary statistics of linear CID data.



(0.1%) and signals (0.2%) are the least common. Infrastructure was surveyed between January 6, 2017 and September 2, 2019 with 76% surveyed in 2017, 24% in 2018 and 0.01% in 2019. Despite regular modifications to the online CID data repository, it appears that no new data has been added since September 2, 2019. All 33 London boroughs are present in the nine datasets apart from 10 boroughs (signals) and six boroughs (restricted points). Most observations (98%) have two photographs and coordinates are present for all observations. The CID only includes one-dimensional linear information, for example, the length but not the width of cycle lanes.

In the remainder of this section we focus on the CID infrastructure most important in providing safe space for cycling namely the ASL, crossings, cycle lanes and tracks, signals and traffic calming datasets.

3.2. Description of specific infrastructure datasets

The ASL, crossings, cycle lanes and tracks, signals and traffic calming datasets are characterised in Table 1. Further descriptions of this infrastructure can be found in tables A1-A.6.

The most common characteristic of ASL is a feeder lane (47%), predominantly on the left (45%). Only seven ASL have more than one feeder lane (Table A1). Most cyclist crossings are signal controlled (76%) and nearly a fifth segregate cyclists from other users (17%). Some crossings have multiple characteristics (Table A3); for example, 45 crossings (2%) are signal-controlled, have cyclist segregation and a gap in the island or kerb. Crossing width varies depending on characteristics, crossings with gaps in kerbs or islands (required for wider crossings) have the highest median value (10.3 m). Fifty-five percent (944.0 km) of cycle lanes and track are on-road (Table A4). The most frequent cycle lane and track characteristics are bi-directional flow (41%, 1911.4 km) and sharing with buses or a footway (41%, 1896.2 km). Unlike ASL, cycle lane and track length varies considerably by characteristic with water routes and park routes having the longest medians (189.6 km and 111.5 km). Only four signals have no characteristics whilst 99% have a cycle symbol on the traffic lights (Table A5). The majority have a separate cyclist lighting phase (58%). Speed humps (57%) and cushions (22%) are the prevalent traffic calming infrastructure. Only nine percent of humps and three percent of cushions are sinu-soidal, the shape that is most comfortable for cyclists (Table A6). Just 15 traffic calming observations (0.03%) have more than one characteristic.

For cycle lanes and tracks, length appears to be a more appropriate measure than count due to the extreme variation in length between observations. For example, 55% of observations are on-road but these account for 33% of total length. This is explained by the varying nature of on-road cycle lanes, necessitating new observations when they change, for example, from segregated to advisory cycle lanes (Table A4). Length rather than count will be used in subsequent analyses.

Cycle lanes and tracks vary by whether they are on or off-road (Fig. 3, Table A4). Unsurprisingly, certain characteristics are almost exclusively found off-road e.g. water or park routes whilst others are predominantly found on-road e.g. mandatory, advisory, con-traflow or priority cycle lanes. Advisory cycle lanes, a cheap form of infrastructure, has the greatest on-road length (489.2 km) whilst Bi-directional tracks have the longest off-road length (1885.4 km).

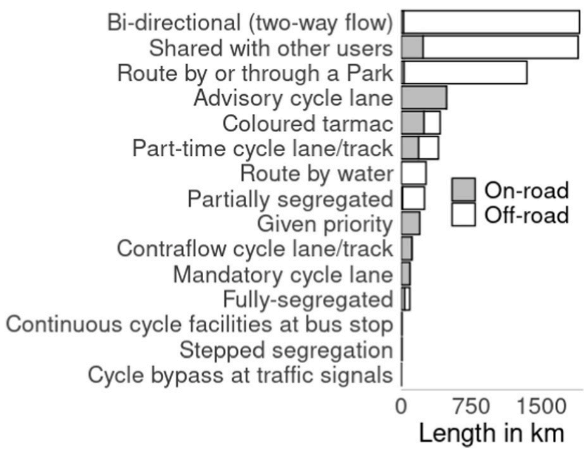


Fig. 3. Comparison of characteristics of on-road cycle lanes and off-road cycle tracks.

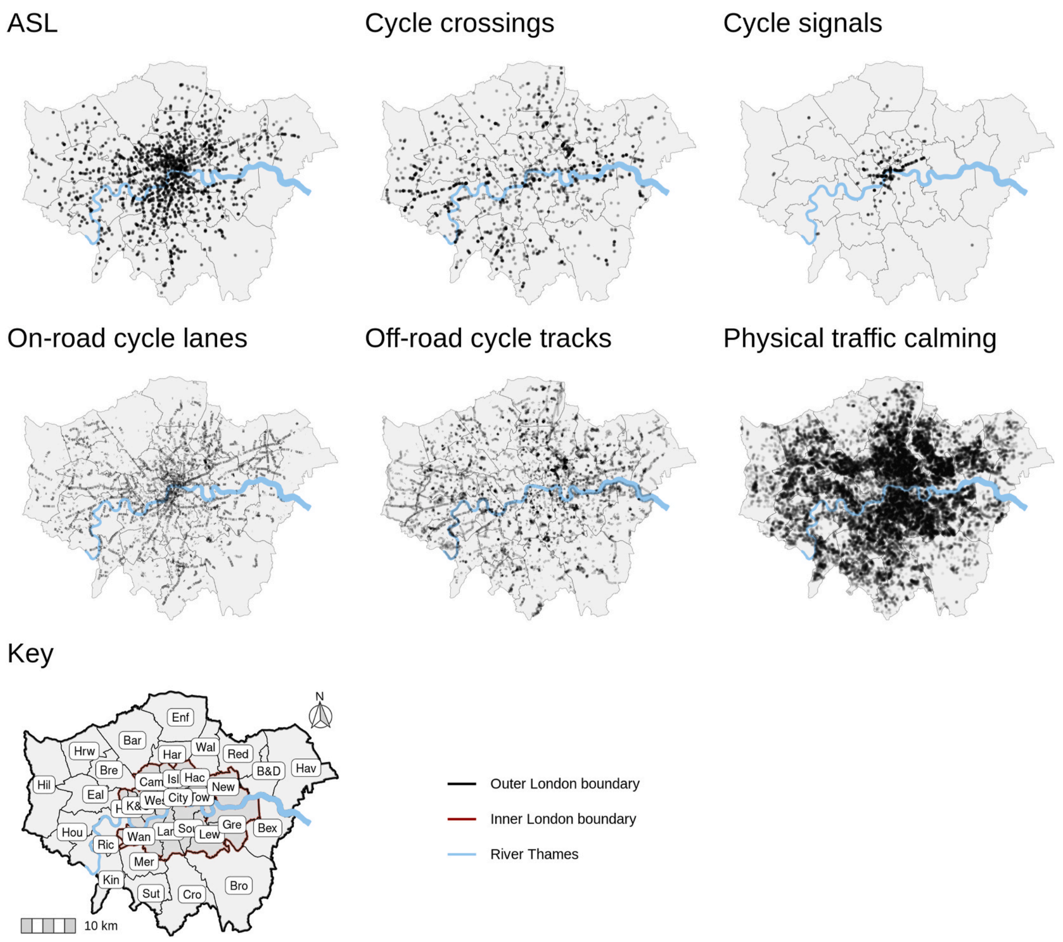


Fig. 4. Spatial distribution of infrastructure across London.
Bro = Bromley, Cam = Camden (I), City = City of London (I), Cro = Croydon, Eal = Ealing, Enf = Enfield, Gre = Greenwich (I), Hac = Hackney (I), H&F = Hammersmith & Fulham (I), Har = Haringey, Hrw = Harrow, Hav = Havering, Hil = Hillingdon, Hou = Hounslow, Isl = Islington (I), K&C = Kensington & Chelsea (I), Kin = Kingston upon Thames, Lam = Lambeth (I), Lew = Lewisham (I), Mer = Merton, New = Newham (I), Red = Redbridge, Ric = Richmond upon Thames, Sou = Southwark (I), Sut = Sutton, Tow = Tower Hamlets (I), Wal = Waltham Forest, Wan = Wandsworth (I), Wes = Westminster (I), (I) = Inner London borough.

3.3. Spatial distribution

The five types of infrastructure are not uniformly distributed across London (Fig. 4). ASL and signals are predominantly located in inner London whilst traffic calming measures are distributed throughout London, particularly in areas of high residential density. On-road cycle lanes correspond to arterial roads and strategic cycling infrastructure (such as the Cycle Superhighways that provide high-quality cycle routes) whereas off-road cycle tracks frequently correspond to areas of green space. Certain locations, particularly boroughs in outer London, appear to have very little cycling infrastructure.

3.4. Borough-level analysis

Comparison of boroughs by absolute amount of infrastructure shows that there is considerable variation (Table 2). Signals are the only type of infrastructure that has no representation in some boroughs (n = 10). Signals, ASL and traffic calming show the greatest variation in values between boroughs. Most boroughs (n = 25) have more off-road than on-road cycle lane length. Examining individual boroughs, we can see that there is no consistent pattern as boroughs with a large amount of one type of infrastructure do not necessarily have large amounts of other types of infrastructure and vice versa.

The maps displaying absolute infrastructure by boroughs (Fig. 5, column 1) show that ASL are predominantly located in the inner London boroughs of Lambeth, Southwark, Camden, Westminster and Wandsworth whilst signals are almost exclusively found in the inner London boroughs of Westminster, Tower Hamlets, City, Lambeth and Southwark. The highest numbers of traffic calming measures are found in Southwark and Lambeth (boroughs with high population density) along with Lewisham, Newham and Hackney (all inner London). Hillingdon, Hounslow (outer) and Newham (inner) have the highest number of crossings. Croydon, Barking and Dagenham and Waltham Forest (outer) and Lambeth and Southwark (inner) have the greatest amount of on-road cycle lanes whilst Richmond upon Thames, Hounslow, Enfield, Ealing (outer) and Newham (inner) have the greatest amount of off-road cycle tracks.

Table 2
Borough raw count or length of infrastructure: Summary statistics and individual borough data.

	ASL	Crossings	Signals	Traffic calming	Cycle lanes and tracks	
					On-road	Off-road
Summary statistics						
Range	6–336	16–140	0–96	182–3604	5.8–58.3 km	1–112.7 km
Mean (SD)	114.4 (79)	60.3 (31.9)	13.4 (22.9)	1774.7 (946.4)	28.6 km (12.0 km)	59.4 km (30.1 km)
Median (IQR)	94 (57–146)	54 (42–71)	2 (0–16)	1513 (1024–2558)	28.8 km (20.9–34.0 km)	58.8 km (43.8–81.3 km)
Inner London boroughs						
Camden	259	19	36	1681	35.8 km	10.9 km
City of London	122	16	58	182	20.8 km	1.0 km
Greenwich	113	93	0	2834	32.2 km	87.6 km
Hackney	188	58	25	2923	32.8 km	60.7 km
Hammersmith & Fulham	81	51	3	1362	31.8 km	36.9 km
Islington	165	22	16	2108	30.6 km	12.1 km
Kensington & Chelsea	89	17	5	360	12.5 km	15.4 km
Lambet	336	46	44	2989	49.6 km	45 km
Lewisham	126	49	1	3604	27.2 km	59.3 km
Newham	146	139	0	3103	31.1 km	108.1 km
Southwark	274	71	44	3542	40.3 km	51.3 km
Tower Hamlets	100	41	59	2320	28.5 km	73.6 km
Wandsworth	228	59	17	2001	34.0 km	55.3 km
Westminster	229	48	96	716	34.1 km	22 km
Outer London boroughs						
Barking & Dagenham	76	54	0	1539	49.4 km	58.8 km
Barnet	6	36	0	377	6.6 km	64.7 km
Bexley	6	42	0	1015	13.8 km	71.0 km
Brent	92	38	1	2921	13.5 km	55.0 km
Bromley	51	45	2	795	21.4 km	90.9 km
Croydon	122	67	2	2167	58.3 km	57.9 km
Ealing	157	60	1	2879	38.8 km	96.5 km
Enfield	38	78	5	1513	17.0 km	100.2 km
Haringey	85	60	0	2156	23.2 km	65.6 km
Harrow	42	45	6	1318	32.0 km	34.5 km
Havering	47	48	0	1024	25.4 km	71.1 km
Hillingdon	57	140	4	920	20.9 km	81.3 km
Hounslow	99	139	0	1365	33.6 km	107.0 km
Kingston upon Thames	68	67	4	1300	28.8 km	21.5 km
Merton	94	78	2	1269	20.9 km	44.1 km
Redbridge	48	37	1	1381	24.5 km	88.9 km
Richmond upon Thames	78	92	0	930	24.3 km	112.7 km
Sutton	30	76	0	1413	5.8 km	54.8 km
Waltham Forest	123	59	11	2558	44.2 km	43.8 km

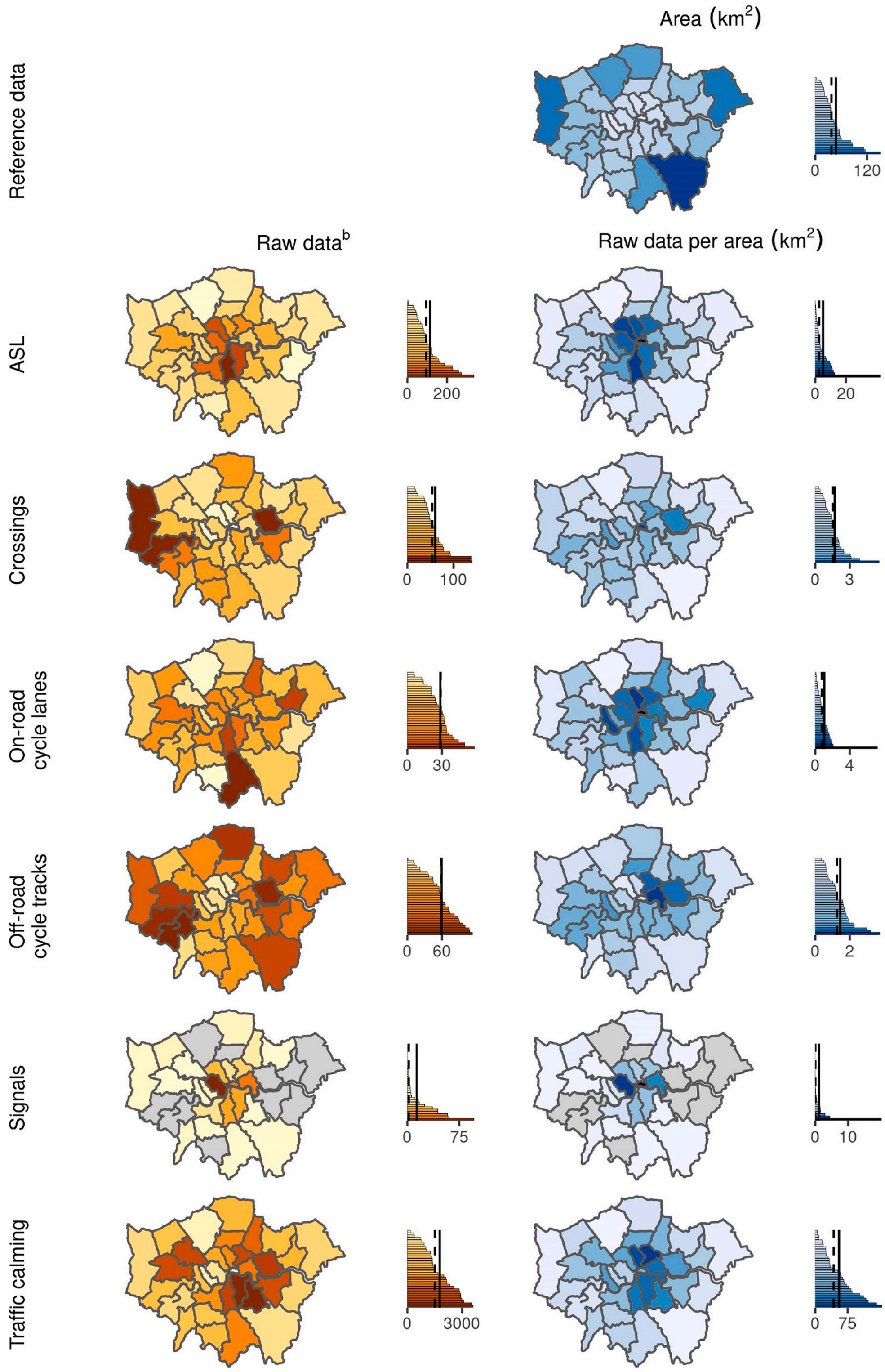


Fig. 5. Visualisations of borough-level cycling infrastructure as raw data and normalised to borough geographical area, population size and commuter cycling (bar chart key: dashed line = median, solid line = mean).
a. The City of London can be an extreme outlier when normalised to borough area and population size due to it being small with a low population. When it is an extreme outlier it is coloured black. b. Raw data is in counts apart from cycle lanes and tracks which is in length (kilometre) c. Estimated amount of commuting cycling in the borough in million kilometres per year.

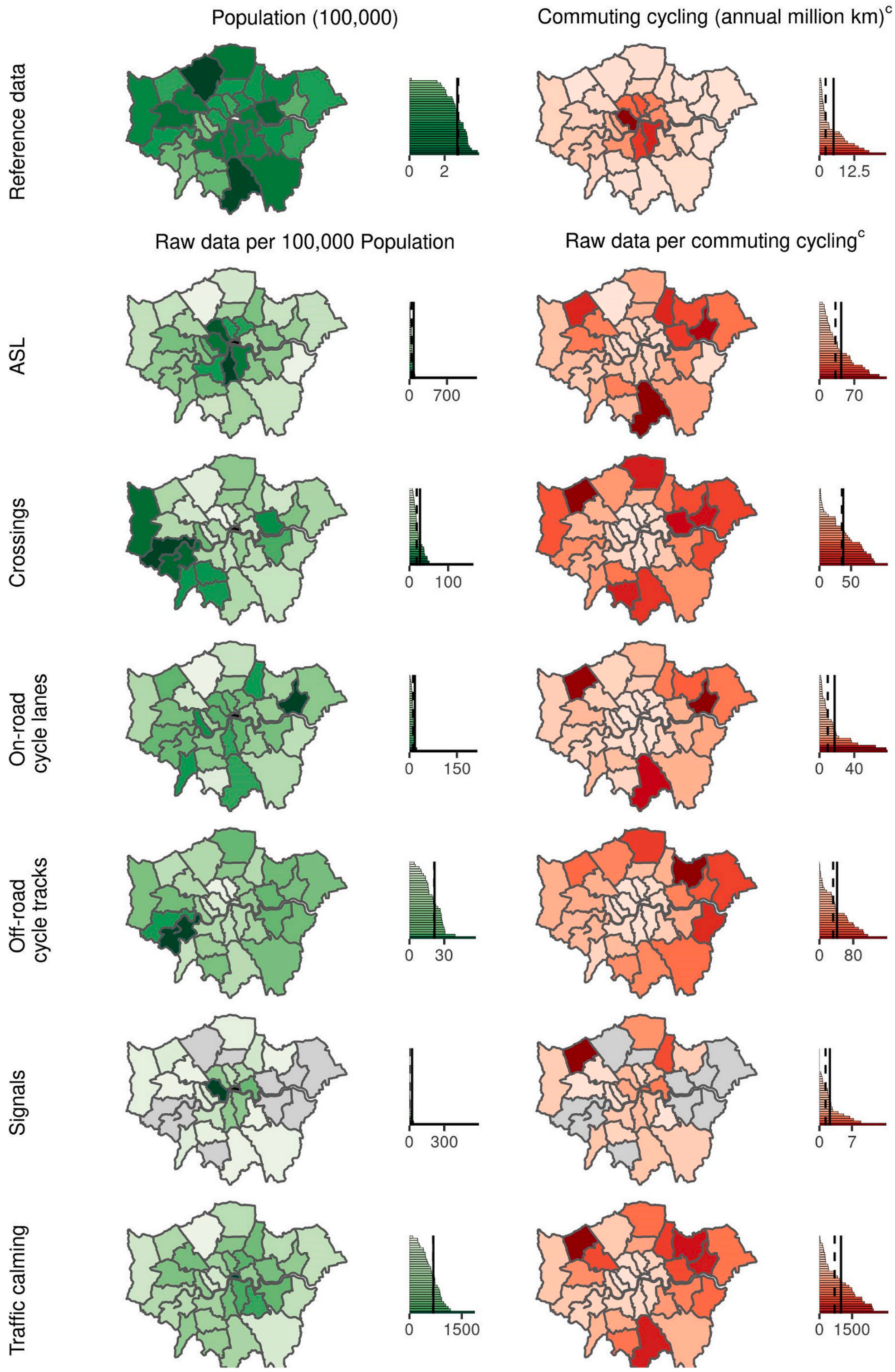


Fig. 5. (*continued*).

Table 3
CID on-road cycle lane length by highest degree of separation from motor vehicles.

Highest degree of cyclist separation from motor vehicles	CID cycle lane length in kilometre		
	Total (Percentage)	Shared bus lane (Percentage of total length of that degree of separation)	Contraflow cycle lane (Percentage of total length of that degree of separation)
Full segregation	39.2 (4)	0.3 (0.8)	5.8 (15)
Stepped	0.7 (0.1)	0.0 (0)	0.0 (0)
Part-segregation	15.7 (2)	0.3 (2)	3.3 (21)
Mandatory cycle lane	85.3 (9)	0.9 (1)	9.9 (12)
Advisory cycle lane	487.0 (52)	2.5 (0.5)	20.8 (4)
No separation	316.1 (34)	232.0 (73)	72.7 (23)
Total	944.0	236.4	112.5

When the absolute data is adjusted (normalised) by borough area and population size (Fig. 5, columns 2 and 3), different patterns emerge. The City of London (the smallest, least populated borough) has the highest density of infrastructure by area and population except for traffic calming (by area) and off-road cycle tracks. For the other 32 boroughs, normalising the raw data by area or population does not tend to alter patterns seen for ASL and signals but does increase the density of this infrastructure in inner London.

Normalisation does appear to reduce variation between boroughs for the other infrastructure types. For example, when normalised by area Hillingdon is no longer the darkest borough for crossings nor is Croydon for on-road cycle lanes, whilst normalising by population size results in greater similarity in colour for crossings in south-western boroughs and off-road cycle tracks in eastern and far-western boroughs. This reduced variability in colour suggests that provision of infrastructure by borough is more equal when normalised by area and population than when evaluated using absolute numbers.

Commuter cycling is predominantly undertaken through inner London boroughs (Fig. 5 column 4). When the raw data is normalised to the estimate of annual commuter cycling an inverse pattern is seen with low infrastructure density in inner London, most

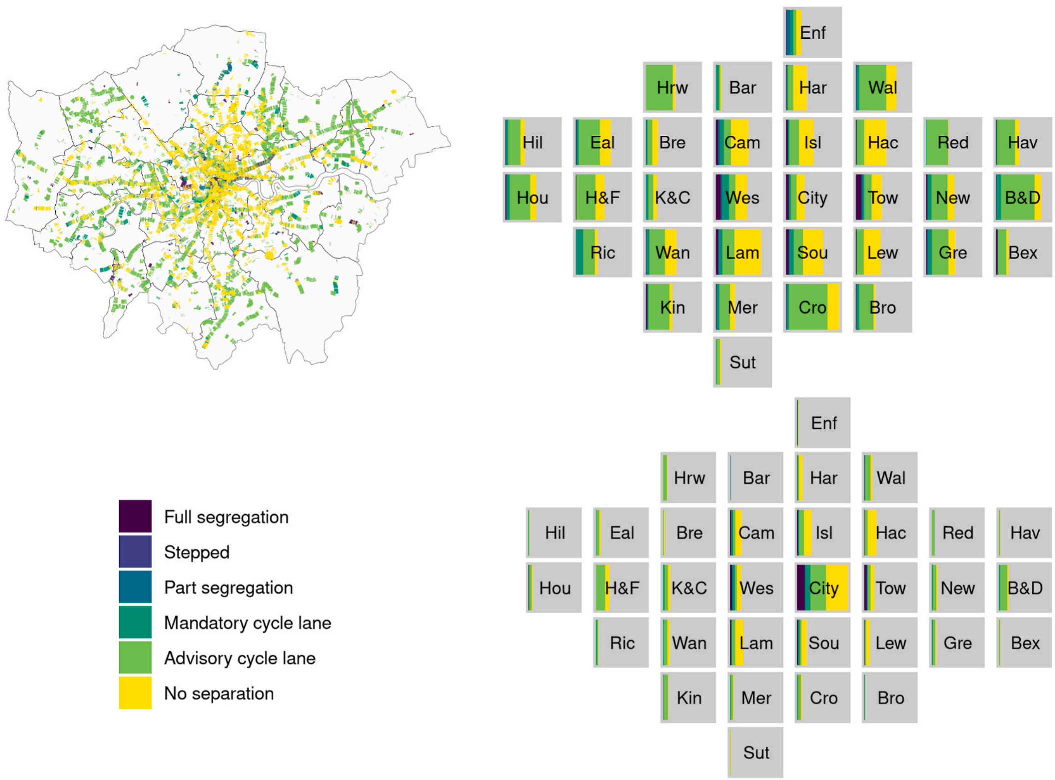


Fig. 6. Highest degree of separation of CID on-road cycle lanes from motor vehicles:
Spatial distribution (left) and spatially arranged (After the flood, 2019a; After the flood, 2019b) borough bar charts showing length in kilometre (top right) and length by borough area in kilometre per square kilometre (bottom right).

markedly for crossings, cycle lanes and tracks and traffic calming. For outer London boroughs there appears to be greater variability between boroughs than seen for the other normalisations. For example, Croydon has a much higher density of ASL whilst Harrow has a high density of crossings, on-road cycle lanes, signals and traffic calming.

3.5. CID on-road cycle lane separation from motor vehicles

In the CID, on-road cycle lanes are characterised by their degree of separation from motor vehicles ranging from physical partition (full, stepped or part-segregation) to painted partition (mandatory or advisory cycle lanes) or no separation (see Fig. 1). Analysis of the highest level of separation shows that advisory cycle lanes account for the greatest length of CID cycle lane separation (487 km, 52%, Table 3). Just 6% (55.6 km) of cycle lane length is physically segregated whilst 61% (572.3 km) is mandatory or advisory cycle lanes. 316.1 km (34%) of CID cycle lanes have no separation with the majority of these being shared bus lanes (73%) or contraflow cycle lanes (23%) (Figure A1).

There are clear spatial patterns to the distribution of separated cycle lanes in London (Fig. 6, Table A7). Physically segregated infrastructure tends to match the strategic cycling infrastructure (for example, parts of Cycle Superhighways 2, 3 and 6 correspond to purple lines running east-west, Fig. 6, left). Such infrastructure is more centrally located as illustrated by the purple bars in Westminster, City of London and Tower Hamlets (Fig. 6, top right). Croydon has the greatest total length of on-road cycle lanes with some separation (45.4 km) whilst Sutton has the least (4.3 km). All London boroughs contain cycle lanes where the highest separation is full segregation, but the amount varies from 21 m (Brent) to 6.0 km (Tower Hamlets). 31 boroughs have part-segregation but vary in length from 7 m (Barnet) to 4.3 km (Enfield). Fully segregated lanes are predominantly found in inner London boroughs whereas advisory cycle lanes are predominantly found in outer London boroughs. When the length of on-road cycle lanes are adjusted for geographical borough area (Fig. 6, bottom right), the City of London has the greatest density of cycle lanes with some form of separation (4.1 km per

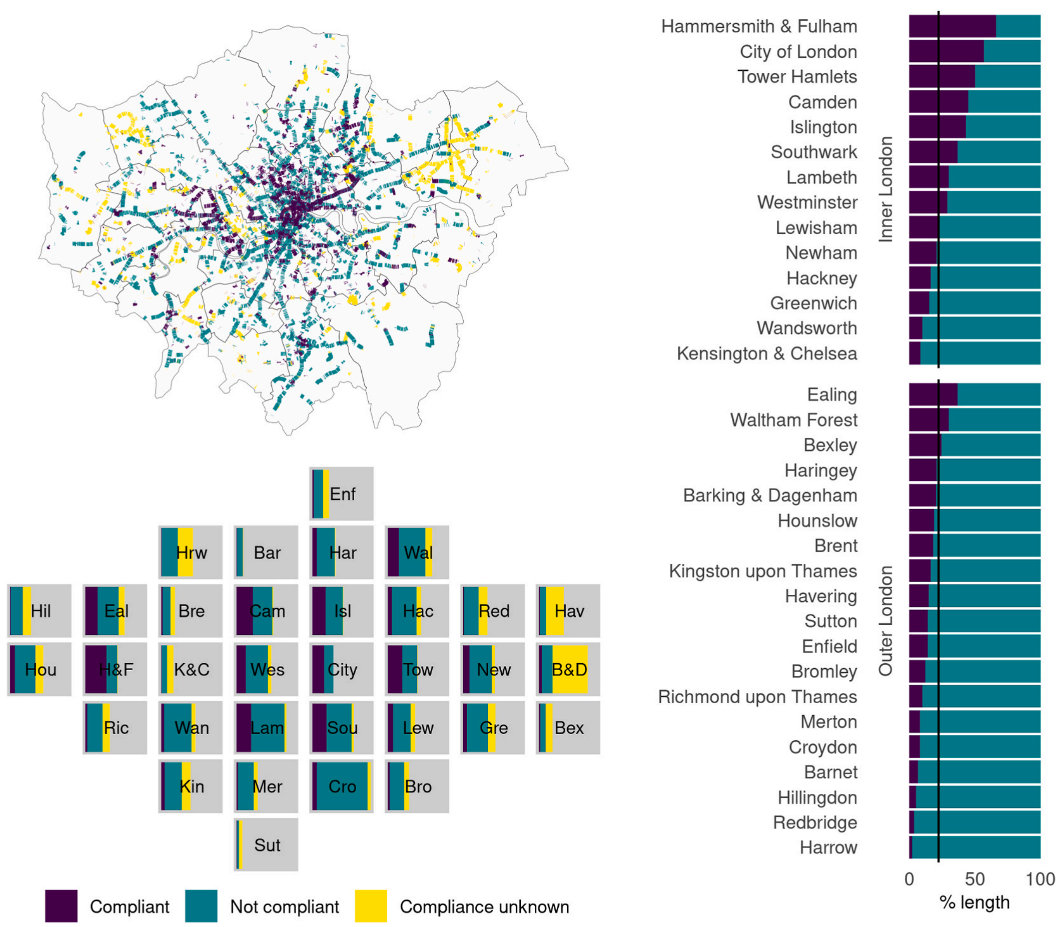


Fig. 7. Estimated compliance of on-road cycle lanes with LTN 1/20: Spatial distribution (top left), spatially arranged (After the flood, 2019a; After the flood, 2019b) borough bar charts showing length in kilometre (bottom left) and percentage of length by borough where speed limit is known (right, solid line = mean).

square km) whilst Barnet has the least (0.05 km per square km). The highest densities are found in the City of London for fully segregated (1.1 km per square km), Waltham Forest for stepped (0.009 km per square km) and Camden for part-segregated (0.08 km per square km).

3.6. Estimated CID on-road cycle lane compliance with UK Cycle Infrastructure Design Guidance

Compliance of CID on-road cycle lanes with UK Cycle Infrastructure Design Standard LTN 1/20 (DfT, 2020a) was estimated using degree of separation from motor vehicles and road speed limit data. This revealed 20% of the total length of CID on-road cycle lanes were compliant (196.4 km). 59% of length was not compliant (565.8 km) and compliance was unknown (due to missing speed limit data) in 21% (197.5 km) (Table A8). This demonstrates that whilst the physical separation from motor vehicles is modest (only 6% of CID cycle lane length is physically segregated), the separation can be appropriate if the road speed limit is low.

There are clear spatial patterns to compliance (Fig. 7). Compliant cycle lanes (purple) tend to be in inner London and follow the strategic cycling infrastructure whilst non-compliant lanes (turquoise) are distributed throughout London. Those where compliance is unknown are mainly located in outer London reflecting the low availability of OpenStreetMap speed limit data in these areas. Hammersmith and Fulham has the greatest compliance (65%) whilst Harrow has the least (2%, Table A8). Less than one percent of cycle lanes in shared bus lanes are compliant (Figure A2) which is unsurprisingly since these tend to have no separation (Figure A1). If we focus on those cycle lanes with known speed limits then the mean borough estimated compliance is 22% with 64% (9/14) of inner but only 16% (3/20) of outer London boroughs exceeding this mean (Fig. 7, right). Even if we remove cycle lanes in shared bus lanes (mean compliance 32%) the proportions exceeding the mean only change for outer London (21%, 4/19, Figure A3). Kensington & Chelsea and Wandsworth have low levels of estimated compliance despite having high levels of commuting cycling (Fig. 5, column 4) and conversely Ealing, Waltham Forest and Bexley have high levels of compliance despite having low levels of commuting cycling.

4. Discussion

4.1. Summary of findings

Analysis of the CID shows that the quantity and quality of infrastructure is not equal across London. Boroughs vary in their provision with none having consistently high or low levels of all types. Outer London has less infrastructure providing safe space for cycling than inner London. This pattern persists even when normalised for area and population but is inverted when normalised for commuter cycling. Traffic calming is the most common infrastructure type whilst cyclist signals are absent in 30% of boroughs. Just six percent of on-road cycle lane length is physically segregated and this is predominantly found in inner London. Estimated compliance with the appropriate level of protection for cyclists in cycle lanes (LTN 1/20) is greatest in inner London where 64% of inner London boroughs exceed the mean compliance of 22% compared to 16% of outer London boroughs. Estimated compliance is greater than perhaps the modest levels of physical segregation would predict due to low road speed limits making non-physical separation acceptable.

4.2. Interpretation of key findings

High levels of traffic calming measures, particularly in residential areas, are unsurprising given their role is protecting all road users rather than just cyclists (Elvik, 2001). The absence of cyclist signals in many boroughs and the low levels of these and ASL is concerning as junctions are known to be especially risky for cyclists in London (Adams and Aldred, 2020; Aldred et al., 2018). This variation in provision may be explained by historical infrastructure design guidance, where traffic calming was prioritised (DfT, 2008; Golbuff and Aldred, 2011), coupled with their lower costs - £10,000 - £15,000 per kilometre for traffic calming versus £0.24 - £1.61 million for junction remodelling and £1.45 million per km for fully segregated cycle lanes (Taylor and Hiblin, 2017).

Given these high costs, it is unsurprising that London's on-road cycle lane provision is low with little segregation for cyclists. Only 6.4% of London's total road length contains CID cycle lanes (944 km out of 14,754 km non-motorway highways) with just 0.4% physically segregated from motor vehicles and only 1.3% compliant with LTN 1/20 (DfT, 2020d). Whilst comparisons are challenging due to limited detailed infrastructure data, some cities have a much greater provision. For example, Seville, a city with a similar population density, has 164 km of segregated cycle lanes (Marqués et al., 2015) compared to just 56 km in London. Such segregation is important, preferred by many users (Aldred et al., 2017) and reduces the risk of cyclist injury (Adams and Aldred, 2020).

The greater provision of dedicated cycling infrastructure in certain boroughs and inner London could be explained by several factors. Central London has a concentration of functions, institutions and businesses whose population increases by 80% daily (Brown et al., 2020). Therefore, centrally located boroughs or those that facilitate transportation into central London, for example, Lambeth being orientated north-south into the centre, have been the focus of historical and current road and infrastructure development (Di Gregorio and Palmieri, 2016). However, this pattern is not the same for every inner London borough, for example, Kensington & Chelsea is a central London borough but has low levels of normalised infrastructure, segregation and compliance. Boroughs are autonomous political and highway entities and, as such, politics, priorities and investment influence their cycling infrastructure development (Deegan and Parkin, 2011; Deegan, 2016). For example, certain boroughs have had low engagement with cycling infrastructure (e.g. Kensington & Chelsea, Barnet) whilst others have focussed on specific infrastructure such as segregated routes (e.g. Tower Hamlets) (Deegan, 2016). This potentially explains the low LTN 1/20 compliance of Kensington & Chelsea compared to the high compliance of Tower Hamlets. Borough priorities such as traffic calming through speed limit reduction may have also affected compliance. For example, Ealing (outer London) has high LTN 1/20 compliance despite low cycle lane segregation due to a high density of 20 mph speed limits. Investment in borough cycling infrastructure is unequal (Martin et al., 2021) and usually subject to bidding processes (London Councils, 2014; Mayor's Question Time, 2020a). Finally, implementing cycling infrastructure can require engagement and collaboration between multiple highway authorities that can be difficult to achieve and may result in variable implementation (Deegan and Parkin, 2011). These aforementioned factors all contribute to the variation in infrastructure provision in London.

4.3. Strengths and limitations

This study provides the first systematic description and use of the CID with method development to influence policy and planning. Given its granularity, completeness and open-access nature, the CID is a highly valuable dataset for analysing cycling infrastructure. We demonstrated that normalisation of absolute infrastructure to borough area, population and cycle commuting enabled fairer comparison than absolute raw data. We have shown that this dataset, particularly when combined with geographical and demographic data, can generate new insights into cycling infrastructure quantity and quality and be used to compare administrative units within London. Developing an approach to combine the CID with other data has demonstrated that it can be used to evaluate infrastructure. Analysis at this level means that our findings can be meaningful to local government who can implement change as well as presenting an overview for those working strategically across London. Our supporting GitHub repository contains all the code used in the analysis (https://github.com/PublicHealthDataGeek/London_CID_analysis) and our CycleInfraLnd R package is freely available (Tait and Lovelace, 2019) . This enables other researchers or interested parties to access and utilise the CID data or our methods in their work in addition to facilitating transparency and reproducibility.

The main CID limitation is the last survey date being September 2, 2019 so it does not reflect infrastructure changes that have occurred since, for example, soon-to-be-completed MiniHolland programmes (DfT, 2020e) and COVID-related infrastructure (TfL, 2020b). The ONS borough population and commuter cycling estimates from the PCT use 2011 Census data. The commuter cycling estimates are based on individual origin-destination data providing road segment level granularity. However, cycling levels increased by 24% from 2012 to 2017 (TfL, 2018) and changed substantially during the COVID-19 pandemic (DfT, 2022). Furthermore, commuter cycling does not reflect leisure and non-commuting cycling and our assumption of bi-directional commuting cycling may result in overestimation, particularly in winter. These limitations could be overcome in future work by incorporating any new cycling and by developing a new approach to estimate multipurpose cycling participation at a borough-level.

Regarding the LTN 1/20 compliance estimates, our road speed limit data was obtained from OpenStreetMap but this may be unreliable. As Volunteered Geographical Information it is subject to quality issues and biases (Basiri et al., 2019) and known to be more complete in urban areas (Haklay, 2010) - something that our research also found. London road speed limits have changed since 2019 with most boroughs now having 20 mph speed limits on the majority of roads (Mayor's Question Time, 2020b). LTN 1/20 compliance guidance indicates that speed limit exceedance and motor vehicle flow should be considered. Unfortunately, data on actual road speeds and motor vehicle flow is not available at a granular level. This may have resulted in over-estimating compliance for mandatory and advisory cycle lanes and under-estimating compliance for cycle lanes with no separation. Furthermore, our buffering method and spatial joins could have misattributed speed limit data that may have affected whether a cycle lane could be compliant or not.

Whilst enabling comparison, aggregating data to administrative boroughs loses granularity and fails to capture the diversity within smaller spatial units. For example, Waltham Forest has a MiniHolland scheme introduced that has increased cycling (Aldred et al., 2019, 2021) but it fails to stand out as a borough in our results. Using aggregated spatial data does introduce two issues (Stewart Fotheringham and Rogerson, 1993). Firstly, borough boundaries are fixed but artificial and may not capture other factors influencing cycling infrastructure location e.g. main roads and cyclist route preferences. Secondly, infrastructure in one borough may influence infrastructure in another, for example, a junction located on a borough boundary.

4.4. Implications and future research

Accurate data on the location, type and characteristics of physical cycling infrastructure such as that provided by the CID is vital for research, policy and planning. The CID addresses issues previously identified in the literature on infrastructure datasets by providing complete, consistent, accurate, detailed, relevant and open-access cycling infrastructure data. Our paper provides the first estimates of compliance with official guidance for on-road cycle lane quality at the UK local government and, as far as we are aware, worldwide level. This highlights the need for more research into different guidance and compliance between cities at national and international levels, with reference to established principles of cycling infrastructure design (Parkin, 2018). Future research could combine the CID with additional datasets such as road traffic crashes, road characteristics, improved estimates of cycling participation, population and routing data. This means it has the potential to examine: the impact of infrastructure on cyclist safety and participation; compliance with other infrastructure design standards; the quality of cycle routes and networks; and inequalities and inequities in infrastructure provision, thus influencing transport and health policy.

We recommend that open inventories of cycling infrastructure such as the CID be considered a critical infrastructure asset in a similar way to other transport assets (Hall, 2019; Schooling et al., 2020). We advocate that open data on all new cycling infrastructure be captured in electronic format using the specification developed by TfL in conjunction with LTN 1/20 and should additionally include date of infrastructure implementation and two-dimensional geometry. This data standard should be mandated as a requirement to secure government funding (LTN 1/20 compliance is a requirement for government funding (DfT, 2020f)). Furthermore, we advocate that comprehensive, granular open data is available for road speed limits, actual road speeds and road traffic volumes.

Aspirations to increase cycling participation, particularly in areas of lower cycling such as outer London, are unlikely to be successful without an increase in infrastructure that promotes safe space for cycling both in quantity and quality. Ambitions to increase equity in cycling are unlikely to be achieved without an increase in infrastructure that supports more people to cycle (Le Gouais et al., 2021), such as physically segregated (Aldred et al., 2017) or LTN 1/20 compliant cycle lanes. Furthermore, opportunities to build on positive cycling changes seen during the COVID pandemic are unlikely to be maximised without concerted focus on high quality, cycling infrastructure. Knowing what cycling infrastructure exists and where, through collecting and analysing infrastructure data, can help realise these goals.

5. Conclusions

This is the first detailed description and analysis of a new, open and comprehensive dataset of cycling infrastructure in London, UK. Examining spatial patterns in infrastructure provision by London borough, we identified inequalities between boroughs even after considering relevant contextual factors such as borough size, population and amount of commuter cycling. When judged against compliance with UK Cycle Infrastructure Design Standards, only 20% (196.4 km) of London's cycle lanes were estimated to be compliant. This varies by borough but is higher in inner London. We have demonstrated that the CID (and thus other such datasets) can be used to evaluate cycling infrastructure quantitatively and qualitatively and highlight areas for intervention. This will enable greater research and more evidence-based policies and interventions to achieve goals in increasing cycling participation and equity. Furthermore, cycling research in general can benefit from such data to expand the evidence-base on cycling participation and equity. Open data on cycling infrastructure should be considered as a 'digital infrastructure asset' that is key to guiding sustainable transport and health policies.

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Author statement

Caroline Tait - Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Formal analysis, Visualization, Writing - Original Draft, Writing - Review and Editing. Dr Roger Beecham - Supervision. Dr Robin Lovelace - Supervision. Dr Stuart Barber - Supervision.

Acknowledgments and Licenses

We would like to acknowledge CycleStreets as the PhD partner for the Doctoral Training Postgraduate Studentship. TfL data: Powered by TfL Open Data. Contains OS data © Crown copyright and database rights 2016 and Geomni UK Map data © and database rights [2019]. ONS data: Contains public sector information licensed under the Open Government Licence v3.0. OpenStreetMap data: Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org and contains Ordnance Survey data © Crown copyright and database right 2010-19. London squared data for spatial visualisation: Copyright 2019 After the Flood Ltd.

Declaration of competing interest

No declared conflicts of interest.

Data availability

The analysis code is available at https://github.com/PublicHealthDataGeek/London_CID_analysis. Data is open data.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.jth.2022.101369.

Appendix

Table A.1
Number of Advanced Stop Line feeder lanes

Number of feeder lanes	Count
1	1786
2	7

Table A.2
Detailed characterisation of Advanced Stop Lines using CID variables

Total number	Characteristic	Number (% [a])	Additional characteristics
1568	No characteristics	1568 (100.0)	Not applicable
1783	Feeder lane present	1 (0.06)	None
		1067 (59.8)	Feeder lane on left
		45 (2.5)	Feeder lane in centre
		15 (0.8)	Feeder lane on right
		1 (0.06)	Feeder lane on left and in Centre
		3 (0.2)	Feeder lane on left and Right
		609 (34.2)	Feeder lane on left and Coloured
		30 (1.7)	Feeder lane in centre and Coloured
		8 (0.4)	Feeder lane on right and Coloured
		2 (0.1)	Feeder lane on left, in Centre and Coloured
		1 (0.06)	Feeder lane on left, Right and Coloured
		1 (0.06)	Coloured
1695	Feeder Lane on Left	11 (0.6)	None
		1067 (62.9)	Feeder lane present
		609 (35.9)	Feeder lane present and Coloured
		1 (0.06)	Feeder lane present and Feeder lane in Centre
		3 (0.2)	Feeder lane present and Feeder lane on Right
		2 (0.1)	Feeder lane present, Feeder lane in Centre and Coloured
		1 (0.06)	Feeder lane present, Feeder lane on Right and Coloured
		1 (0.06)	Coloured
78	Feeder Lane in Centre	45 (64.3)	Feeder lane present
		30 (38.5)	Feeder lane present and Coloured
		1 (1.3)	Feeder lane present and Feeder lane on Left
		2 (2.6)	Feeder lane present, Feeder lane on Left, and Coloured
27	Feeder Lane on Right	15 (55.6)	Feeder lane present
		8 (29.6)	Feeder lane present and Coloured
		3 (11.1)	Feeder lane present and Feeder lane on Left
		1 (3.7)	Feeder lane present, Feeder lane on Left and Coloured
7	Shared Nearside Lane (e.g. with buses)	2 (28.6)	None
		5 (71.4)	Coloured
1062	Colour present [b]	405 (38.1)	None
		5 (0.5)	Shared
		1 (0.09)	Feeder lane present
		1 (0.09)	Feeder lane on Left
		30 (2.8)	Feeder lane present and in Centre
		8 (0.8)	Feeder lane present and on Right
		609 (57.3)	Feeder lane present and on Left
		2 (0.2)	Feeder lane present, on Left and in Centre
		1 (0.09)	Feeder lane present, on Left and Right

[a] Percentage calculated within characteristic group.
[b] Actual colour is specified in the CID but for this table we indicate whether colour is present or not.

Table A.3
Detailed characterisation of crossings using CID variables

Total number	Characteristic	Number (% [a])	Additional characteristics
224	No characteristics	224 (100.0)	None
1520	Signal-controlled Crossing	1348 (88.7)	None
		100 (6.6)	Cyclist segregation
		2 (0.13)	Gap in island/kerb allowing cyclists through
		25 (1.6)	Pedestrian-Only Crossing (cyclists dismount)
		45 (3.0)	Cyclist segregation and Gap in island/kerb
338	Cyclists segregated from other users	121 (35.8)	None
		72 (21.3)	Gap in island/kerb allowing cyclists through
		100 (29.6)	Signal-controlled

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Table A.3 (*continued*)

Total number	Characteristic	Number (% [a])	Additional characteristics
		45 (13.3)	Signal-controlled and Gap in island/kerb
134	Gap in island/kerb allowing cyclists through	15 (11.2)	None
		2 (1.5)	Signal-controlled
		72 (53.7)	Cyclist segregation
		45 (33.6)	Cyclist segregation and Signal-controlled
48	Pedestrian-Only Crossing (cyclists dismount)	17 (35.4)	None
		25 (52.1)	Signal-controlled
		6 (12.5)	Crossing over rail or tram tracks
21	Crossing over rail or tram tracks	15 (71.4)	None
		6 (28.6)	Pedestrian-Only Crossing (cyclists dismount)

[a] Percentage calculated within characteristic group.

Table A.4
Detailed characterisation of cycle lane and track infrastructure in total and by on-road (cycle lanes) or off-road (cycle tracks) status using CID variables

Characteristic	Total		On road		Off road	
	Count (%)	Length (%)	Count (%)	Length (%)	Count (%)	Length (%)
On carriageway	13965 (55.2)	944.0 km (32.5)	13965 (55.2)	944.0 km (32.5)	11350 (44.8)	1959.6 km (67.5)
Fully segregated	1931 (7.6)	93.7 km (3.2)	1371 (71.0)	39.2 km (41.8)	560 (29.0)	54.5 km (58.2)
Stepped	104 (0.4)	7.7 km (0.3)	94 (90.4)	7.1 km (91.4)	10 (9.6)	0.7 km (8.6)
Partially segregated	3583 (14.2)	251.1 km (8.6)	349 (9.7)	15.7 km (6.3)	3234 (90.3)	235.4 km (93.7)
Shared lane (buses or footway)	10391 (41.0)	1896.2 km (65.3)	2845 (27.4)	236.4 km (12.5)	7546 (72.6)	1659.8 km (87.5)
Mandatory cycle lane (painted line)	1857 (7.3)	95.5 km (3.3)	1854 (99.8)	95.5 km (100.0)	3 (0.2)	0 km (0.0)
Advisory cycle lane (painted line)	7277 (28.7)	490.0 km (16.9)	7273 (99.9)	489.2 km (99.8)	4 (0.1)	0.8 km (0.2)
Cycle lane/track has priority over other users	2286 (9.0)	200.9 km (6.9)	2285 (100.0)	200.9 km (100.0)	1 (0.0)	0 km (0.0)
Contraflow lane/track (not bi-directional)	1493 (5.9)	116.3 km (4.0)	1463 (98.0)	115.2 km (99.1)	30 (2.0)	1.1 km (0.9)
Bi-directional (two-way flow)	10432 (41.2)	1911.4 km (65.8)	381 (3.7)	26.1 km (1.4)	10051 (96.3)	1885.4 km (98.6)
Cycle bypass allowing cyclists to turn without stopping at traffic signals	63 (0.2)	1.6 km (0.1)	5 (7.9)	0.3 km (17.0)	58 (92.1)	1.4 km (83.0)
Continuous cycle facilities at bus stop	132 (0.5)	9.9 km (0.3)	68 (51.5)	4.3 km (43.6)	64 (48.5)	5.6 km (56.4)
Route through park	4194 (16.6)	1348.1 km (46.4)	108 (2.6)	30.1 km (2.2)	4086 (97.4)	1318.0 km (97.8)
Route by river, canal or water feature	611 (2.4)	268.0 km (9.2)	0 (0.0)	0 km (0.0)	611 (100.0)	268.0 km (100.0)
Part-time cycle lane/track	2800 (11.1)	400.9 km (13.8)	2308 (82.4)	188.4 km (47.0)	492 (17.6)	212.5 km (53.0)
Colour [a]	6191 (24.5)	419.8 km (14.5)	4338 (70.1)	246.3 km (58.7)	1853 (29.9)	173.6 km (41.3)

[a] Actual colour is specified in the CID but for this table we indicate whether colour is present or not.

Table A.5
Detailed characterisation of cyclist signals using CID variables

Total number	Characteristic	Number (% [a])	Additional characteristics
4	No characteristics	4 (100.0)	None
438	Cycle symbol on lights	132 (30.1)	None
		186 (42.5)	Separate cyclist stage
		36 (8.2)	Early cyclist release
		8 (1.8)	Two-stage right turn
		2 (0.5)	Signal gate
		28 (6.4)	Separate cyclist stage and Early cyclist release
		16 (3.7)	Separate cyclist stage and Two-stage right turn
		15 (3.4)	Separate cyclist stage and Signal gate
		3 (0.7)	Early cyclist release and Two-stage right turn
		1 (0.2)	Early cyclist release and Signal gate
		10 (2.3)	Separate cyclist stage; Early cyclist release and Signal gate
		1 (0.2)	Separate cyclist stage; Early cyclist release and Two-stage right turn

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Table A.5 (*continued*)

Total number	Characteristic	Number (% [a])	Additional characteristics
256	Separate stage for cyclists	186 (72.6)	Cycle symbol on lights
		28 (10.9)	Cycle symbol on lights and Early release for cyclists
		16 (6.3)	Cycle symbol on lights and Two-stage right turn
		15 (5.9)	Cycle symbol on lights and Signal gate
		10 (3.9)	Cycle symbol on lights; Early cyclist release and Signal gate
		1 (0.4)	Cycle symbol on lights; Early cyclist release and Two-stage right turn
80	Early release for cyclists	1 (1.3)	None
		36 (45.0)	Cycle symbol on lights
		28 (35.0)	Cycle symbol on lights and Separate cyclist stage
		10 (12.5)	Cycle symbol on lights; Separate cyclist stage and Signal gate
		1 (1.3)	Cycle symbol on lights; and Signal gate
		3 (3.8)	Cycle symbol on lights; and Two-stage right turn
		1 (1.3)	Cycle symbol on lights; Separate cyclist stage and Two-stage right turn
28	Two-stage right turn	8 (28.6)	Cycle symbol on lights
		3 (10.7)	Cycle symbol on lights and Early cyclist release
		16 (57.1)	Cycle symbol on lights and Separate cyclist stage
		1 (3.6)	Cycle symbol on lights; Separate cyclist stage and Early cyclist release
28	Signal gate	2 (7.1)	Cycle symbol on lights
		15 (53.6)	Cycle symbol on lights and Separate cyclist stage
		1 (3.6)	Cycle symbol on lights and Early cyclist release
		10 (35.7)	Cycle symbol on lights; Separate cyclist stage and Early cyclist release

[a] Percentage calculated within characteristic group.

Table A.6
Detailed characterisation of traffic calming using CID variables

Total number	Characteristic	Number (% [a])	Additional characteristics
12	No characteristics	12 (100.0)	None
33271	Hump	26948 (81.0)	None
		6319 (19.0)	Sinusoidal shape
		1 (0.0)	Road narrowing
		3 (0.0)	Side entry treatment
12626	Cushion	12217 (96.7)	None
		400 (3.2)	Sinusoidal shape
		8 (0.06)	Road narrowing
		1 (0.01)	Sinusoidal shape and Road narrowing
7581	Side entry treatment	7576 (99.9)	None
		3 (0.04)	Hump
		2 (0.03)	Raised table at junction
2772	Raised table at junction	2770 (99.9)	None
		2 (0.07)	Side entry treatment
935	Barrier	935 (100.0)	None
662	Narrowing	652 (98.5)	None
		8 (1.2)	Cushion
		1 (0.2)	Sinusoidal cushion
		1 (0.2)	Hump
721	Other traffic calming measure	721 (100.0)	None

[a] Percentage calculated within characteristic group.

Table A.7
Borough length of CID on-road cycle lanes by highest degree of separation from motor vehicles (in descending order of full segregation length)

Borough	CID cycle lane length in kilometres					
	Full segregation	Stepped	Part segregation	Mandatory cycle lane	Advisory cycle lane	No separation
Tower Hamlets [a]	6.012	0.150	1.342	1.735	7.734	11.530
Westminster [a]	5.682	0	1.505	7.166	7.021	12.681
City of London [a]	3.077	0	0.140	2.205	6.347	9.063
Southwark [a]	3.037	0	0.516	5.133	9.802	21.861
Camden [a]	2.836	0	1.804	3.883	8.01.0	19.278
Lambeth [a]	2.829	0	0.627	3.378	13.714	29.057
Islington [a]	1.998	0	0.126	1.577	10.547	16.392
Kingston upon Thames	1.697	0.026	0.044	1.017	22.747	3.288
Bexley	1.520	0	0.161	0.358	9.143	2.654
Newham [a]	1.507	0	0.190	4.369	17.570	7.471
Greenwich [a]	1.005	0	1.140	4.294	17.953	7.812
Merton	0.861	0	0.146	2.627	12.085	5.193
Hackney [a]	0.723	0	0.010	0.576	7.511	24.008
Ealing	0.708	0	0.404	2.312	23.072	12.334

(*continued on next page*)

Table A.7 (*continued*)

Borough	CID cycle lane length in kilometres					
	Full segregation	Stepped	Part segregation	Mandatory cycle lane	Advisory cycle lane	No separation
Hounslow	0.683	0	0.070	3.572	22.636	6.594
Hammersmith & Fulham [a]	0.513	0	0.071	0.136	20.876	10.227
Lewisham [a]	0.498	0	0.057	0.687	7.141	18.856
Havering	0.470	0.169	0.009	0.499	19.401	4.828
Wandsworth [a]	0.454	0	0.143	3.456	16.853	13.081
Bromley	0.386	0	0.024	3.242	15.317	2.398
Haringey	0.368	0	0.272	1.606	5.744	15.239
Croydon	0.354	0	0.163	2.859	42.05	12.906
Enfield	0.349	0	4.303	3.307	3.466	5.563
Hillingdon	0.288	0	0.008	2.454	13.301	4.851
Barnet	0.282	0	0.007	2.923	1.488	1.888
Barking & Dagenham	0.234	0	0.154	5.023	36.738	7.205
Waltham Forest	0.180	0.367	0.747	2.392	29.481	11.08
Sutton	0.179	0	0.098	0.471	3.583	1.501
Redbridge	0.167	0	0	0.248	23.365	0.755
Kensington & Chelsea [a]	0.147	0	0.022	2.838	5.191	4.280
Harrow	0.064	0	0.307	0.043	29.325	2.255
Richmond upon Thames	0.048	0	0	8.375	12.449	3.453
Brent	0.021	0	1.110	0.508	5.382	6.513

[a] Inner London boroughs.

Table A.8
Estimated borough compliance of CID on-road cycle lanes with LTN 1/20 (in descending order of Compliant percentage)

Borough	Percentage (length in kilometres)		
	Compliant	Non-compliant	Compliance unknown [b]
Hammersmith & Fulham [a]	65 (21.1)	33 (10.8)	2 (0.6)
Camden [a]	44 (16)	54 (19.8)	3 (0.9)
Tower Hamlets [a]	49 (14.7)	49 (14.7)	2 (0.5)
Southwark [a]	35 (14.7)	60 (25.2)	5 (2.1)
Lambeth [a]	29 (14.6)	67 (33.9)	4 (1.9)
Islington [a]	43 (13.4)	56 (17.6)	1 (0.2)
City of London [a]	57 (12.2)	43 (9.2)	1 (0.1)
Ealing	31 (12.2)	53 (21)	16 (6.2)
Waltham Forest	26 (11.4)	59 (26.6)	15 (6.7)
Westminster [a]	26 (9.1)	64 (22.3)	10 (3.4)
Newham [a]	19 (6)	72 (23)	9 (3)
Lewisham [a]	19 (5.2)	64 (17.8)	17 (4.8)
Hounslow	14 (4.8)	61 (20.7)	25 (8.3)
Haringey	20 (4.7)	76 (18)	3 (0.8)
Hackney [a]	14 (4.7)	73 (24.2)	13 (4.5)
Croydon	8 (4.6)	87 (51.7)	5 (2.9)
Greenwich [a]	12 (3.8)	65 (21.2)	23 (7.4)
Kingston upon Thames	11 (3.4)	60 (17.6)	29 (8.5)
Wandsworth [a]	9 (3)	79 (27.5)	12 (4.2)
Barking & Dagenham	6 (2.9)	22 (11.2)	72 (35.6)
Bromley	10 (2.1)	69 (14.9)	21 (4.6)
Richmond upon Thames	7 (1.7)	62 (15.1)	32 (7.8)
Brent	12 (1.7)	56 (7.7)	32 (4.4)
Bexley	12 (1.7)	37 (5.2)	51 (7.2)
Enfield	9 (1.6)	56 (9.7)	34 (5.9)
Merton	7 (1.4)	74 (15.7)	20 (4.2)
Havering	4 (1.1)	26 (6.5)	70 (17.7)
Hillingdon	3 (0.6)	58 (12.2)	39 (8.3)
Redbridge	2 (0.6)	61 (14.9)	37 (9.1)
Kensington & Chelsea [a]	4 (0.5)	45 (5.6)	51 (6.4)
Barnet	6 (0.4)	85 (5.7)	9 (0.6)
Harrow	1 (0.4)	52 (16.7)	47 (15.1)
Sutton	6 (0.4)	37 (2.2)	57 (3.4)
TOTAL	20 (196.4)	59 (565.8)	21 (197.5)

[a] Inner London boroughs.
[b] Compliance unknown as speed limit data is not available.

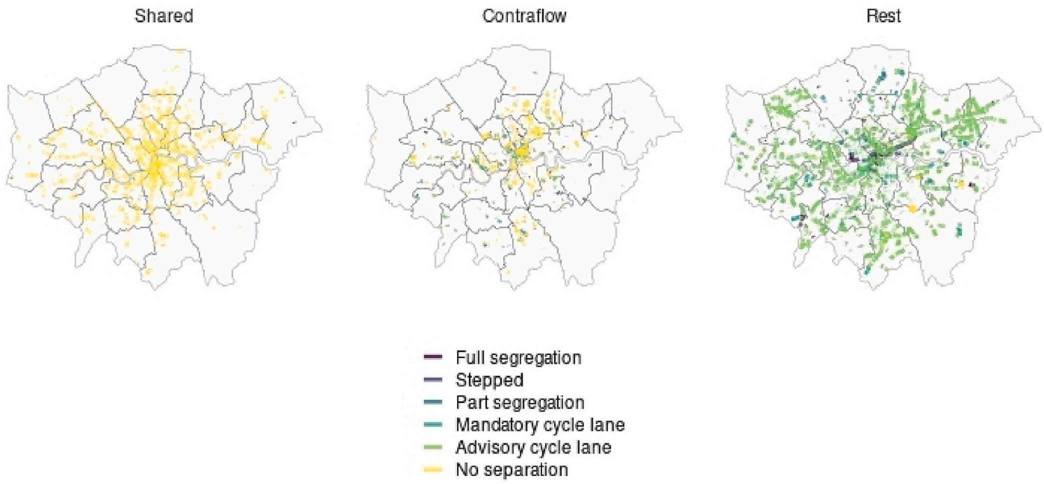

Fig. A.1. Degree of separation of CID on-road cycle lanes from motor vehicles by whether cycle lanes are shared, contraflow or neither ('Rest')

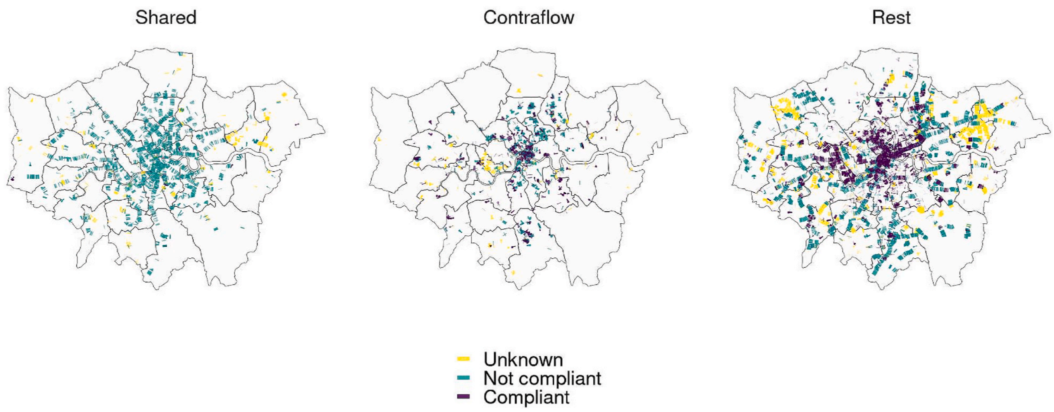

Fig. A.2. Estimated on-road CID cycle lane compliance with LTN 1/20 by whether cycle lanes are shared, contraflow or neither ('Rest')

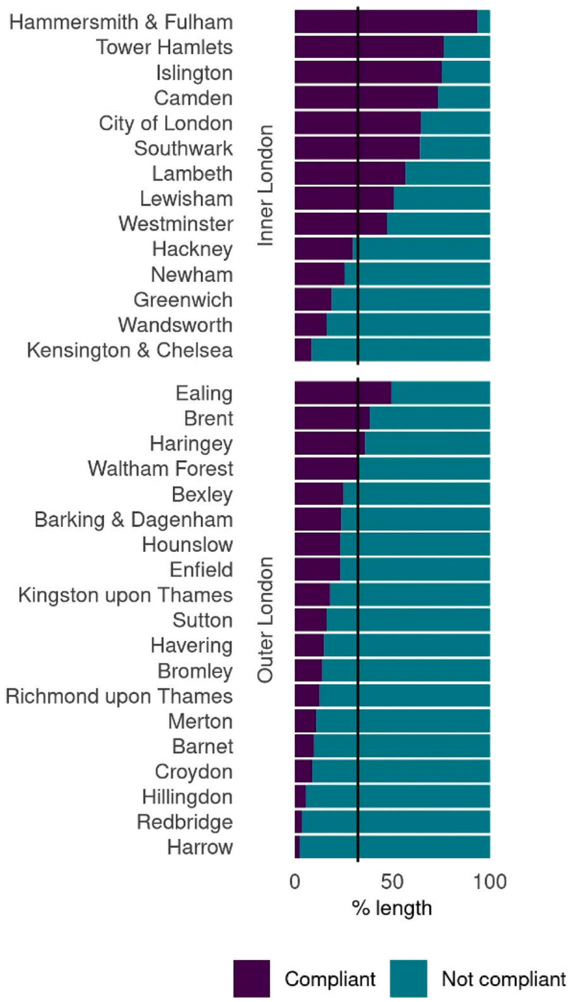

Fig. A.3. Estimated borough CID on-road cycle lane compliance with LTN 1/20 where speed limit is known and shared lanes are excluded (solid line = mean)

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Chapter 3

Paper 2: Contraflows and cycling safety: Evidence from 22 years of data involving 508 one-way streets

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Contraflows and cycling safety: Evidence from 22 years of data involving 508 one-way streets

Caroline Tait [a,1,*], Roger Beecham [b], Robin Lovelace [a,c,d], Stuart Barber [e]

[a] Leeds Institute for Data Analytics, University of Leeds, Leeds, United Kingdom
[b] School of Geography, University of Leeds, Leeds, United Kingdom
[c] Institute for Transport Studies, University of Leeds, Leeds, United Kingdom
[d] Interim Director of Data and Analysis, Active Travel England
[e] School of Mathematics, University of Leeds, Leeds, United Kingdom

A R T I C L E I N F O

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A B S T R A C T

Contraflow cycling on one-way streets is a low cost intervention that research shows can improve the cycling experience and increase participation. Evidence from several studies suggest that cyclists on contraflows have a lower crash risk. However, implementing contraflow cycling is often controversial, including in the United Kingdom (UK). In this paper we examine whether contraflow cycling on one-way streets alters crash or casualty rates for pedal cyclists.

Focusing on inner London boroughs between 1998 and 2019, we identified 508 road segments where contraflow cycling was introduced on one-way streets. We identified road traffic crashes occurring within 10 m of these segments and labelled them as pre-contraflow, contraflow or contraflow removed crashes. We calculated rates using the number of crashes or casualties divided by the time exposed and generated 95 % confidence intervals using bootstrap resampling. We adjusted the rates for changes in cordon cycling volume and injury severity reporting.

There were 1498 crashes involving pedal cyclists: 788 pre-contraflow, 703 contraflow and 7 following contraflow removal. There was no change in adjusted overall pedal cyclist crash or casualty rates when contraflow cycling was introduced. Proximity to a junction doubled the crash rate. The crash rate when pedal cyclists were travelling contraflow was the same as those travelling with flow.

We have found no evidence that introducing contraflow cycling increases the crash or casualty rate for pedal cyclists. It is possible that such rates may indeed fall when contraflow cycling is introduced if more accurate spatio-temporal cycling volume data was available. We recommend all one-way streets are evaluated for contraflow cycling but encourage judicious junction design and recommend UK legislative change for mandatory-two-way cycling on one-way streets unless exceptional circumstances exist.

1. Introduction

Contraflow cycling is where cycling can occur in both directions along a street that is one-way for motor vehicles. Allowing contraflow cycling on one-way streets can improve the cycling experience as it enables cyclists to utilise quieter roads, reduces the distance and energy required to travel between two points, reduces the route planning necessary to accommodate differences in outward and return journeys (PRESTO, 2010) and increases the connectivity of their routes (Putta and Furth, 2021). It is a low-cost intervention compared to other cycling infrastructure such as segregated cycle lanes or junction remodelling (Taylor and Hiblin, 2017). It increases the amount of cycling (Bjørnskau et al., 2012; Pritchard et al., 2019; Ryley and Davies, 1998), results in re-routing onto the new infrastructure (Pritchard et al., 2019) and off main roads (Alrutz et al., 2002) and reduces cycling on pavements (Alrutz et al., 2002; Bjørnskau et al., 2012; UDV, 2016). Concentrations of one-way streets, such as those found in urban environments, that do not allow contraflow cycling violate core design principles for cycling infrastructure networks and routes by reducing coherence, directness, attractiveness and comfort (DfT, 2020a). This discourages people from

* Corresponding author.
E-mail addresses: ugm4cjt@leeds.ac.uk (C. Tait), r.j.beecham@leeds.ac.uk (R. Beecham), r.lovelace@leeds.ac.uk (R. Lovelace), s.barber@leeds.ac.uk (S. Barber).
[1] Address: Leeds Institute for Data Analytics, Level 11 Worsley Building, Clarendon Way, Leeds, LS2 9NL.

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cycling and challenges ambitions to increase cycling participation (DfT, 2020b).

In the United Kingdom (UK) the introduction of contraflow cycling on one-way streets is often controversial (e.g. Bloxham, 2008; Pettitt, 2011; Taylor, 2008) with planned schemes cancelled due to public opposition (e.g. Ryley and Davies, 1998; Roberts, 2020) and people cycling the 'wrong way' down one-way streets pilloried, including the former Prime Minister (BBC News, 2008). In contrast, in Europe such schemes are standard practice (UDV, 2016; Depoortere, 2019) and UK Cycling Infrastructure Design Guidance states that contraflow cycling should be implemented unless it is unfeasible for financial, operational or safety reasons (DfT, 2020a).

A key concern expressed in the UK is that contraflow cycling may increase road traffic crashes. Reasons suggested for this by Police Scotland include: narrow road widths resulting in close passing between motor vehicles and contraflow pedal cycles; reduced eye contact between motor vehicle drivers and contraflow cyclists, particularly when motor vehicles are exiting parking spaces or where the direction of the one-way street changes; and omission of specific infrastructure such as painted cycle lanes or junction changes (Police Scotland, 2021). This concern is at odds with the evidence-base on contraflow cycling. Allowing contraflow cycling on one-way streets does not increase road traffic crashes (Alrutz et al., 2002; Ryley and Davies, 1998; Vandenbulcke et al., 2014). Instead it has been shown to reduce cyclist crash risk (Chalanton and Dupriez, 2014; Vandenbulcke et al., 2014; UDV, 2016) and may reduce crash numbers, density and severity (Alrutz et al., 2002). Contrary to the opinion expressed above, conflicts and crashes have been shown to be greater for cyclists travelling with motor vehicle flow on one-way streets rather than contraflow (Alrutz et al., 2002; Chalanton and Dupriez, 2014) whilst motorists have been shown to reduce vehicle speed when encountering contraflow cyclists on narrow one-way streets and increase speeds as the road widens (Alrutz et al., 2002; UDV, 2016). However, this evidence base is predominantly based in mainland Europe, using short time scales (three to four years) and a few hundred crashes. The sole UK observational study examined five contraflow one-way streets with one day of video counts pre- and post-implementation and an analysis of crash data for three years before and eight months after introduction (Ryley and Davies, 1998). They found that cycling flow increased by 54 % after introduction (partially attributed to seasonal variation) with no crashes reported on these streets before or after contraflow cycling.

To enable contraflow cycling on one-way streets in the UK the local transport authority must issue statutory orders known as Traffic Regulation Orders (TRO) (Road Traffic Regulation Act 1984, 1984). Initially a TRO proposal is consulted upon with the public and interested parties then subsequently a TRO is issued to introduce the change (The Local Authorities' Traffic Orders Regulations, 1996). This process was made easier for transport authorities in 2011 when changes to contraflow traffic sign legislation (DfT, 2011a) increased clarity for all road users (Sewell and Nicholson, 2010) and reduced the administrative burden.

London provides a unique environment to improve the existing evidence base and provide meaningful evidence in the UK context of the impact of introducing contraflow cycling on road traffic crashes. Firstly, there are numerous one-way streets with contraflow cycling. Secondly, the TRO for the roads that allow contraflow cycling, including the crucial implementation date, is published in The Gazette (TSO, 2022b) and available online. Thirdly, the volume of cycling has increased dramatically (Tfl, 2019a) so the exposure of cyclists to contraflows is higher than in other UK locations. Fourthly, there is open data available for all road traffic crashes (DfT, 2022a). Finally, all of this data and information is available for decades thus providing long time-scales and large volumes of data for examination.

This paper presents an analysis of the impact of contraflow cycling on road traffic crashes using a before and after method. We identify road segments that implement contraflow cycling over a 22 year period in inner London and examine road traffic crashes involving pedal cycles occurring within 10 m of these road segments prior to and following contraflow cycling introduction. After describing the road segments, crashes, casualties and vehicles involved, we calculate crash rates using time exposed to the road segment as the denominator. We then present crash rates where the number of crashes has been adjusted for the change in cyclist volume using manual cordon counts indexed to the baseline year. Here we specifically focus on aspects such as proximity to junctions (a known risk factor for pedal cycle crashes e.g. Aldred et al., 2018; Kapousizis et al., 2021), significant change to the road segments (for example, two-way street to one-way with contraflow cycling) and pedal cyclist direction (with or contraflow). Finally we examine the pedal cyclist casualty rates to investigate whether introducing contraflow cycling has an impact on injury severity and thus associated costs and consequences.

2. Methods

2.1. Study period and location

London was chosen as the study location for the reasons outlined above: it is a large city with good data on road traffic crashes and casualties, cycling levels, and contraflow infrastructure, including introduction dates. We focused on the 14 London boroughs that constitute central and inner London (GLA, 2021) as these are where the majority of one-way streets with contraflow cycling are located and have the highest cycling participation (Tfl, 2019a). The start date of the study period, 1st January 1998, was selected as this is the date the first electronic TRO records became available online in The Gazette. The end date, 31st December 2019, was chosen as it is the last day of the year prior to the COVID-19 pandemic, which had a significant impact on UK transport (DfT, 2022b; Hadjidemetriou et al., 2020) and road traffic crashes (DfT, 2021a).

2.2. Data

2.2.1. Road segments that allow contraflow cycling

We collected primary data on the road segments with contraflow introduction from the TROs identified using the online search facility of The Gazette (TSO, 2022b). For each road segment, the following data was recorded: borough name, road name, description of contraflow spatial extent (for example, between junctions X and Y), contraflow start and/or stop date. We consider these variables to define the 'uniqueness' of a road segment. For each TRO, details including ID, date of publication and action (consultation, introduction or revocation) were recorded (Table A1). Significant changes to the road segments such the introduction of a one-way street or a contraflow bus lane and whether additional cycling infrastructure such as segregated cycle lanes were proposed were collected where clearly specified in the TRO. As some TROs are consulted upon but not introduced or introduced and removed, we cross-referenced each road segment to ensure it existed or had existed using The Gazette (if there was only a consultation TRO), the London Cycling Infrastructure Database (CID, Tfl, 2019b) and OpenStreetMap (OSM, OpenStreetMap contributors, 2022). We also used these sources to validate that all road segments were true one-way streets with contraflow cycling rather than 'false' one-way streets where motor vehicles can travel in both directions but only pedal cycles are able to enter at both ends of the segment.

We validated the completeness of our road segment data by identifying all roads that allow contraflow cycling in the CID and OSM and then using these road names as free text searches in The Gazette to identify any TROs that may have been missed by the initial search. The detected TROs were reviewed and managed as described in the previous section.

Spatial data for each road segment was obtained from the CID or OSM when present in these datasets. If not present, segments were visualised in OSM and their spatial data constructed from connecting discrete OSM point locations that represent the spatial extent specified in the TRO.

Following the primary data collection we performed various validation checks to ensure the data was correct. These included ensuring: uniqueness of each road segment; no duplication of data; that variables do not contradict each other; and that dates are appropriate and within the study period. We reviewed missing data to ensure it was truly missing, visualised the data on maps and examined road segment lengths to ensure these were correct and appropriate. Where any concerns were identified we returned to the TRO, CID or OSM to validate or correct the data.

2.2.2. UK road traffic crash data

We obtained the official UK road traffic crash data (DfT, 2022a), known as STATS19, corresponding to the years of our road segment data collection (1998 to 2019 inclusive). This data contains "All road accidents involving human death or personal injury occurring on the Highway … and notified to the police within 30 days of occurrence, and in which one or more vehicles are involved" (DfT, 2011b, pg. 4). It contains in depth data that describes the crash, its circumstances, the vehicles involved and the casualties. We excluded crashes that were 'self-reported' as this facility was introduced late in the study period (2016) and use of this data is not recommended when comparing across years (DfT, 2020e).

2.2.3. Cyclist volume data

We obtained the official manual count data of the volume of pedal cycles crossing traffic counter 'cordons' into central, inner and outer London during the study period from Transport for London publications (TFL, 2019c; TFL, 2021). As some official counts are only performed biennially, interpolation was used to impute count data for the missing years. The only exception to this was 2019 inner cordon count data. As there was no 2020 inner cordon count data, the 2019 inner cordon count data was estimated by calculating the mean difference in percentage change for central and outer counts and applying this to the 2018 inner count. Spatial data for traffic counter cordons was generated in QGIS by geo-referencing a static map (TFL, 2022) and creating spatial polygons representing the cordons.

2.3. Data analysis

2.3.1. Identifying pedal cycle crashes associated with contraflows

Spatial joins were used to identify all crashes involving pedal cycles that occurred within 10 m of contraflow interventions. Where crashes could be spatially associated with more than one road segment, they were allocated to the nearest road segment. The 10 m distance was chosen as it takes into account the multiplicity of street designs that contraflow cycling on one-way streets may encompass (DfT, 2020a); differences in road segment spatial geometry collection (e.g. CID v OSM); and changes in the positional accuracy of crash data location over time (DfT, 2005; DfT, 2011b). This distance was visually validated by checking that the 10 m buffer covered the road segment in OSM (highway width is determined by OSM highway type (Allan et al., 2022).

2.3.2. Categorising pedal cycle crashes

We limited crashes to those linked to a road segment with a known contraflow start date. Using the start date along with the date the contraflow was removed (if appropriate), each crash was categorised as occurring during the pre-contraflow, contraflow or contraflow removed time period. For each pedal cyclist crash we identified the vehicles involved, casualties injured and whether the cyclist was travelling 'with flow' or 'contraflow'. We removed crashes that met the definition of a single bicycle crash (all crash types in which only the cyclist is involved, Schepers et al., 2015) as they are likely to be under-reported in crash datasets (Davidson, 2005; Jeffrey et al., 2009; Juhra et al., 2012).

STATS19 contains a variable that indicates whether a crash is within 20 m of a junction or roundabout. We reduced this distance to 10 m to have a greater sample of crashes occurring away from intersections. We utilised the trafficalmr R package to identify all road junctions and roundabouts in inner London in 2019 and used this to determine if a crash occurred within or beyond 10 m of these intersections.

2.3.3. Estimating pedal cyclist crash and casualty rates

To estimate the crash rate we used the number of crashes that occurred during the 22 year study period prior to, during or after the contraflow was removed (numerator) and divided it by the duration of time exposed to unique road segments in that status during that 22 year period (denominator). This duration of time exposure for each road segment in the three possible statuses was calculated in days from the study start date, contraflow start date, contraflow stop date (if removed) and study end date. For example, the pre-contraflow crash rate is the total number of crashes that occurred on road segments with contraflow start dates prior to contraflow cycling being introduced divided by the total amount of time all the road segments with contraflow start dates were 'pre-contraflow' (Eq. (1)).

$$\textit{Raw precontraflow crash rate (crashes per 100 years of exposure)} = \frac{\textit{Total number of crashes occurring on road segments during the precontraflow period}}{(\textit{Total number of days during the 22 years that road segments were precontraflow}/365) \times 100} \quad (1)$$

However, during the study period the amount of cycling changed significantly. This means the total exposure of pedal cyclists to the road segments is likely to have changed and that the number of crashes that occurred in 1998 is not comparable to that of 2019. To account for this we created an index of cycling volume baselined to 1998 for each of the three cordon counts (outer, inner and central London). We adjusted the annual number of crashes occurring in each cordon location by the cordon-specific cycling volume index for that year (Eq. (2)) and then calculated the adjusted crash rate (Eq. (3)). Crash rates calculated in this manner are referred to as adjusted rates as opposed to raw rates in this paper.

$$\textit{Adjusted number of crashes occurring precontraflow by year } [i] \textit{ and cordon } [j] = \frac{\textit{Raw number of crashes occurring precontraflow in year } [i] \textit{ and cordon } [j]}{\textit{Index of cycling volume in year } [i] \textit{ and cordon } [j]} \quad (2)$$

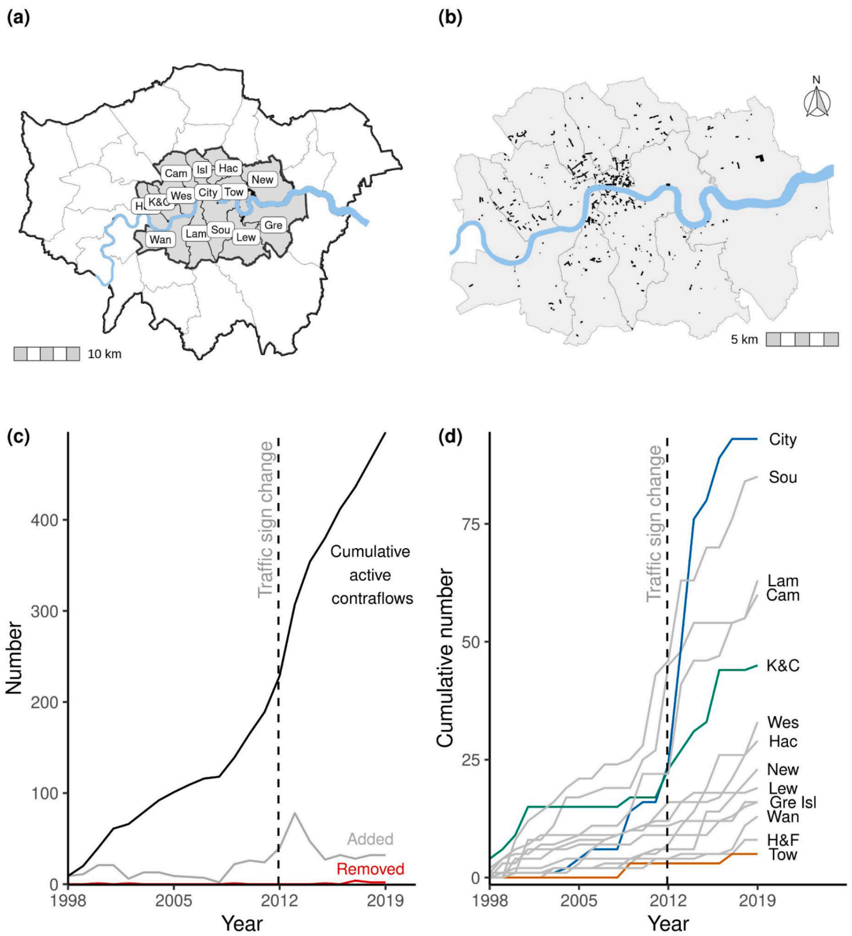


Fig. 1. Road segments with contraflows introduced a) Map of London showing location of inner London boroughs used in the study; b) Map of inner London boroughs showing the location and spatial extent of road segments; c) Line chart showing number of contraflows added, removed and active over time; and d) Line chart showing cumulative number of contraflows introduced over time by borough. The dashed line shows when traffic sign change was introduced.

$$\textit{Adjusted precontraflow crash rate (crashes per 100 years of exposure)} = \frac{\textit{Total adjusted number of crashes occurring precontraflow}}{(\textit{Total number of days during the 22 years that road segments were precontraflow}/365) \times 100} \tag{3}$$

Pedal cyclist casualty rates were calculated using the same approach as the crash rates. However, because there were changes in the way that 'severe' and 'slight' casualty injuries were classified during the study period, we limited the casualty rate analysis to 2005–2019 data as recommended by the Department for Transport (DfT, 2021b; DfT, 2020c). We calculated raw rates and then calculated rates adjusted for the change in severity categorisation using crash-specific, casualty-level adjustment probabilities produced for this purpose (DfT, 2020d). Finally we calculated casualty rates adjusted for both change in injury severity categorisation and change in cordon cycling volume.

2.3.4. Estimating uncertainty of rates

We wanted to estimate the uncertainty around our rates. To achieve this we utilised the bootstrapping method and generated 1000 random resampled datasets from our crash and casualty datasets. The resampling was done with replacement to generate bootstrap datasets that were of the same size as the original datasets (Efron and Tibshirani, 1986). For each bootstrapped sample we derived the relevant raw and adjusted rates. We then calculated the standard error from the standard deviation of our bootstrap sampling distribution of rates and a 95 % confidence interval for the rate by calculating the 2.5 % and 97.5 % percentiles of the bootstrap sampling distribution.

2.3.5. Replication materials

There is additional information about the methods used in Appendix A. The road segment dataset that we collected is available at https://github.com/PublicHealthDataGeek/Contraflow_cycling_safety. Code used in the analysis is available at https://github.com/PublicHealthDataGeek/Contraflow_cycling_safety.

3. Results

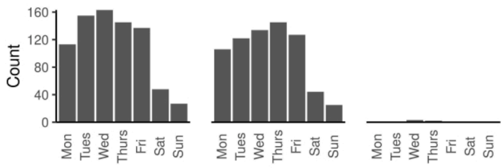
3.1. Road segments with contraflow cycling

We identified 508 unique road segments that had TROs published

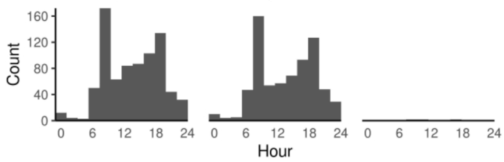
Table 1
Characteristics of crashes involving pedal cycles within 10 m of road segments by crash segment status occurring between 1st January 1998 and 31st December 2019 (inclusive). These characteristics are derived from the STATS19 dataset. Data is presented as 'number (percentage)' unless otherwise stated.

Characteristics		Crash segment status		
		Pre-contraflow	Contraflow	Contraflow removed
Number of crashes		788	703	7
Total number of vehicles		1550	1352	13
Mean number of vehicles per crash (SD)		2.0 (0.3)	1.9 (0.3)	1.7 (0.4)
Total number of casualties		819	740	8
Mean number of casualties per crash (SD)		1.0 (0.3)	1.1 (0.2)	1.1 (0.4)
Crashes involving cyclist casualties		753 (95.6)	652 (92.7)	6 (85.7)
Crashes involving pedestrian casualties		42 (5.3)	63 (9.0)	1 (14.3)
Mean road segment speed limit in mph (SD)		29.9 (1.3)	27.8 (4.2)	30.0 (0.0)
Crash severity	Fatal	6 (0.8)	4 (0.6)	0 (0.0)
	Serious	90 (11.4)	98 (13.9)	1 (14.3)
	Slight	692 (87.8)	601 (85.5)	6 (85.7)
Vehicles involved in crash with the pedal cycle [1]	Car	448 (56.9)	361 (51.4)	2 (28.6)
	Light Goods Vehicle	99 (12.6)	75 (10.7)	0 (0.0)
	Taxi	79 (10)	86 (12.2)	2 (28.6)
	Single pedal cycle – no additional vehicle	40 (5.1)	62 (8.8)	1 (14.3)
	Bus, coach or minibus	40 (5.1)	40 (5.7)	1 (14.3)
	Motorcycle	36 (4.6)	29 (4.1)	0 (0.0)
	Heavy Goods Vehicle	31 (3.9)	34 (4.8)	1 (14.3)
	Other vehicle type	6 (0.8)	5 (0.7)	0 (0.0)
	Two pedal cycles	3 (0.4)	9 (1.3)	0 (0)
	Two motor vehicles	6 (0.8)	2 (0.3)	0 (0)
Police officer attended the scene	Yes	531 (67.4)	517 (73.5)	6 (85.7)
	No	194 (24.6)	184 (26.2)	1 (14.3)
	Data missing or out of range	63 (8.0)	2 (0.3)	0 (0.0)
Junction details	At or within 20 m of a junction or roundabout	726 (92.1)	656 (93.3)	7 (100.0)
	Not at or within 20 m of a junction or roundabout	62 (7.9)	47 (6.7)	0 (0.0)
First road class [2]	A	498 (63.2)	383 (54.5)	6 (85.7)
	B	64 (8.1)	43 (6.1)	0 (0.0)
	C	141 (17.9)	193 (27.5)	0 (0.0)
	Unclassified	85 (10.8)	84 (11.9)	1 (14.3)
Road type	Single carriageway	602 (76.4)	533 (75.8)	7 (100.0)
	One way street	36 (4.6)	99 (14.1)	0 (0.0)
	Dual carriageway	56 (7.1)	52 (7.4)	0 (0.0)
	One way street slip road	88 (11.2)	8 (1.1)	0 (0.0)
	Unknown	3 (0.4)	1 (0.1)	0 (0.0)
	Roundabout	3 (0.4)	10 (1.4)	0 (0.0)
Light conditions	Daylight	618 (78.4)	530 (75.4)	7 (100.0)
	Darkness	170 (21.6)	173 (24.6)	0 (0.0)
Weather conditions	Fine	715 (90.7)	631 (89.8)	7 (100.0)
	Rain, snow, fog or other	61 (7.7)	67 (9.5)	0 (0.0)
	Unknown	12 (1.5)	5 (0.7)	0 (0.0)
Road surface conditions	Dry	692 (87.8)	607 (86.3)	6 (85.7)
	Wet, icy or muddy	96 (12.2)	96 (13.7)	1 (14.3)

Day of week



Hour of day



[1]Each crash involves a pedal cyclist. Crashes may involve one or more pedal cycles and one or more other vehicles. 'Single bicycle crashes' that involve a single pedal cycle and a single pedal cyclist casualty are excluded from this analysis.
[2]A roads are major roads providing large-scale transport connections and B roads connect different areas and A to C roads. C roads are smaller roads whilst unclassified are local roads for local traffic (DfT, 2012).

between 1st January 1998 and 31st December 2019 (inclusive) to introduce contraflow cycling in inner London boroughs. These road segments measure 64.4 km in total length. Ten road segments had contraflow cycling removed (Fig. 1c). Significant changes to the roads included the conversion of 115 (22.6 %) segments from two-way for vehicles to one-way and the introduction of contraflow bus lanes on 11 (2.2 %) segments. Some TROs mentioned that one or more specific types of additional cycling infrastructure was to be introduced on road segments, namely cycle lanes (139, 27.4 %), segregated cycle lanes (19, 3.7 %) and cycle tracks (7, 1.4 %) (see Fig. A1 for images of UK infrastructure). Contraflow cycling was allowed on a footway in seven (1.4 %) segments.

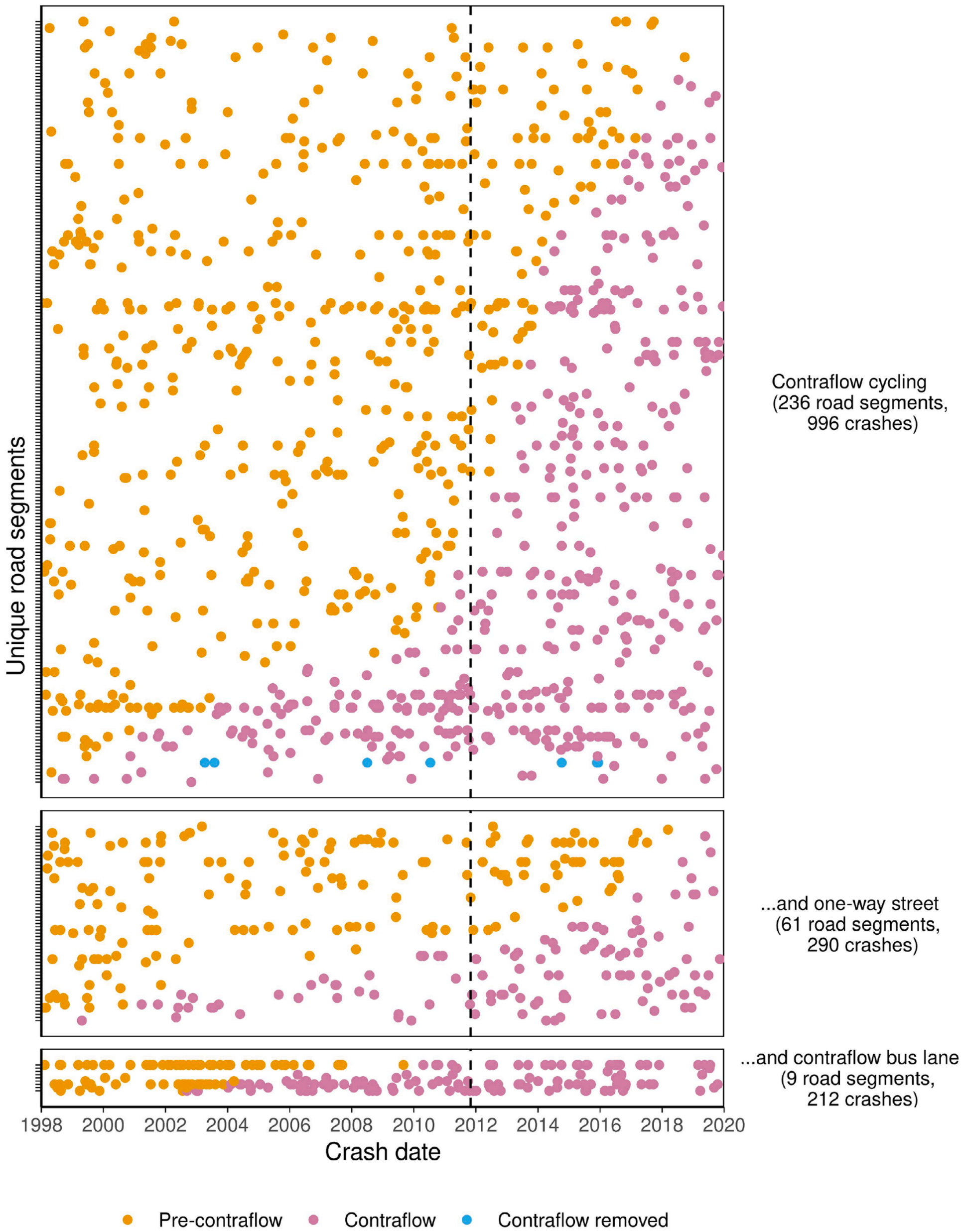


Fig. 2. Dot visualisation of all crashes involving pedal cycles within 10 m of a road segment by: unique road segment (vertical position); date of crash (horizontal position); crash segment status (colour); and significant change to road segment (pane). The dashed line shows when the traffic sign change was introduced. Colour palette sourced from Wong (2011) to promote visual accessibility.

The road segments are spatially concentrated in central London (Fig. 1b). There is considerable variation between the 14 London boroughs with City of London (the smallest borough in terms of geographic area) introducing the most (93) whilst Tower Hamlets introduced just five during the study period (Fig. 1d, Table B1). There are differences between boroughs in terms of when they introduced contraflow cycling (Fig. 1c and 1d). Immediately prior to and in the year following the relaxation of traffic sign legislation in 2011, there was significant expansion in many boroughs and exponential growth in City, Southwark and Lambeth. Two boroughs have consistent low-levels of contraflow introduction; Tower Hamlets and Hammersmith and Fulham.

For 35 road segments, a contraflow start date could not be identified (6.9 %). This is because these road segments have a 'Consultation' but not a 'Introduction' TRO. They are known to exist through validation with the CID and/or OSM. However, this means that these segments are not used in our crash analysis as we are unable to identify whether a crash occurred before or after contraflow implementation.

3.2. *Road traffic crashes involving pedal cycles within 10 m of road segments*

We identified 1498 crashes involving pedal cycles within 10 m of a road segment identified in section 3.1 that had a contraflow start date (n = 306) between 1st January 1998 and 31st December 2019 (inclusive).

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Table 2
Characteristics of casualties in crashes involving pedal cycles within 10 m of road segments by crash segment status occurring between 1st January 1998 and 31st December 2019 (inclusive). These characteristics are all determined from the STATS19 dataset. Data is presented as 'number (percentage)'.

Characteristics			Crash segment status		
			Pre-contraflow	Contraflow	Contraflow removed
Total number of casualties			819	740	8
Casualty type	Cyclist		755 (92.2)	662 (89.5)	6 (75.0)
	Pedestrian		44 (5.4)	64 (8.6)	1 (12.5)
	Motorcyclist		10 (1.2)	9 (1.2)	0 (0.0)
	Car driver or passenger		8 (1.0)	2 (0.3)	0 (0.0)
	Other		2 (0.2)	3 (0.4)	1 (12.5)
Casualty severity [1]	Fatal	Cyclist	6 (0.7)	3 (0.4)	0 (0.0)
		Pedestrian	0 (0.0)	1 (0.1)	0 (0.0)
	Serious	Cyclist	76 (9.3)	79 (10.7)	1 (12.5)
		Pedestrian	12 (1.5)	19 (2.4)	0 (0.0)
		Motorcyclist	1 (0.1)	1 (0.1)	0 (0.0)
		Car	1 (0.1)	0 (0.0)	0 (0.0)
	Slight	Cyclist	673 (82.2)	580 (78.4)	5 (62.5)
		Pedestrian	32 (3.9)	45 (6.1)	1 (12.5)
		Motorcyclist	9 (1.1)	8 (1.1)	0 (0.0)
		Car	7 (0.9)	2 (0.3)	0 (0.0)
		Other	2 (0.2)	3 (0.4)	1 (12.5)

[1] In November 2015 London Police Forces moved to injury-based classifications systems for casualty severity to standardise the severity assessment. (DfT, 2021b). Adjustment probabilities have been developed so that severity can be compared across the years (DfT, 2020c; DfT, 2020e). The data presented in this table is unadjusted.

Of these crashes, 788 occurred before whilst 703 occurred during the time period when contraflow cycling was legally allowed and a further 7 occurred after contraflow cycling was rescinded. Our remaining analysis is focused on these 1498 crashes where we have determined the crash timescale in relation to the road segment status, referred to as 'crash segment status'.

Table 1 shows the characteristics of the crashes by crash segment status. In general, the characteristics of crashes that occurred before or when contraflow cycling is allowed are very similar. The mean number of vehicles involved per crash was 1.9–2.0, the mean number of casualties was 1.0–1.1 and the mean road speed limit was 30 mph or less (the normal speed limit for UK built-up areas (DfT, 2022c)). The vast majority of crashes resulted in cyclist casualties with less than 10 % having pedestrian casualties. Fortunately, very few crashes were fatal and less than 14 % considered serious. The commonest other single vehicles involved in these crashes with pedal cyclists are cars, taxis and light goods vehicles which account for around three-quarters of crashes. Over 92 % of crashes occurred within 20 m of a junction or roundabout despite only 63 % of road segment length being within 20 m of a junction (Table B2). Over 75 % occurred on single carriageway roads and over 54 % occurred on A roads. Crashes tended to occur in daylight hours (over 75 %), in fine weather (90 %) and on dry roads (86 %). Most crashes occurred in rush hours on weekdays. It is hard to draw any conclusions about crashes that occurred after contraflow cycling is removed due to the small numbers.

Fig. 2 shows the 1498 crashes involving pedal cycles, each represented as a dot, arranged vertically by road segment and ordered from left-to-right as they occurred over time (please see Fig. B1 and Table B3 for a breakdown by additional cycling infrastructure mentioned in the TRO, for example cycle lanes). Only 306 (60 %) out of the 508 road segments had a crash within 10 m. Some road segments have a greater number of crashes, represented by more dots along their horizontal row. This is particularly obvious for crashes associated with road segments where contraflow bus lanes are introduced with contraflow cycling (lowest pane). There were 212 crashes on these 9 road segments despite this action only affecting 11 (2.2 %) of all road segments. 80 (37.7 %) crashes occurred before and 132 (62,3%) occurred after the new contraflow bus lane was introduced. For road segments that were two-way, 176 (60.7 %) crashes occurred before they became one-way streets with contraflow cycling and 114 (39.3 %) occurred afterwards. For the existing one-way streets, 532 (53.4 %) crashes occurred before contraflow cycling, 457 (45.9 %) occurred after and 7 (0.7 %) occurred following contraflow removal.

3.3. *Casualties*

The 1498 crashes within 10 m of a road segment resulted in 1567 casualties of which 1423 were cyclists, 109 were pedestrians, 19 were motorcyclists, 10 were car occupants and six were 'other' (Table 2). The majority of crashes resulted in just one casualty (96 %) but 57 crashes had two casualties and three crashes had three, four and eight casualties each. There were 10 fatalities, nine of whom were cyclists with 60 % of these occurring in the pre-contraflow period. There were 189 seriously injured casualties of whom 83 % were cyclists and 16 % pedestrians and 1368 slightly injured casualties with cyclists accounting for 92 % and pedestrians 6 %. Only 9 % of non-cyclist, non-pedestrian casualties experienced a serious injury from the crashes with the rest being slightly injured.

3.4. *Pedal cycle direction*

Utilising the STATS19 vehicle direction variables, the spatial

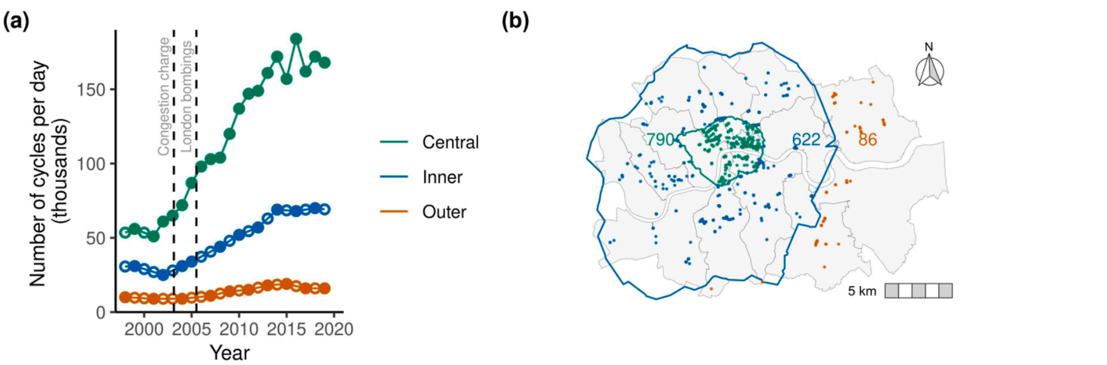

Fig. 3. a) **cordon counts of number of cyclists over time and b) spatial location of crashes and the central and inner cordon s.** Circle points (a) indicate values interpolated from data whereas dots (a) show actual count data. Numbers in (b) show the number of crashes occurring within each cordon. Count data sources: TFL (2019e) and TFL (2021). Colour palette: Wong (2011).

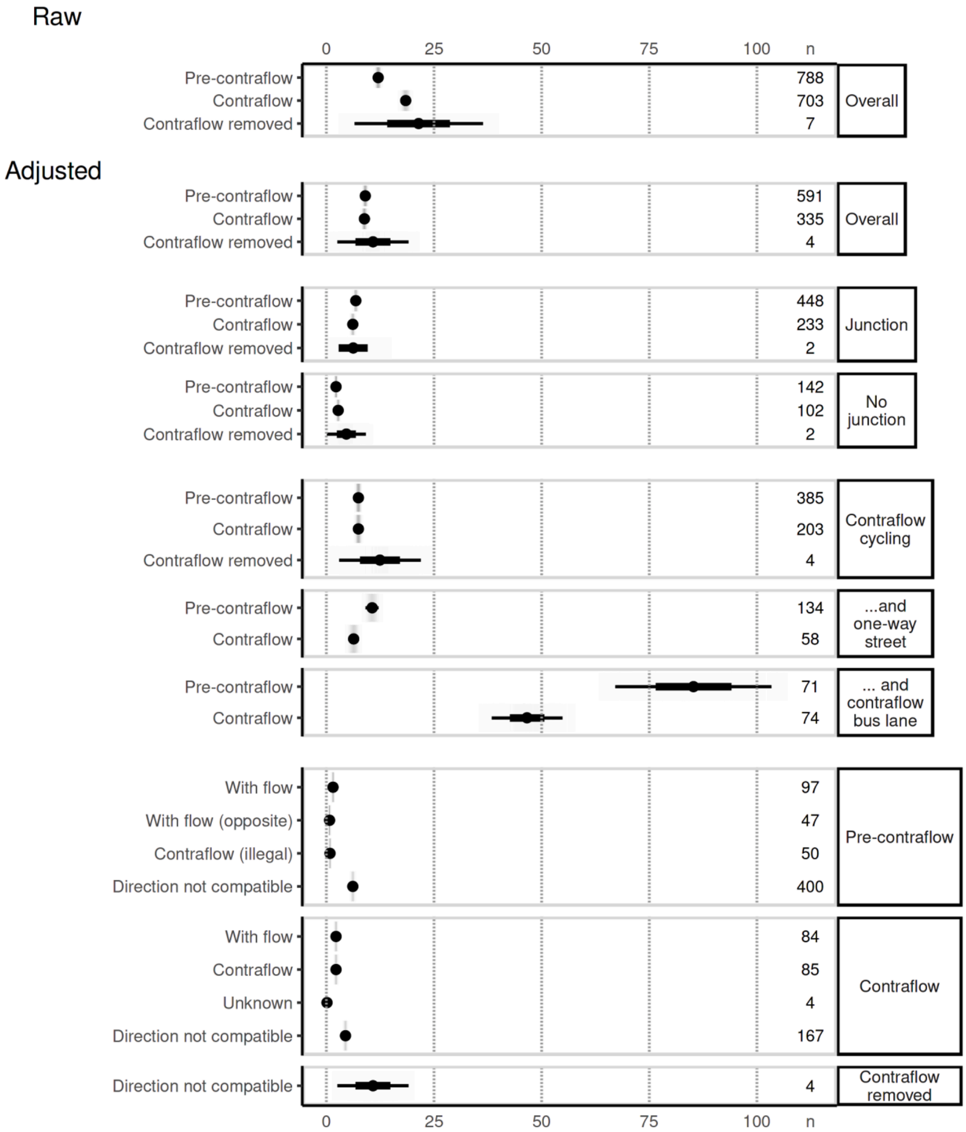

Fig. 4. Crash rates involving pedal cyclists per 100 years of exposure by crash segment status. Rates are presented as raw and adjusted for cordon cycling volume (1998 index) as: overall; by proximity to junctions or roundabouts (within 10 m); by significant change to road segments; and by pedal cycle direction. Visualisation shows point estimates for rates with 95 % confidence intervals generated by bootstrapping. n represents the number of crashes, rounded to the nearest integer for adjusted data.

orientation of the road segment, the crash location and the crash segment status, we could determine whether the pedal cycle was travelling with or against the motor vehicle traffic flow. This data is shown in Table B4. The commonest pedal cycle direction is 'direction not compatible' and that this proportion is greatest for crashes within 10 m of a junction or roundabout (up to 76 %). This indicates that these pedal cyclists are turning rather than travelling with or contraflow along the road segment.

Focusing on road segments that had been one-way streets, there are pre-contraflow crashes where cyclists are travelling illegally contraflow but this proportion is lower than the with-flow crashes, for example it is 15.3 % v 27.1 % for crashes more than 10 m from a junction. Looking at segments that were two-way streets, the proportion of crashes where the pedal cyclist is travelling contraflow is similar to that of one-way streets - around 21–28 %. Where the contraflow was removed, none of the seven crashes had a pedal cycle direction.

3.5. Changes to cordon cycling volume over time

The number of people cycling and thus the number of people potentially exposed to cycling on roads with contraflows in London has changed during the study time period. Fig. 3a shows the number of pedal cycles counted crossing cordons around outer, inner and central London over time (cordons shown in Fig. 3b). This demonstrates a large increase in the number of pedal cycles entering London with the volume doubling (inner) and tripling (central) over time. The number of crashes within our study area also varies in relation to these cordons with 5.7 % occurring outside the inner cordon, 42.0 % occurring between the inner

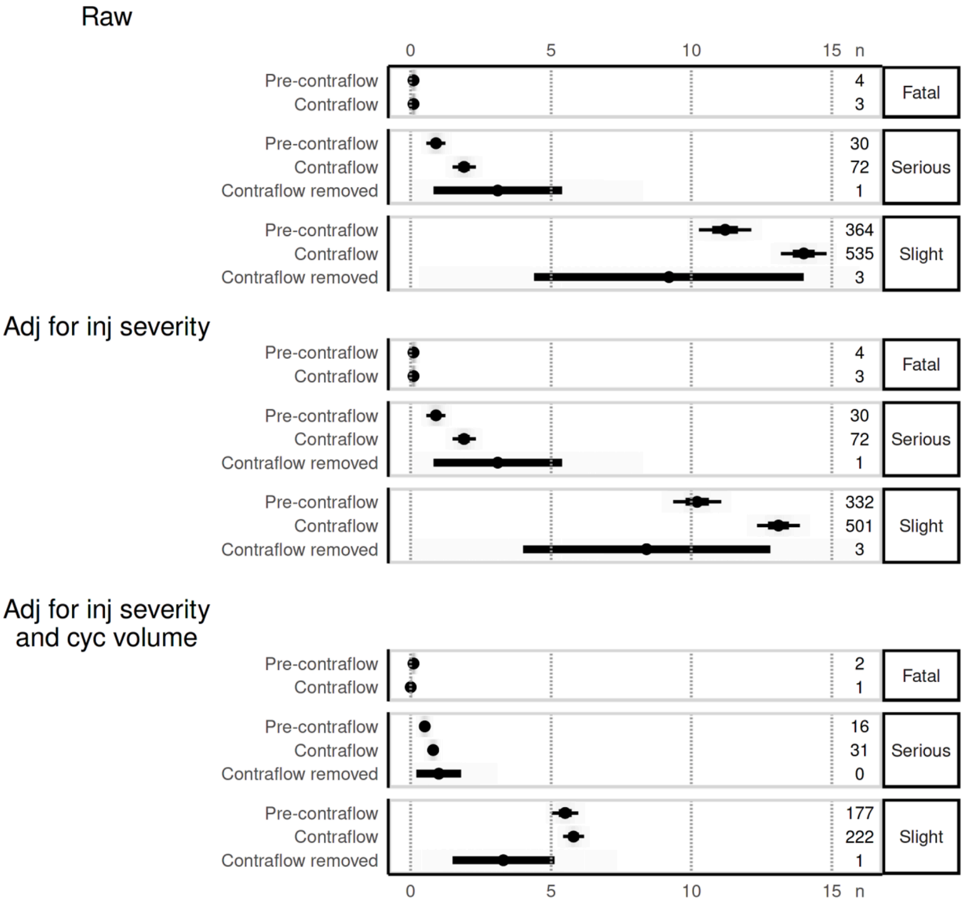

Fig. 5. Pedal cyclist casualty rates per 100 years of exposure by crash segment status and injury severity, 2005–2019. Rates are presented as raw, adjusted for change in injury severity classification; and adjusted for change in injury severity classification and cordon cycling volume (1998 index). Visualisation shows point estimates for rates with 95 % confidence intervals generated by bootstrapping. n represents the number of pedal cyclist casualties, rounded to the nearest integer for adjusted data.

and central cordons and 52.7 % occurring within the central cordon (Fig. 3b). This change in exposure of cyclists to infrastructure is important when considering the crash risk to which they may be subjected.

3.6. Pedal cycle crash rates

In Table B5 we present crash numbers, rates and their 95 % confidence intervals for crashes involving pedal cycles within 10 m of a road segment. These rates are expressed per 100 years of exposure to the road segment status (i.e. pre-contraflow, contraflow or following removal) as raw and adjusted for change in cordon cycling volume baselined to 1998 (we have predominantly included the adjusted rates in our visualisation, Fig. 4). This allows easier interpretation of the rates, so for example, the overall adjusted pre-contraflow crash rate is 9.0 which means that we would expect 9.0 crashes involving pedal cyclists to occur during 100 years of use of these road segments given the levels of cycling that have occurred over the study period.

Examining the overall crash rate shows that when raw numbers are utilised there appears to be a higher crash rate when contraflows are implemented (pre-contraflow crash rate = 12.0, 95 % confidence interval 11.4–12.6 v contraflow crash rate = 18.4, 17.4–19.4, Fig. 4, Table B5). However, once the number of crashes are adjusted to take into account the change in cordon cycling volume there is no statistically significant change in the crash rates when contraflows are implemented (9.0, 8.5–9.5 v 8.8, 8.2–9.3). This pattern - raw crash rates suggesting a difference between the pre and contraflow periods that is removed after accounting for change in cycling volume - exists for most rate comparisons. It is hard to draw any conclusions about the impact of removing contraflow cycling as the number of crashes on these segments are in single digits and therefore the confidence intervals around these crash rates are extremely wide.

Focusing now on crashes near junctions or roundabouts, there is no statistical difference in the cordon cycling volume adjusted crash rates occurring within or beyond 10 m of a junction between the pre- or contraflow time periods. However, the adjusted crash rate within 10 m of junctions is more than double that for crashes occurring over 10 m away. This is true irrespective of whether they occur in the pre-contraflow (6.8, 6.4–7.3 v 2.2, 1.9–2.5) or contraflow period (6.1, 5.6–6.6 v 2.7, 2.3–3.1).

Examining the cordon cycling volume adjusted crash rates by significant change to road segment demonstrates differences. Whilst there is no statistically significant change in crash rate when contraflow cycling is introduced on existing one-way streets (both rates are 7.4, 6.8–8.0), there is a statistically significant difference when two-way streets are converted to one-way with contraflow cycling - the crash rate falls by over a third from 10.6 (8.9–12.0) to 6.3 (5.2–7.6). There is also a statistically significant drop, again by over a third, in crash rates when two-way streets are converted to one-way with contraflow bus lanes and cycling from 85.3 (67.2–104.5) to 46.6 (39.5–55.4).

Comparing cordon cycling volume adjusted crash rates by pedal cycle direction shows that in the pre-contraflow period the crash rate involving pedal cycles travelling contraflow illegally on one-way streets is 0.8 (0.6–1.0) and is comparable to those travelling with flow in the opposite direction on two-way streets (0.7, 0.5–0.9) but lower than those travelling with flow (1.5, 1.2–1.8). This illegal contraflow crash rate is lower than that when people are legally allowed to cycle contraflow (2.2, 1.9–2.6). Examining the crash rate when contraflow cycling is allowed, the rate of crashes involving pedal cyclists travelling with the motor vehicle flow is identical to the crash rate of those travelling against the flow (both rates are 2.2, 1.9–2.6) and this is true even for raw rates (4.5, 3.9–5.2). The adjusted crash rate for those whose direction is not compatible, i.e. they are turning, is double that of those travelling along the road segment irrespective of whether occurring in pre-contraflow (6.1, 5.6–6.5) or contraflow (4.4, 3.9–4.8) period. These pedal cyclist direction rates confirm the earlier finding that pedal cyclists travelling on segments between junctions experience lower crash rates than those near junctions or roundabouts but additionally show that turning pedal cyclists experience lower crash rates after contraflow introduction.

3.7. Pedal cyclist casualty rates

In Table B6 we present pedal cyclist casualties numbers, rates and their 95 % confidence intervals for crashes involving pedal cycles within 10 m of a road segment by injury severity for the years that severity adjustment factors are available (2005–2019). Again, these rates are expressed per 100 years of exposure to the road segment status. They are presented as raw rates and rates adjusted for change in classification of injury severity and change in cordon cycling volume baselined to 1998. The casualty rates for the 1012 pedal cyclist casualties injured between 2005 and 2019 are visualised in Fig. 5.

Our analysis shows there is no difference in fatal pedal cyclist injury rates when contraflows are introduced. The raw rates suggest that seriously injured pedal cyclist casualties double when contraflows are introduced (pre-contraflow = 0.9, 0.6–1.3 v contraflow = 1.9, 1.5–2.3) and that slight injuries increase by nearly a third (11.2, 10.3–12.2 v 14.0, 13.2–14.8). Adjusting for the change in injury severity classification only alters the casualty rates for those with slight injuries. It reduces the slight casualty rate but does not alter the suggestion that they increase by nearly a third when contraflows are introduced. However, when the changes in cordon cycling volume are taken into consideration the findings change. There is no statistically significant difference in rates of pedal cyclist casualties that are seriously (0.5, 0.3–0.7 v 0.8, 0.6–1.0) or slightly injured (5.5, 5.0–6.0 v 5.8, 5.5–6.2) when contraflow cycling is introduced.

4. Discussion

4.1. Summary of key findings

During the 22 year study period, 508 road segments in inner London had contraflow cycling introduced with 10 having it removed. 1498 crashes involving pedal cycles occurred within 10 m of the 473 segments with a contraflow start date, although 167 of these road segments were not associated with any crashes. 788 crashes occurred prior to contraflow cycling being implemented, 703 occurred after the contraflow cycling was allowed and 7 occurred following its removal. Over 92 % of crashes occurred close to junctions or roundabouts.

Crash rates calculated using raw numbers suggest contraflow cycling increases crashes involving pedal cyclists. However, when the rate is adjusted using cordon cycling count data to take into account the significant changes in cycling volume that has occurred in London during the 22 years, there is no difference in overall crash rates before or after contraflow cycling is introduced.

The presence of a junction or roundabout within 10 m is associated with a doubling of the crash rate whilst converting a two-way street to one-way and contraflow cycling, with or without a contraflow bus lane, is associated with a reduction in the crash rate by over a third. The crash rate when pedal cyclists are cycling contraflow is identical to those travelling with the flow of motor vehicles. However, the crash rate when pedal cyclists are travelling in directions that are not compatible with the road segment, i.e. they are turning, is double that of cyclists travelling in compatible directions. Illegal contraflow cycling crash rates are no different than those cycling with flow. The pedal cyclist direction rates confirm the earlier finding that pedal cyclists travelling on segments between junctions experience lower crash rates than those near junctions or roundabouts but additionally demonstrate turning pedal cyclists experience lower crash rates after contraflow introduction.

Our casualty analysis demonstrates that there is no difference in the fatal, severely or slightly injured cyclist casualty rate when contraflows are introduced once change in cordon cycling volume and injury severity reporting changes are taken into account.

4.2. Interpretation of findings and contextualisation with the literature

Our findings corroborate existing evidence suggesting that there is no increase in crash risk when contraflow cycling is introduced on one-way streets (Vandenbulcke et al., 2014; Chalanton and Dupriez, 2014; UDV, 2016). It may even be true that the crash rate falls when contraflow cycling is introduced. This could be the case as contraflow interventions attract more cycling and route substitution onto the new infrastructure (Pritchard et al., 2019), raising the question of whether ‘safety in numbers’ effects apply to contraflows (Elvik and Goel, 2019). However, more data on cycling levels on specific road segments, including those with contraflows, are needed before conclusions on this question can be answered. If higher cycling volumes than we included in our adjustment are found on contraflows this would further reduce estimates of crash rates on contraflows.

In contrast to the existing evidence (Alrutz et al., 2002; Chalanton and Dupriez, 2014), we did not find any difference in crash rates for those travelling with or against motor traffic on road segments with contraflows. This may be explained by different approaches to calculating crash rates. We used the time duration of exposure to the different contraflow states to allow for the fact that some road segments were ‘pre-contraflow’ for most of the 22 years whilst others were ‘contraflow’ for a substantial period whereas Alrutz et al. (2002) and Chalanton and Dupriez (2014) use total length of contraflow segments and express their crash rates as ‘per kilometre’. Alrutz et al. (2002) only included crashes that were indisputably on a contraflow road segment whereas Chalanton and Dupriez (2014) utilised a 10 m buffer to identify crashes. In common with both the contraflow cycling and wider cycling infrastructure literature, including that focussed on London (e.g. Collins and Graham, 2019; Adams and Aldred, 2020), we identify proximity to junctions or roundabouts as being a significant cyclist crash association.

We found that converting a two-way road to one-way with contraflow cycling was associated with reduced adjusted crash rates of over a third. This contrasts with research from the USA where two-way streets are considered safer. However, this also reflects contrasting street designs: in the USA one-way streets tend to be wide, multilane structures thus conversion to two-way improves safety (Riggs and Gilderbloom, 2016; Riggs and Gilderbloom, 2017). Previous UK research has found that bus lanes are associated with both increasing (Kapousizis et al., 2021) and decreasing cycling injury risk (Adams and Aldred, 2020; Aldred et al., 2018). However, none of these studies have focused on contraflow bus lanes where we found the adjusted crash rate was over a third lower after their introduction.

Our findings need to be considered in real world terms. The overall adjusted crash rates where the pre-contraflow crash rate is 9.0 and the contraflow rate is 8.8, this equates to a crash occurring on such a road segment once every 11 years, respectively. Whilst the adjusted severe pedal cyclist injury rates of 0.5 during the pre-contraflow and 0.8 during the contraflow period correspond to a single severely injured pedal cyclist every 200 (pre-contraflow) or 125 (contraflow) years of exposure to such road segments.

5. Strengths and limitations

Our study is the first large data analysis of crashes occurring on road segments before and after contraflow cycling has been implemented, to the best of our knowledge. It examines a substantial time period (22 years) and large physical area (inner London) with hundreds of road segments. We utilised The Gazette (TSO, 2022a) where it is legally mandatory for London transport authorities to publish information on certain road infrastructure changes and the official UK road traffic crash datasets, both of which should be considered the gold standard for this data. In line with accepted practice, we have adjusted the crash rate for cycling exposure both in terms of duration of exposure to the specific road segment status and cycling volume (Vanparijs et al., 2015). We used a recognised statistical technique (bootstrapping) to vary crashes by year and crash timescale in order to estimate uncertainty of our crash rates and generate confidence intervals.

We believe our pedal cycle direction crash rate analysis provides the most compelling evidence about safety of contraflows themselves as it identifies cyclists most likely to be travelling on the road segments as opposed to those interacting with junctions and negates any crashes that may have been erroneously included by our 10 m buffering process. We also believe this is the first analysis of the impact of introducing contraflow bus lanes and the first use of injury adjustment factors for UK road traffic crashes.

Our approach is not without limitations. First, we assumed that the road segment data coded and provided in The Gazette is high-quality data and as such is accurate, complete, reliable, relevant and timely (Wand and Wang, 1996). We have assumed that: all contraflows that were implemented have a TRO that can be detected using the 'contraflow' search term; the TRO content contains accurate information about the contraflow order including location, action and whether consulting, introducing or rescinding an order etc; and the contraflow start date is accurate. Furthermore we have assumed that none of the infrastructure had been changed further unless a new TRO exists. We attempted to mitigate these issues by validating the TRO data against other datasets such as the CID and OSM and identifying contraflows in the CID and OSM and cross-referencing them with The Gazette. It would have strengthened the analysis if we had been able to consider the additional cycling infrastructure, for example, cycle lanes, in our rate calculations as such infrastructure may have affected crashes. This is something that none of the previous contraflow studies had examined (Pritchard et al., 2019; Ryley and Davies, 1998; Alrutz et al., 2002; Bjørnskau et al., 2012; Chalanton and Dupriez, 2014; UDV, 2016). However, there are considerable unmeasured aspects of such infrastructure in our data; for example, whether it was installed, positional uncertainty and measurement uncertainty. This lack of data coupled with the challenge of how to include this 'exposure' in our rate calculation meant we were unable to consider this aspect.

Second, the UK road traffic crash dataset has limitations. Concerns exist around the accuracy of data on vehicle direction of travel and geospatial crash location (Anderson, 2003; DfT, 2021c; Imprialou and Quddus, 2019) and casualty severity reporting (DfT, 2020e). We have addressed these issues by validating pedal cycle direction against road axes, using 10 m buffers around the road segments and adjusting casualties using the official severity probabilities. It is known that there is under-reporting of crashes involving pedal cycles (e.g. Ward et al., 2005; Jeffrey et al., 2009) and so our rates may not reflect the true number of these crashes occurring on London roads.

Third, we have not adjusted for all potential confounders. For example, road traffic crashes involving pedal cyclists are affected by weather, light conditions, road conditions, driver behaviour and road speed (Knowles et al., 2009; Prati et al., 2018; Young and Whyte, 2020). However, our descriptive tables suggest that the crashes, casualties and vehicles occurring pre and during the contraflow period are comparable despite occurring at different points during our 22 year study period.

Fourth, whilst we have adjusted for change in cycling volume, our cycling volume data is based on cordon traffic counters not individual road segment cycling volume. This data does not accurately reflect cyclist spatial distribution or volume (von Stülpnagel et al., 2022). It also does not take into account potential increases in cycling volume on the contraflow segment as a consequence of this infrastructure being introduced (Pritchard et al., 2019). We have also assumed a linear relationship between crash risk and cycling volume but this does not make allowances for the safety-in-numbers effect that suggests this relationship may not be linear (Aldred et al., 2018; Elvik and Goel, 2019). Obtaining and utilising quality cyclist exposure data is difficult (Vanparijs et al., 2015) and the cordon traffic counters are the best official open cycling volume data we have for the full duration of the study period. Additionally, using a long study period, multiple road segments, official data sets, adjusting over time and aggregating the rates means that any confounders or systematic biases are likely to even out over the 22 year period making this the most comprehensive data analysis of UK pedal cyclist crash risks on contraflows.

5.1. *Implications for policy and future research*

Our research provides strong evidence that all UK one-way streets should allow contraflow cycling unless there are compelling reasons against this position. This is already recommended by the Department for Transport (DfT, 2020a) and provides a cost-effective alternative to more substantial cycling infrastructure changes. We recommend all UK local transport authorities review their one-way (for motor traffic) streets with a view to allowing contraflow cycling and examine their two-way streets for potential to reconfigure to one-way streets or contraflow bus lanes with contraflow cycling. Our results suggest that safe junction design should be a priority. We call on national governments to consider implementing legislative change making it mandatory for one-way streets to be two-way for pedal cyclists unless there are exceptional conditions. Such laws have been introduced in Belgium (Depoortere, 2019). More broadly, large scale investment in contraflows will strengthen cycling networks and routes by not only improving the coherence, directness, attractiveness and comfort but also their safety, increasing their level of compliance with design guidance (DfT, 2020a).

The substantial benefits of preventing crashes involving pedal cyclists are felt by health services, businesses and the economy as well as individuals, families and communities. The value of preventing urban crashes are estimated to be £2.5 million for fatal, £280,000 for severe and £28,000 for slight crashes whilst the average value of preventing a pedal cyclist casualty is £90,000 (2022 estimates, DfT, 2022d). Our findings suggest that introducing contraflow cycling is an intervention that may improve road safety and could reduce crash and casualty costs particularly if it attracts more cyclists who then benefit from a safety-in-numbers effect. However, our analysis does not consider crashes or casualties that occur on nearby streets that might have been used by cyclists in the pre-contraflow period because there was no contraflow cycling allowed on their direct route. If these adjacent street crashes and casualties were considered then additional benefits may be accrued. This is because pre-contraflow routes may have included busier and faster nearby roads with concomitant greater number of crashes and casualties whilst when contraflow cycling is introduced there is greater route directness and route substitution from the nearby streets onto the new contraflows that may decrease crashes on these adjacent streets.

Our research has highlighted the difficulties and importance in obtaining good quality data and evidence around cycling infrastructure to challenge arguments that are not evidence-based. It may be that other beliefs and assumptions in this arena are unfounded and under-researched. This may be due to the long time duration required to generate enough exposure and crashes and hindered by lack of open granular data such as actual road speeds, cycling volumes and motor vehicle volumes. Building on our previous call for open data inventories of cycling infrastructure (Tait et al., 2022), our research demonstrates their importance and utility to build the evidence base around cycling infrastructure. We welcome the proposed new requirement for English transport authorities to publish standardised open TRO data (DfT, 2022e) as this will enable many types of cycling infrastructure to be evaluated more easily using the approaches we have demonstrated.

We have shown the importance of using an appropriate denominator in the calculation of crash rates. When we accounted for the change in cycling volume we found no evidence that contraflow cycling increases crash risk. However, our denominator lacked granularity or specificity for contraflows. We believe our findings could be reproduced and strengthened by performing the analysis with better cyclist volume data but to achieve this there must be better monitoring of cyclist volume. This could be realised through traditional manual counting or newer technologies such as machine learning analysis of video camera images (e.g. Foroozandeh Shahraki et al., 2017; Edwardes et al., 2021) augmented with emerging data sources (Alattar et al., 2021) such as crowdsourced data to improve the spatial and temporal granularity (Conrow et al., 2018; Kwigizile et al., 2022).

6. Conclusion

This is the first large-scale analysis of the impact of introducing contraflow cycling on one-way streets. We have found no evidence that contraflow cycling infrastructure alters the crash or casualty rate for pedal cyclists and it may be protective. Crash rates are consistent whether the cyclist is travelling with or contraflow. Transport authorities should consider implementing contraflow cycling on all one-way streets and consider conversion of appropriate two-way streets to one-way with contraflow cycling to improve cycling networks and routes. As crash rates are elevated at junctions and when cyclists are turning, careful junction design must form part of any such improvement. Governments with suitable styles of one-way streets should explore legislative options to make them two-way for pedal cyclists by default.

Our analysis was only possible after intensive primary data collection from TROs that identified contraflow cycling infrastructure and their introduction dates and association of this data with spatial road segment data and spatio-temporal pedal cycle crashes and casualties. We have demonstrated an approach that can be replicated, strengthened and applied to other areas of cycling infrastructure evaluation that are urgently needed through the use of new datasets such as the proposed digital TRO dataset. Further research on contraflows should utilise new ways to collect cyclist levels (exposure) and utilise site-specific cycling volume data to improve rate calculation. Such research should also investigate the impact of different types of cycling infrastructure implemented on contraflows and evaluate impact on cycling volume including route substitution onto the new contraflows. This research would be strengthened through detailed datasets on the exact nature of contraflow interventions and the surrounding active travel environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and code that form this analysis is available at: https://github.com/PublicHealthDataGeek/Contraflow_cycling_safety.

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TfL data: Powered by TfL Open Data. Contains OS data © Crown copyright and database rights 2016 and Geomni UK Map data © and database rights [2019].

The Gazette, Office of National Statistics and UK Road Traffic crash data: Licensed under the Open Government Licence v3.0. http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3.

OpenStreetMap data: © OpenStreetMap contributors and available under Open Database Licence. Contains Ordnance Survey data © Crown copyright and database right 2010-19. https://www.openstreetmap.org/copyright.

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Appendix A. Additional information about the methods

Road segments that allow contraflow cycling

Relevant TROs were identified by searching The Gazette for Road Traffic Regulation Act Notices (notice code 1501) (TSO, 2022c) containing the text ‘contraflow’ or ‘contra-flow’ (lower case text search returned the same results as upper case or capitalised words). Search results were limited to those in the study time period and location. We utilised the following search terms to identify TROs issued by relevant

Table A1
TRO data collection dataset.

Variable name	Variable description	Source
unique_row_ID	Unique ID for row in dataframe	Created
Borough	Borough name	TRO content
Organisation	Organisation involved (borough, Transport for London, Corporation of London	TRO content
road_name	Road name	TRO content
unique_contraflow_ID	Unique ID for the contraflow segment. Unique means unique in terms of road name, road contraflow limits, borough, contraflow start date, contraflow stop date and the type of action in terms of introducing: one way street, contraflow cycling, contraflow cycle lane, contraflow cycle track, contraflow cycling in footway, a contraflow bus lane, contraflow cycling in a bus lane or segregated contraflow cycle lane.	Created
road_limits_char	Describes the extent of the contraflow segment e.g. entire length of named road or length of named road between junctions A and B	TRO content
order_action	Text string that describes action: enable contraflow cycling, contraflow cycle track, contraflow lane, contraflow cycling in bus lane	TRO content
introduces_one_way_street	TRUE if TRO specifies that one way working/one way street introduced at the same time	TRO content
Introduces_cf_Cyclelane	TRUE if TRO states a contraflow cycle lane will be introduced	TRO content
Introduces_cf_Cycletrack	TRUE if TRO states a contraflow cycle track will be introduced	TRO content
Introduces_cf_footway	TRUE if TRO specifically mentions allowing contraflow cycling on the footway or if when looking at OpenStreetMap the area is pedestrianised	TRO content
introduces_contraflow_bus_lane	TRUE if TRO specifies that contraflow bus lane introduced at the same time	TRO content
Enables_cf_cycling_in_bus_lane	TRUE if TRO states cycling will be allowed in a contraflow bus lane	TRO content
Introduces_cf_seg_cyclelane	TRUE if TRO states contraflow cycle lane will be segregated	TRO content
FEATURE_ID	CID contraflow ID that spatially matches the contraflow	CID (identified spatially)
osm_id	OSM contraflow that spatially matches the contraflow	OSM (identified spatially)
spatial_data_ok	TRUE if all spatial dimensions of contraflow covered by OSM or CID data, FALSE if it isn't	Decision on examining spatial data
sp_d_not_ok_create_new	TRUE if spatial dimensions of contraflow not covered by CID/OSM data and need to create new spatial object (lat and long for linestring of spatial object recorded, if line bends then create new line for each part of linestring	Decision on examining spatial data
point_1	lat long of point 1	OSM (identified spatially)
point_2	lat long of point 2	OSM (identified spatially)
contraflow_start_date	Date contraflow becomes operational	TRO content
Evid_contraflow_exists	TRUE if have OSM or later TRO that says the contraflow exists, FALSE if no evidence - these ones will probably be deleted	CID, OSM, TRO content
contraflow_stop_date	Date contraflow is revoked	TRO content
notice_id_1	ID for first TRO (the earliest TRO regarding the contraflow)	Gazette listing
publication_date_1	Publication date of first TRO (defined by content of TRO or if not in content then the 'date of publication in the gazette)	TRO content (some cases Gazette listing)
pub_date_1_source_TRO	TRUE if the date of publication is contained within the body text of the TRO. FALSE means no date is contained within the body text of the TRO and instead date of publication in the Gazette is taken as the date	TRO content
tro_type_1	Type of TRO: Permanent or Experimental	TRO content
tro_action_1	Action of TRO: Consultation, Introduction, Revocation	TRO content
notice_id_2	ID for second TRO	Gazette listing
publication_date_2	Publication date of second TRO (defined by content of TRO or if not in content then the 'date of publication in the gazette)	TRO content (some cases Gazette listing)
pub_date_2_source_TRO	TRUE if the date of publication is contained within the body text of the TRO. FALSE means no date is contained within the body text of the TRO and instead date of publication in the Gazette is taken as the date	TRO content
tro_type_2	Type of TRO: Permanent or Experimental	TRO content
tro_action_2	Action of TRO: Consultation, Introduction, Revocation	TRO content
notice_id_3	ID for third TRO	Gazette listing
publication_date_3	Publication date of third TRO (defined by content of TRO or if not in content then the 'date of publication in the Gazette)	TRO content (some cases Gazette listing)
pub_date_3_source_TRO	TRUE if the date of publication is contained within the body text of the TRO. FALSE means no date is contained within the body text of the TRO and instead date of publication in the Gazette is taken as the date	TRO content
tro_type_3	Type of TRO: Permanent or Experimental	TRO content
tro_action_3	Action of TRO: Consultation, Introduction, Revocation	TRO content

Fig. A1. Types of UK cycling infrastructure (images taken from TFL 2019d).

bodies not listed in the drop-down borough search option: 'Transport for London', 'Corporation of London', 'City of London' and 'City of Westminster'.

Each TRO description was read to identify new contraflow cycling interventions on specific road segments and their details Table A1. Some TRO specified that additional cycling infrastructure was due to be introduced. Fig. A1 illustrates the UK types of additional cycling infrastructure that may be introduced (NB images do not necessarily show how such infrastructure would look on a contraflow street).

Changes to unique segments, for example upgrading to segregated contraflow cycle lanes, were captured as separate data observations. Subsequent TROs, for example a second TRO ordering the introduction of contraflow cycling following a consultation TRO, were also captured and linked to previous TRO.

Cyclist volume data

Manual cordon count data for all types of traffic has been collected since 1971 by Transport for London (TFL, 2012). 3 cordons exist covering central, inner and outer London. Counts are taken on every road site crossing the cordon. They are performed four times each hour between 6am and 10 pm on weekdays. Some additional counts have been made on weekends to enable comparison between weekdays and weekends, Central cordon counts are performed in autumn whilst inner and outer cordon counts are performed in the summer. For our study period the following cyclist cordon counts data was available (TFL, 2019c; TFL, 2021). Central cordon data was available for the year 1999 and then for all years between 2001 and 2019. For the inner London cordon, counts were available for the years 1999, 2002, 2004, 2005, 2008 and biannually until 2018 that whilst outer cordon counts were available for the years 1998, 2001, 2004, and biannually from 2007 to 2019.

Pedal cycle direction

We utilised the following method to identify the direction the pedal cycle was travelling in relation to whether this was 'with flow' or 'contraflow'. The direction the pedal cycle was travelling in was obtained from the STATS19 variables "vehicle direction from' and 'vehicle direction to'. We identified the traffic flow direction on the road segments from the TRO and/or OSM. Where the pedal cycles' direction from and to matched the axis of the road segment traffic flow then the pedal cycle flow was defined as either: 'with flow'; 'with flow (opposite)' when travelling in the opposite direction on a pre-contraflow or contraflow removed road segment that was two-way; 'contraflow (illegal)' when travelling against the flow on a one-way street prior to contraflow introduction; or 'contraflow' when travelling contraflow when contraflow cycling was allowed. Where a pedal cycle direction did not match the axis, for example, travelling perpendicular or the 'from' matched but the 'to' did not these were labelled as 'Direction not compatible' and assumed to be travelling on other road segments (such as at a crossing) or turning on or off the road segment. For road segments that had more than one axis, for example, those that have a bend, the road segment and crashes were visually mapped to identify the axis at the crash location and the appropriate flow was then attributed.

When calculating crash rates by pedal cycle direction, we included all pedal cycles where we have a vehicle direction. This means that in the small number of crashes where two pedal cycles were involved, these are both included in the numerator.

Appendix B. Additional results tables

(See Fig. B1 and Tables B1 – B6).

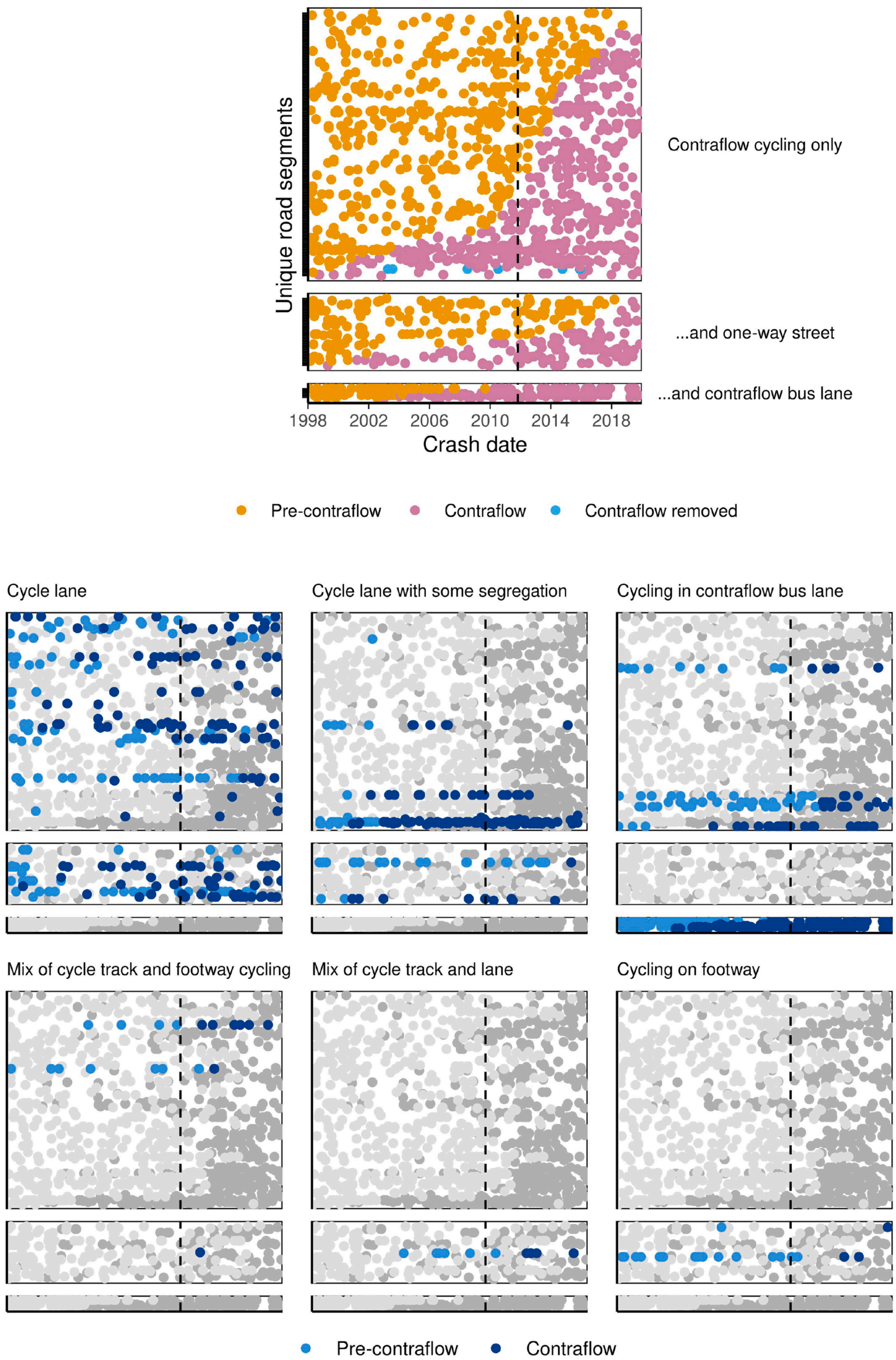

Fig. B1. Dot visualisation of all crashes involving pedal cycles within 10 m of a road segment by unique road segment (vertical position); date of crash (horizontal position); crash segment status (colour); and significant change to road segments (pane). Top visualisation represents all crashes. Lower visualisations highlight crashes by additional cycling infrastructure mentioned in Traffic Regulation Order. The seven contraflow removed crashes have been omitted to aid visualisation.

Table B1
Number (%) of contraflow cycling road segments introduced by borough.

Borough	Number (%)
City of London	93 (18.3)
Southwark	85 (16.7)
Lambeth	63 (12.4)
Camden	60 (11.8)
Kensington and Chelsea	45 (8.9)
Westminster	33 (6.5)
Hackney	29 (5.7)
Newham	23 (4.5)
Lewisham	19 (3.7)
Greenwich	16 (3.1)
Islington	16 (3.1)
Wandsworth	13 (2.6)
Hammersmith and Fulham	8 (1.6)
Tower Hamlets	5 (1.0)

Table B2
Calculation of proportion of road segment length within 20 m of a junction.

Number of road segments with a crash	306
Total length of these road segments within 20 m of a junction*	27564 *m*
Total length of these road segments	43805 *m*
Proportion of road segment length within 20 m of a junction	63 %

* Junctions extracted from OSM January 2019 data.

Table B3
Number of unique road segments where contraflow cycling was introduced by significant change to road segments, additional cycling infrastructure, whether they had a crash on the road segment or not and crash segment status; and number of crashes by significant change to road segments, additional cycling infrastructure and crash segment status.

Significant change to road segment	Additional cycling infrastructure mentioned in Traffic Regulation Order	Number of unique road segments (proportion of total number of segments)					Number of crashes		
		Total	Any crash	Crash segment status			Crash segment status		
				Pre-contraflow	Contraflow	Contraflow removed	Pre-contraflow	Contraflow	Contraflow removed
Contraflow cycling only	No additional action	265	167 (63)	137 (51.7)	92 (34.7)	0 (0)	346	204	0
	Cycle lane	71	48 (67.6)	29 (40.8)	33 (46.5)	1 (1.4)	83	96	7
	Cycle lane with some segregation	14	12 (85.7)	8 (57.1)	11 (78.6)	0 (0)	26	108	0
	Cycling in contraflow bus lane	9	7 (77.8)	7 (77.8)	6 (66.7)	0 (0)	64	42	0
	Cycle track and cycling on footway	3	2 (66.7)	2 (66.7)	2 (66.7)	0 (0)	13	7	0
One-way street and contraflow cycling	No additional action	59	38 (64.4)	34 (57.6)	17 (28.8)	0 (0)	84	40	0
	Cycle lane	32	16 (50)	8 (25)	12 (37.5)	0 (0)	41	55	0
	Cycle lane with some segregation	5	3 (60)	2 (40)	3 (60)	0 (0)	28	10	0
	Cycling on footway	2	2 (100)	2 (100)	2 (100)	0 (0)	17	3	0
	Cycle track and cycling on footway	1	1 (100)	0 (0)	1 (100)	0 (0)	0	1	0
	Cycle track and lane	1	1 (100)	1 (100)	1 (100)	0 (0)	6	5	0
Contraflow bus lane and contraflow cycling	Cycling in contraflow bus lane	11	9 (81.8)	6 (54.5)	9 (81.8)	0 (0)	80	132	0

Table B4
Pedal cycle direction in crashes involving pedal cycles within 10 m of road segments by crash segment status occurring between 1st January 1998 and 31st December 2019 (inclusive) by crash segment status, pre-TRO road status and proximity to junctions or roundabouts.

Pre- TRO status	Proximity to junction or roundabout		More than 10 m from a junction or roundabout (OSM determined)			Within 10 m of a junction or roundabout (OSM determined)		
	Crash segment status		Pre - contraflow	Contraflow	Contraflow removed	Pre - contraflow	Contraflow	Contraflow removed
One way	Number of crashes		118	109	4	414	348	3
	Pedal cycle 1 direction	With flow	32 (27.1)	34 (31.2)	0 (0.0)	51 (12.3)	66 (19.0)	0 (0.0)
		Contraflow (illegal)	18 (15.3)	–	0 (0.0)	48 (11.6)	–	0 (0.0)
		Contraflow	–	30 (27.5)	–	–	82 (23.6)	–
		Direction not compatible	68 (57.6)	43 (39.4)	4 (100.0)	315 (76.1)	196 (56.3)	3 (100.0)
		Unknown	0 (0.0)	2 (1.8)	0 (0.0)	0 (0.0)	4 (1.1)	0 (0.0)
	Pedal cycle 2 direction	With flow	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	1 (14.3)	0 (0.0)
		Contraflow (illegal)	1 (100.0)	–	0 (0.0)	2 (66.7)	–	0 (0.0)
		Contraflow	–	0 (0.0)	–	–	3 (42.9)	–
		Direction not compatible	0 (0.0)	0 (0.0)	0 (0.0)	1 (33.3)	3 (42.9)	0 (0.0)
		Unknown	0 (0.0)	1 (100.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
Two way	Number of crashes		80	98	0	176	148	0
	Additional TRO action from two-way to…	One-way street	56 (70.0)	39 (39.8)	1 (100.0)	120 (68.2)	75 (50.7)	0 (0.0)
		One-way street with contraflow bus lane	24 (30.0)	59 (60.2)	0 (0.0)	56 (31.8)	73 (49.3)	0 (0.0)
	Pedal cycle 1 direction	With flow	16 (20.0)	36 (36.7)	0 (0.0)	25 (14.2)	34 (23.0)	0 (0.0)
		With flow (opposite)	23 (28.7)	–	0 (0.0)	29 (16.5)	–	0 (0.0)
		Contraflow	–	21 (21.4)	–	–	33 (22.3)	–
		Direction not compatible	41 (51.2)	41 (41.8)	0 (0.0)	122 (69.3)	78 (52.7)	0 (0.0)
		Unknown	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	3 (2.0)	0 (0.0)
	Pedal cycle 2 direction	With flow	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
		With flow (opposite)	0 (0.0)	–	0 (0.0)	0 (0.0)	–	0 (0.0)
		Contraflow	–	2 (100.0)	–	–	1 (50.0)	–
		Direction not compatible	0 (0.0)	0 (0.0)	0 (0.0)	1 (100.0)	1 (50.0)	0 (0.0)
		Unknown (self reported)	0 (0.0)	0 (0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)

No crashes involved more than two pedal cycles. Direction not compatible means that the direction the pedal cycle was travelling from and to is not compatible with the road segment direction. '-' indicates that this type of direction is not possible given the road segment status and crash timescale. Data is presented as 'number (percentage)'.

Table B5

Pedal cyclist crash rates within 10 m of road segments per 100 years of exposure to road segment status. Rates are presented as raw and adjusted for cordon cycling volume (1998 index) as: overall; by proximity for junction or roundabout (within 10 m); by significant change to road segment; and by pedal cycle direction. 95 % confidence intervals generated by bootstrapping 1000 resamples with replacement.

Analysis	Rate type	Crash segment status	Sub-analysis	Number of crashes [1]	Time duration of segment exposure (days)	Crash rate per 100 years of exposure to road segment at that status (95 % confidence interval)
Overall	Raw	Pre-contraflow		788	2,396,119	12.0 (11.4–12.6)
		Contraflow		703	1,392,487	18.4 (17.4–19.4)
		Contraflow removed		7	11,949	21.4 (9.2–39.7)
	Adjusted	Pre-contraflow		591	2,396,119	9.0 (8.5–9.5)
		Contraflow		335	1,392,487	8.8 (8.2–9.3)
		Contraflow removed		4	11,949	10.8 (3.8–19.9)
By junction status	Raw	Pre-contraflow	Junction or roundabout within 10 *m*	590	2,396,119	9.0 (8.4–9.5)
		Contraflow		496	1,392,487	13.0 (12.1–13.9)
		Contraflow removed		3	11,949	9.2 (3.1–21.4)
		Pre-contraflow	No junction or roundabout in 10 *m*	198	2,396,119	3.0 (2.6–3.4)
		Contraflow		207	1,392,487	5.4 (4.8–6.2)
		Contraflow removed		4	11,949	12.2 (3.1–24.4)
	Adjusted	Pre-contraflow	Junction or roundabout within 10 *m*	448	2,396,119	6.8 (6.4–7.3)
		Contraflow		233	1,392,487	6.1 (5.6–6.6)
		Contraflow removed		2	11,949	6.2 (1.2–15)
		Pre-contraflow	No junction or roundabout in 10 *m*	142	2,396,119	2.2 (1.9–2.5)
		Contraflow		102	1,392,487	2.7 (2.3–3.1)
		Contraflow removed		2	11,949	4.6 (1.0–9.7)
By significant change to road segment	Raw	Pre-contraflow	Contraflow cycling only	532	1,900,788	10.2 (9.5–10.9)
		Contraflow		457	997,484	16.7 (15.4–18)
		Contraflow removed		7	10,398	24.6 (10.5–45.6)
		Pre-contraflow	One-way street and contraflow cycling	176	464,771	13.8 (12.0–15.5)
		Contraflow		114	337,250	12.3 (10.3–14.5)
		Pre-contraflow		80	30,560	95.5 (75.2–115.9)
		Contraflow	Contraflow bus lane and contraflow cycling	132	57,753	83.4 (70.8–98.6)
	Adjusted	Pre-contraflow	Contraflow cycling only	385	1,900,788	7.4 (6.8–8.0)
		Contraflow		203	997,484	7.4 (6.8–8.0)
		Contraflow removed		4	10,398	12.4 (4.4–22.9)
		Pre-contraflow	One-way street and contraflow cycling	134	464,771	10.6 (8.9–12.0)
		Contraflow		58	337,250	6.3 (5.2–7.6)
		Pre-contraflow	Contraflow bus lane and contraflow cycling	71	30,560	85.3 (67.2–104.5)
		Contraflow		74	57,753	46.6 (39.5–55.4)
By pedal cycle direction	Raw	Pre-contraflow	With flow [2]	124	2,396,119	1.9 (1.6–2.2)
			With flow (opposite) [3]	52	2,396,119	0.8 (0.6–1.0)
			Contraflow (illegal) [4]	69	2,396,119	1.1 (0.8–1.3)
			Direction not compatible	548	2,396,119	8.3 (7.8–8.9)
		Contraflow	With flow	171	1,392,487	4.5 (3.9–5.2)
			Contraflow	172	1,392,487	4.5 (3.9–5.2)
			Direction not compatible	362	1,392,487	9.5 (8.6–10.4)
			Unknown	10	1,392,487	0.3 (0.1–0.4)
		Contraflow removed	Direction not compatible	7	11,949	21.4 (9.2–39.7)
	Adjusted	Pre-contraflow	With flow [2]	97	2,396,119	1.5 (1.2–1.8)
			With flow (opposite) [3]	47	2,396,119	0.7 (0.5–0.9)
			Contraflow (illegal) [4]	50	2,396,119	0.8 (0.6–1.0)
			Direction not compatible	400	2,396,119	6.1 (5.6–6.5)
		Contraflow	With flow	84	1,392,487	2.2 (1.9–2.6)

(*continued on next page*)

Table B5 (*continued*)

Analysis	Rate type	Crash segment status	Sub-analysis	Number of crashes [1]	Time duration of segment exposure (days)	Crash rate per 100 years of exposure to road segment at that status (95 % confidence interval)
			Contraflow	85	1,392,487	2.2 (1.9–2.6)
			Direction not compatible	167	1,392,487	4.4 (3.9–4.8)
			Unknown	4	1,392,487	0.1 (0.0–0.2)
		Contraflow removed	Direction not compatible	4	11,949	10.8 (3.8–19.9)

[1]Number of crashes rounded to nearest integer.
[2]This includes all one and two-way roads in the pre-contraflow period.
[3]This only includes two-way roads in the pre-contraflow period.
[4]This only includes one-way roads in the pre-contraflow period.

Table B6
Pedal cyclist casualty rates per 100 years of exposure by road segment status and injury severity, 2005–2019. Rates are presented as raw, adjusted for change in injury severity classification; and adjusted for change in injury severity classification and cordon cycling volume (1998 index). 95 % confidence intervals generated by bootstrapping 1000 resamples with replacement.

Analysis	Crash segment status	Injury severity	Number of pedal cyclist casualties [1]	Time duration of segment exposure (days)	Pedal cyclist casualty rate per 100 years of exposure to road segment at that status (95 % confidence interval)
Raw	Pre-contraflow	Fatal	4	1,186,657	0.1 (0.0–0.3)
		Serious	30	1,186,657	0.9 (0.6–1.3)
		Slight	364	1,186,657	11.2 (10.3–12.2)
	Contraflow	Fatal	3	1,392,488	0.1 (0.0–0.2)
		Serious	72	1,392,488	1.9 (1.5–2.3)
		Slight	535	1,392,488	14.0 (13.2–14.8)
	Contraflow removed	Serious	1	11,949	3.1 (3.1–12.2)
		Slight	3	11,949	9.2 (3.1–21.4)
Adjusted for change in injury severity classification	Pre-contraflow	Fatal	4	1,186,657	0.1 (0.0–0.3)
		Serious	30	1,186,657	0.9 (0.6–1.3)
		Slight	332	1,186,657	10.2 (9.4–11.1)
	Contraflow	Fatal	3	1,392,488	0.1 (0.0–0.2)
		Serious	72	1,392,488	1.9 (1.5–2.3)
		Slight	501	1,392,488	13.1 (12.4–13.9)
	Contraflow removed	Serious	1	11,949	3.1 (3.1–12.2)
		Slight	3	11,949	8.4 (2.7–19.4)
Adjusted for change in injury severity classification and annual cycle volume (1998 index)	Pre-contraflow	Fatal	2	1,186,657	0.1 (0.0–0.2)
		Serious	16	1,186,657	0.5 (0.3–0.7)
		Slight	177	1,186,657	5.5 (5.0–6.0)
	Contraflow	Fatal	1	1,392,488	0.0 (0.0–0.1)
		Serious	31	1,392,488	0.8 (0.6–1.0)
		Slight	222	1,392,488	5.8 (5.5–6.2)
	Contraflow removed	Serious	0	11,949	1.0 (1.0–4.2)
		Slight	1	11,949	3.3 (0.8–7.7)

[1] Number of casualties rounded to nearest integer.

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Chapter 4

Paper 3: Build it but will they come? Exploring the impact of introducing contraflow cycling on cycling volumes with crowd-sourced data

4.1 Abstract

Contraflow cycling on one-way streets is a low cost intervention that is safe and can improve the cycling experience. The evidence on its impact on cycling participation is patchy and based on small studies involving a few streets and short duration of follow up. In this paper, we use crowd-sourced data to assess the impact of introducing contraflow cycling on cycling volumes on multiple one-way streets. We qualitatively assess factors that are associated with change in cycling volume on such infrastructure.

Using a primary dataset of roads where contraflow cycling was introduced in inner London between April 2018 and October 2019, we matched these roads with monthly Strava Metro cycling count data before and after the intervention. We identified the count direction as either with or against motor vehicle flow. We generated expected counts adjusted for changes in Strava trips, users, seasonality and time of year by examining global change in monthly Strava counts during the study period. We used national cycle infrastructure design guidance for contraflow infrastructure and Google Street View to qualitatively assess the quality of the contraflow infrastructure.

There were 28 one-way streets and 14 two-way streets (which were converted to one-way streets) that introduced contraflow cycling. Three one-way streets experienced significant increases in mean contraflow trips (260, 630 and 1750 percent) that were much higher than expected. They also had increased numbers of people post-implementation. A number of other streets had higher counts post-intervention. Increases in contraflow cycling were less apparent for the former two-way roads. Illegal contraflow cycling was popular on many

streets pre-introduction. Qualitative assessment of 12 streets demonstrated that local context such as connectivity, protected entrances and segregation of infrastructure and external factors (e.g. construction) were important in determining whether the intervention increased contraflow cycling.

We have found that the introduction of contraflow cycling can increase cycling participation on one-way streets but that local factors are important in determining volumes. Large-scale adoption of this low cost infrastructure could significantly improve cycle routes and networks. Legislative change to make all one-way streets contraflow by default would facilitate such implementation. Further work could utilise other data sources to assess the representativeness of the Strava Metro data and to triangulate these findings.

4.2 Introduction

Contraflow cycling, where cycling occurs bidirectionally along a road that is limited to one-way for motor vehicles, can improve cycling networks and routes by making them more coherent, direct, attractive, comfortable and safe (DfT, 2020). It can improve the cycling experience by enabling cyclists to use quieter rather than busy streets; make journeys more direct thus reducing the distance, energy and time; and simplify journey planning by using the same road each way (PRESTO, 2010). Furthermore, it has been claimed to increase cycling volumes (Ryley and Davies, 1998; Bjørnskau et al., 2012; Burkin, 2019; Pritchard et al., 2019) and result in route substitution onto the new infrastructure (Pritchard et al., 2019).

However, the evidence base examining the impact on cycling volume is limited to a few streets that were existing one-way roads and a small number of locations. Studies have used short time scales (hours or months), predominantly video cyclist counting methods and rarely adjust for other factors that can impact cycling volume such as seasons or weather. For example, Ryley and Davies (1998) investigated introducing contraflow cycling with no or minimal additional infrastructure (intermittent painted dashed lines) on three one-way roads in England. Using video filming they counted cyclists for 24 hours in the months before (winter) and after (summer) introduction. They reported a 54% increase in cycling volume with a bigger increase in cyclists travelling contraflow but did not adjust for seasonality. Bjørnskau et al. (2012) examined two streets with red contraflow cycle lanes in Oslo, Norway and used two other streets as controls. Cycle counting before and after implementation demonstrated around a 50% increase in cycling volume on the contraflow roads with a greater increase in cyclist travelling contraflow than with flow whilst there was a decrease in cycling volume on the control streets. However, no detail was provided on the duration or method of counting nor on whether other aspects such as seasonality were considered. Pritchard et al. (2019) examined the impact of replacing a vehicle parking lane with a wide, red contraflow cycle lane on a one-way street that already allowed contraflow cycling in Oslo. Using 113 cyclists with GPS devices for a month before and after implementation, supplemented with 39 and 86 hours of pre and post (respectively) video observation counts and adjusted for seasonality, they found that there were between 50 and 100 more trips on the new contraflow cycle lane per month. Finally, Burkin (2019) examined a one street in Somerville, Massachusetts, USA, that had contraflow cycling introduced and extensive junction tarmac painting using a total of 10 hours of video footage counts. They found that the number of bikes per hour increased by 75%.

Traditionally, cycling volume has been measured by on-site manual or automatic counts performed by people or equipment such as pneumatic road tubes or via automated or manual video processing (NACTO, 2022). Each method has strengths and limitations but key challenges are accuracy, cost, granularity, coverage and capturing additional information such as rider demographics, journey purpose, bicycle type and bicycle location on/off the highway. These counts can be augmented with large datasets such as census or survey data for additional information or GPS devices and smartphone apps to increase spatial and temporal coverage and granularity (Nelson et al., 2021; NACTO, 2022).

Strava Metro is an example of crowd-sourced cycling volume data. It is large dataset of processed, aggregated, de-identified cyclist data generated by users of Strava, a GPS activity tracking product available via a device or smartphone app, who have given permission for their data to be used by authorised researchers and other parties (Strava, 2023; Strava Metro, 2023a). Strava Metro data has been used to examine cycling patterns, demand and route choice (Lee and Sener, 2021). Researchers have also used Strava Metro data to evaluate the impact of cycling infrastructure on cycling volumes such as the opening of new cycleways (Heesch et al., 2016; Heesch and Langdon, 2016) or cycle bridges (Boss et al., 2018) and the impact of multiple improvements to cycling infrastructure at a city-wide level (Hong, McArthur and Stewart, 2020; Hong, McArthur and Livingston, 2020).

However, concerns exist around using Strava Metro cycling data (Nelson et al., 2021; Lee and Sener, 2021). Firstly, users are not necessarily representative of the wider cycling population in terms of geographical coverage, demographic coverage, origins and destinations, route choice and distance travelled (Leao et al., 2019). Researchers have found that Strava users tend to be male, younger and more likely to use bicycles for leisure (Lee and Sener, 2021). Secondly, Strava Metro is a sampled dataset as users have to opt in to data sharing so it does not actually represent all Strava users or journeys. Thirdly, there is an anonymisation and aggregation policy that means counts are only present if three or more trips or people transverse that road segment. Counts are rounded down to zero if less than three trips or people use them whilst all other counts are rounded up to the nearest five. This causes challenges when using smaller time scales (e.g. hourly counts) or smaller demographic subgroups thus limiting its usefulness. Finally, the datasets are processed before being made available meaning that any errors or omissions may be difficult to unearth and algorithms used for processing are opaque. Methods to address some of these challenges include: using multiple data sources; comparing Strava counts to manual counts or survey data; utilising qualitative data; adjusting for temporality and change in

Strava users; using modelling techniques; careful consideration of level of data aggregation that is appropriate to the research question; and acknowledging the issues it causes when interpreting findings (Griffin et al., 2020; Nelson et al., 2021; Lee and Sener, 2021).

The aim of this study is to examine cycling volume when contraflow cycling is introduced across multiple locations in London, UK. A recently constructed dataset of inner London roads that introduced contraflow cycling (Tait, 2022; Tait et al., 2023) will provide the intervention sites whilst Strava Metro data, adjusted for seasonality and change in Strava users, before and after implementation will be used to consider the impact of the infrastructure on trip and unique people counts. After identifying locations that appear to have had an impact on such counts and those that have not, we will qualitatively assess the infrastructure to identify factors that may explain the differences. There are two types of interventions we will examine: existing one-way streets where contraflow cycling is introduced; and two-way streets that are converted to one-way streets with contraflow cycling. In the former, prior to intervention any contraflow cycling would be considered 'illegal' whilst in the latter contraflow cycling is legal before and after implementation. To our knowledge, there are no published studies on the latter type of intervention. Our overall approach will address key challenges with the current evidence base by using; large volumes of spatio-temporal cycling count data; many roads over a large geographical area; and multiple years' worth of data.

4.3 Methods

4.3.1 Data

4.3.1.1 Strava data

Strava Metro maps Strava activity data onto OpenStreetMap roads and trails before deconstructing these roads at decision points (e.g. junctions) to create edges (Strava Metro, 2023c). Strava user activity data is matched or aligned to these edges to generate aggregate counts that are available to authorised users of Strava Metro at an edge or area spatial level for hourly, daily, monthly or yearly time periods [Strava Metro (2022)][1]. The aggregate count data consists of trip counts (the number of bicycle trips on that edge) and people counts (the number of unique people who have cycled on that edge) (Strava Metro, 2023b). These are available in a forward or reverse direction that represents the direction of road digitisation in OpenStreetMap (see appendix B.1 for data definitions).

The years 2018 and 2019 were chosen for this study as these were unaffected by the COVID-19 pandemic and were the earliest years with Strava Metro count data available. As an anonymisation process is applied to Strava counts to maintain privacy, we chose to

[1]The use of graph theory in transportation where roads are constructed of edges (links) and nodes (interchanges) is well established (e.g. Derrible and Kennedy (2011)). Historically, Strava Metro has made node data available (Lee and Sener, 2021) but this was not available when the research was conducted.

use monthly count data as this maximises granularity whilst minimising data loss (Raturi et al., 2021).

Using the Strava Metro Dashboard GUI that allows the user to select edges or areas of up to 25 square miles, we performed multiple downloads of areas and their associated counts for inner London as shape and csv files (respectively) (Strava Metro, 2022). We combined the data and removed duplicates to generate a dataset representing inner London. Where the download areas spatially overlapped, some edges (2.6% of total) had non-identical duplicate month counts (for example a trip count was 30 in version one of January 2018 and 35 in version two of January 2018). Having established that the variation between versions was very small and as it was unknown which version was the true count for these edges, we randomly selected a non-identical duplicate month count as the true count.

4.3.1.2 Roads with contraflow cycling

We used the primary dataset to identify roads in inner London that had contraflow cycling introduced in 2018 or 2019 (Tait, 2022; Tait et al., 2023). We excluded those whose contraflow start date was within the first 3 months of 2018 or the last 3 months of 2019 to ensure we had a minimum of three monthly counts both before and after contraflow implementation. Key variables in this dataset are: road name, description of contraflow spatial extent (for example, between junctions X and Y), contraflow start date and spatial data. Roads were either existing one-way streets that had contraflow cycling introduced or were two-way streets converted to one-way streets with contraflow cycling. One road, Saltram Crescent, had two sections of contraflow cycling introduced separated by a two-way road and these sections had opposing motor vehicle flow therefore they were considered as two road segments.

4.3.2 Data analysis

Using the Strava Metro Dashboard map we identified all Strava edges that corresponded to the roads with contraflow cycling. Most roads were represented by multiple sequential Strava edges. Some roads were represented by one or more parallel Strava edges. For example, a road with a main carriageway and a segregated cycle lane could correspond to two parallel Strava edges.

We examined the monthly counts for all road edges and dropped any road that had less than 23 months of count data to ensure maximum count data available before and after contraflow implementation. Where a road was made up of multiple sequential Strava edges we calculated the mean Strava count along the whole road as the monthly count. Where a road included parallel Strava edges, we summed the counts for the parallel Strava edges before then calculating the mean Strava count for the full road length.

We identified the direction of each Strava edge by examining the start and end nodes for each edge in the OpenStreetMap basemap that underpins this download of Strava data (basemap version = 220124) (OpenStreetMap contributors, 2023). We identified the motor vehicle one-way direction of the road from OpenStreetMap. Using the Strava edge and motor vehicle directionalities we were able to classify whether the Strava counts were with or against one-way motor vehicle flow. There was one road (Upper Marsh) where motor vehicle direction was reversed when contraflow cycling was introduced but to prevent misinterpretation due to this change we have not altered road direction so that before and after counts are comparable.

4.3.2.1 Generating expected Strava counts that adjust for changes in Strava trips, users, seasonality and time

Cycling volume can change due to external factors such as daylight, season and weather (Miranda-Moreno and Nosal, 2011; Tin Tin et al., 2012; Bean et al., 2021). Participation in Strava Metro can also change (e.g Strava Press (2021)). Therefore, we wanted to adjust our observed monthly Strava count data to take into account these changes. To achieve this we created a dataset of Strava edges that are broadly comparable to our contraflow roads of interest using the following method. We extracted all inner London 'highways' from OpenStreetMap (basemap version = 220124) and removed highways that were not appropriate for road cycling such as footways, bridleways or steps and those with incompatible surfaces (e.g. gravel, dirt or grass); see Appendix B.2 for full details. We identified parks in OpenStreetMap and removed highways that went through this green space. We matched these highways to our existing Strava edges for Inner London and removed any edges that did not match our selected highways.

Using this dataset of broadly comparable edges, we identified the monthly counts for each edge and then summed these counts to obtain total counts per month for total trip, trip purpose (commuting/leisure) and people counts. Using January 2018 as the baseline, we calculated the percentage change from this for each month and each count type.

We calculated the expected monthly count for each road segment by multiplying the observed January 2018 counts by the percentage change for that type of count and month then dividing it by 100. As Strava observed counts are anonymised by rounding down any counts that are less than three to zero and rounding up all other counts to the nearest multiple of five, we applied this logic to our expected counts to create rounded expected monthly counts.

4.3.2.2 Remote qualitative assessment of contraflow cycling infrastructure

National cycle infrastructure design guidance provides advice on implementing contraflow cycling infrastructure (DfT, 2020). It suggests that contraflow cycling can be allowed without any segregation or painted cycle lanes if the traffic volume and road speed are low (max 20mph) but advises that a mandatory cycle lane should be considered. Additional protection such as traffic islands at the contraflow exit is desirable and increased conspicuity through road markings and coloured surfaces that can improve awareness for other road users are advised. However, there is no prescriptive standard for introducing contraflow cycling infrastructure. Therefore, to qualitatively assess the roads that have introduced contraflow cycling we used the overriding design principles of coherence, directness, safety, comfort and attractiveness plus accessibility of such infrastructure for all. We used OpenStreetMap to identify the roads, their locality and surrounding area to examine how the roads connect to other cycling infrastructure and places people may wish to cycle from or to. We utilised Google Street View (Google, 2023) to assess the contraflow cycling infrastructure including its quality, road surface, lighting and general experience of cycling.

4.4 Results

4.4.1 Roads with contraflow cycling introduced in 2018-2019

We identified 28 one-way (total length 3.4km) and 14 two-way (total length 1.5km) roads that introduced contraflow cycling between April 2018 and October 2019 that had 23 months or more Strava count data (Figure 4.1 and see appendix B.3: Table B.1; Table B.2). The one-way roads consisted of fewer Strava edges (50% had 1 or 2 edges compared to 29% of two-way roads) with 89% of one-way roads having no parallel Strava edges compared to 57% of two-way roads. These findings indicate that the one-way roads that had fewer junctions and fewer parallel cycling options compared to those roads that had been two-way. However, the one-way roads were longer (mean length 121m and median 104m versus mean 110m and median 94m).

FIGURE 4.1: Maps showing the a) One-way roads and b) Two-way roads that implement contraflow cycling between April 2018 and October in inner London

4.4.2 Change in Strava cycle counts during the study period

Using our dataset of highways that are broadly comparable to the road segments that introduced contraflow cycling, we can see that there is variation in Strava trip and people counts across the two-year study period (Figure 4.2). Numbers increase during the summer months and fall during winter corroborating previous Strava Metro research (e.g. Hong, McArthur and Stewart, 2020; Venter et al., 2023). This seasonal change is more marked for certain counts: the volume of people increases more than the volume of trips, females increase more than males and leisure trips more than commuting. The greatest percentage changes are associated with change in temperature, although this may also reflect length of daylight, but appear to be less associated with wet months (weather data sources: Met Office (2020a); Met Office (2020b)).

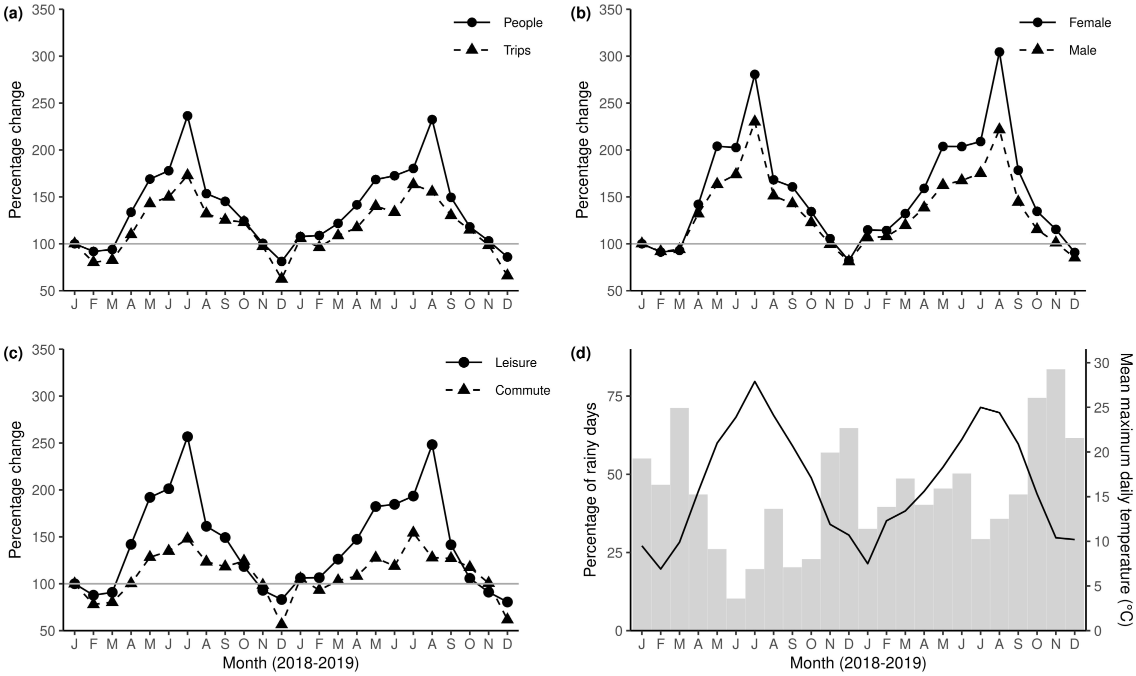

FIGURE 4.2: Percentage change in inner London monthly Strava count baselined to January 2018 for a) total trip and unique people counts, b) unique female and male counts and c) total leisure and commute trip counts. d) Climatograph showing percentage of rainy days per month (bars) and mean maximum daily temperature (line chart) (St James's Park weather station, Westminster, London, Met Office, 2020a; Met Office, 2020b)

4.4.3 Existing one-way streets with contraflow cycling introduced

4.4.3.1 Total trip counts

This section describes the findings for the 28 one-way streets that had contraflow cycling introduced. Figure 4.3 shows the monthly variation in total observed and expected (based on the background changes in cycling activity on Strava for inner London) number of Strava trips on these roads before and after contraflow introduction. The observed counts are the actual Strava Metro counts whilst the expected counts are the Strava Metro counts we would expect on that road if the usage reflected the wider change in Strava counts across Inner London roads (both sets of counts have been rounded as per Strava Metro privacy policy).

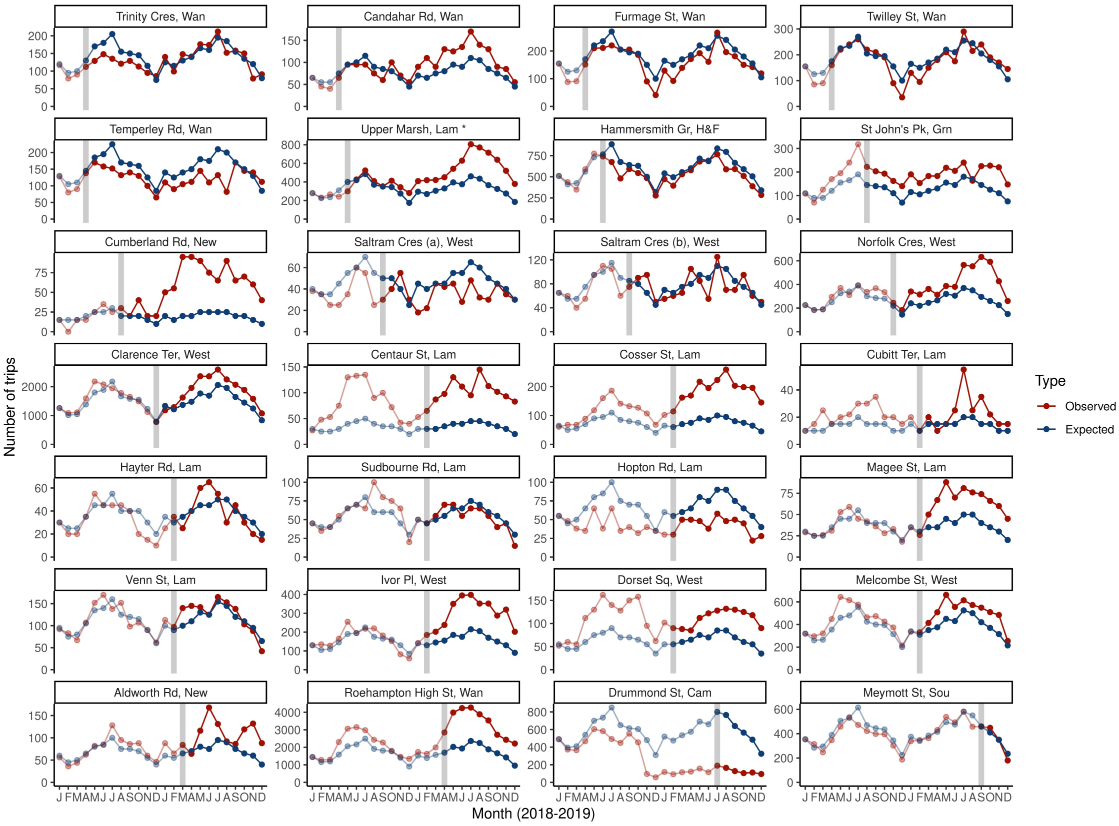

FIGURE 4.3: Monthly variation in total observed and expected total Strava trip counts on each existing one-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

Figure 4.3 shows that there is considerable variation in the volume of Strava trips between different roads. For example, Clarence Terrace and Roehampton High Street have thousands of trips per month whereas Cubitt Terrace and Hayter Road have less than 100 trips per month. As expected, roads with high volumes have smoother lines compared to those with smaller volumes. We can see that cycling volume on Drummond Street reduced to low levels long before contraflow cycling was introduced, which suggests some sort of local effect on or near that road. There are roads where observed counts increased after contraflow introduction (Candahar Road, Upper Marsh, Cumberland Road, Norfolk Crescent, Clarence Terrace, Cosser Street, Magee Street, Ivor Place, Melcombe Street, Aldworth Road, Roehampton High Street) and that they increased more than would be expected should the change reflect the wider change in Strava usage.

On Dorset Square the observed cycling seems to drop after contraflow introduction. For roads where the contraflow implementation was near the start or end of the study period - i.e. was in early spring or autumn, there are few before or after (respectively) counts which makes it hard to see the impact. This is apparent for Trinity Crescent, Candahar Road, Furmage Street, Twilley Street, Temperley Road and Meymott Street. Of the remaining ten roads, three seem to have a small increase in observed counts after contraflow implementation (Centaur Street, Hayter Road and Venn Street) but only one of them has an observed count higher than expected (Centaur Street). The other seven do not appear to have experienced a change. These findings suggest that there are multiple factors influencing change in cycling volume on these roads, some of which are local, and that the introduction of contraflow cycling may be one such factor.

4.4.3.2 Contraflow trip counts

We can examine the change in trip counts by cyclist direction. The monthly variation in total observed and expected Strava trips travelling contraflow (in the opposite direction of motor traffic) is shown as counts (Figure 4.4) and as proportion of total trips (Figure 4.5). These figures represent contraflow cycling in absolute and relative terms. Focussing on the 12 roads that have observed contraflow counts greater than 100 per month, we can see three roads that display low levels of illegal contraflow cycling and high levels of contraflow cycling when it is allowed. Clarence Terrace, Melcombe Street and Roehampton High Street demonstrate 260, 630 and 1750 percent increases in mean observed contraflow counts before and after implementation and these counts are higher than expected. These roads also show an increase in the proportion of contraflow cycling trips that is much higher than expected after contraflow cycling is legalised, increasing from around 3% to a maximum of 39% in the case of Roehampton High Street. A further five roads have medium levels of illegal contraflow cycling and high levels of legal contraflow cycling (Upper Marsh, St John's Park, Norfolk Crescent, Cosser Street and Ivor Place) and the observed counts are higher than expected. However, the proportion of contraflow cycling trips remains fairly static for these streets. Only three roads experienced a fall in mean contraflow counts after contraflow implementation: Hammersmith Grove, Saltram Crescent (a) and Meymott Street; with the former two both having observed counts lower than those expected). These findings provide evidence that contraflow cycling trips can increase when it is legalised but again suggest that local factors may be affecting cycling levels. The high levels of illegal contraflow cycling on some roads (best viewed in Figure 4.5) demonstrates unmet need and desire to use the roads in that direction prior to implementation.

Strava Metro provides trip counts by journey purpose where commuting trips are defined either by the Strava user or identified by a Strava Metro model whilst all other trips are labelled as leisure. Examination of contraflow cycling trips by purpose provides greater insight into the roads (Appendix B.4, Figure B.1). This shows that people use the contraflow roads for different journey purposes. Around three quarters of contraflow trips on Roehampton High Street are leisure trips whereas commuting and leisure trips are equally split for Clarence Terrace. For most other roads, the trips are predominantly

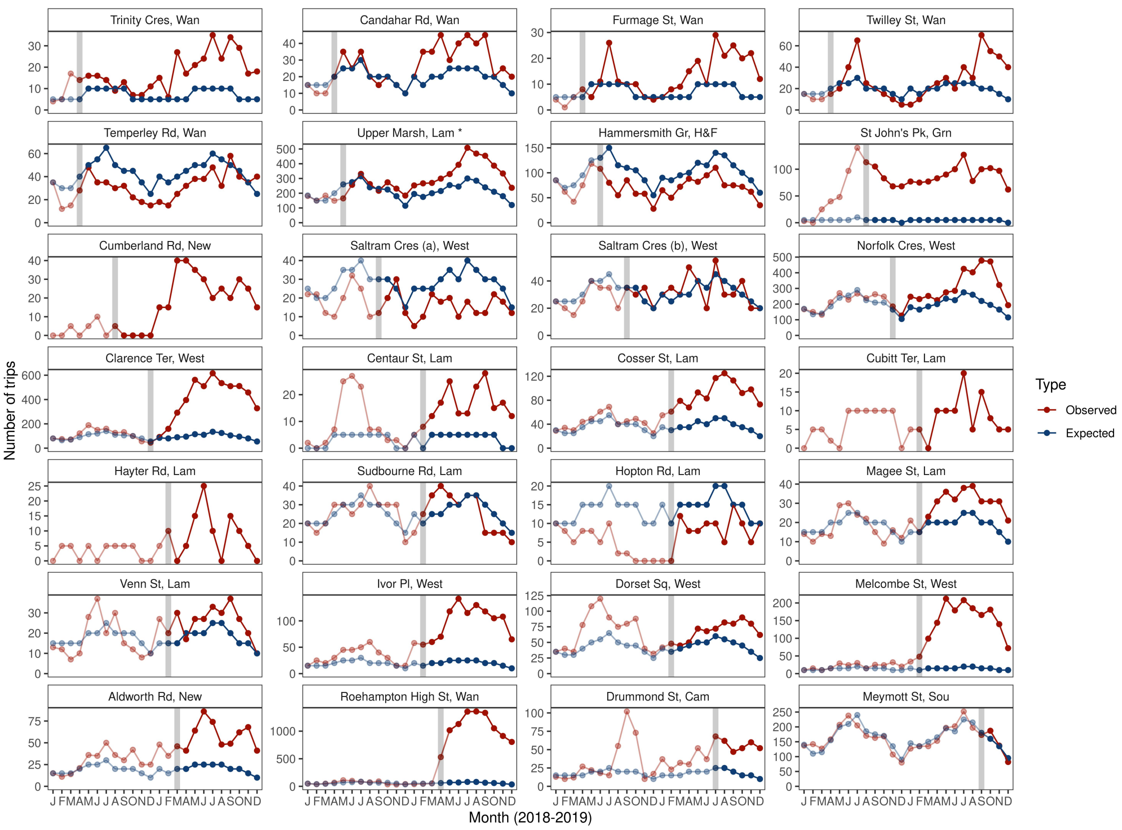

FIGURE 4.4: Monthly variation in observed and expected contraflow Strava trip counts on each existing one-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

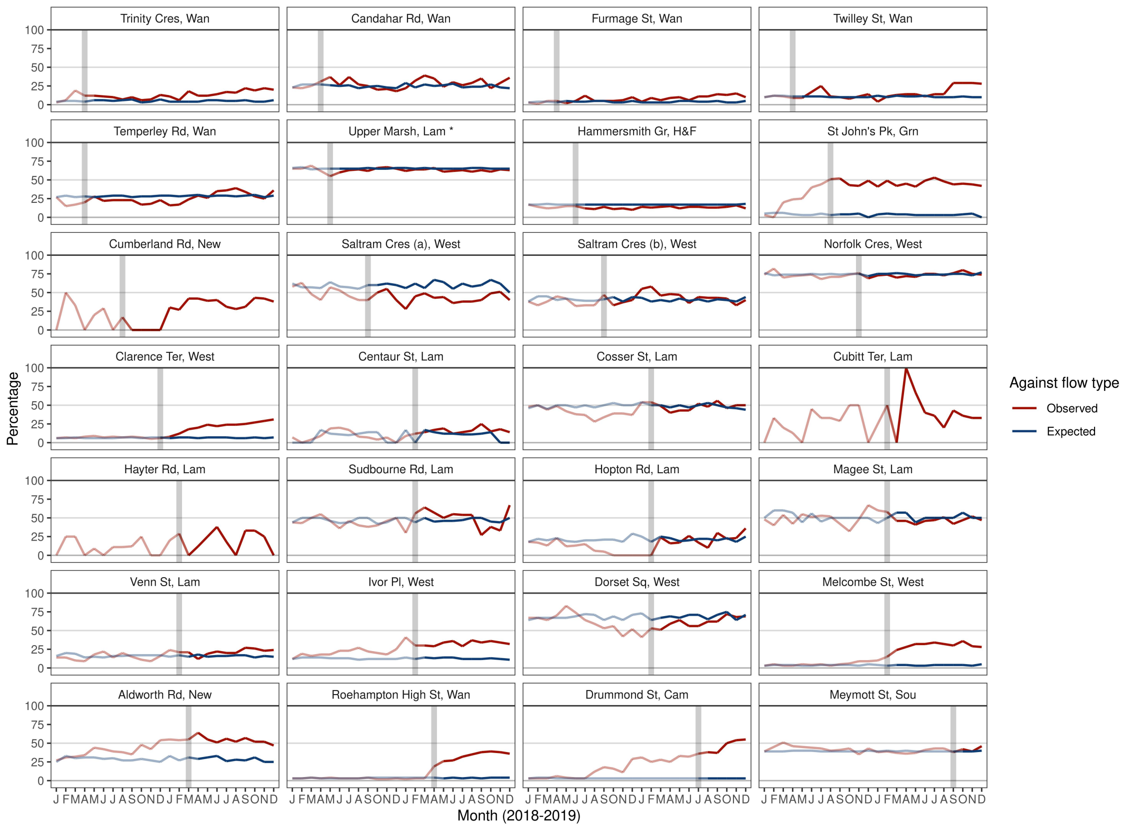

Figure 4.5: Monthly variation in observed and expected contraflow Strava trip counts as a percentage of all trips on each existing one-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

commutes. Contraflow introduction appears to be associated with different effects on commuting and leisure trips depending on the road and related factors. Seven of the eight roads with commute or leisure monthly counts of over one hundred, show increases in mean count for both leisure and commute trips after contraflow introduction. Roehampton High Street shows the largest mean change after contraflow introduction with leisure rides increasing by 1675% and commutes by 2029%. Other streets also show a larger increase in commute trips compared to leisure trips (Melcombe Street, Ivor Place and Clarence Terrace) whilst Upper Marsh, Norfolk Crescent and Cosser Street show larger increases in leisure than commute trips. Meymott Street experienced a drop in commuting trips and Hammersmith Grove had a drop in leisure trips whilst Saltram Crescent (a) had a drop in both types after contraflow introduction (28% drop in leisure and 22% drop in commuting). This shows that the connectivity of these roads to places of work and places people want to cycle from and to are important.

4.4.3.3 Contraflow unique people counts

Another aspect that may offer insight into changes in contraflow cycling is examining the unique number of people cycling contraflow on each road (see Figure 4.6). As there are fewer unique people than trips, many of the roads have low counts, although when compared with the contraflow trip counts (Figure 4.4) the patterns are relatively similar. There are six roads where the monthly count of unique people cycling contraflow exceeds 100. Three of these roads show large increases in the mean number of people cycling contraflow after implementation from low levels of illegal contraflow cycling: Clarence Terrace, Melcombe Street and Roehampton High Street (310 to 1153% increase) and the observed counts are much higher than expected. Others experienced an increase but had high illegal contraflow levels prior to implementation (Upper Marsh 198% and Norfolk Crescent 146%) and the observed counts are not that much more than expected. Meymott Street again experienced a decrease post-implementation. These findings add credence to local factors affecting contraflow usage and that there is desire to cycle contraflow prior to implementation on many roads.

4.4.3.4 Examining the factors that may contribute to successful contraflow implementation

To explore factors that may contribute to the success of new contraflow implementation, defined in this study as increased contraflow cycling trips and/or people after legalising contraflow cycling, we examined Drummond Street whose cycling counts dropped drastically months prior to contraflow implementation, the three most “successful” streets (Clarence Terrace, Melcombe Street and Roehampton High Street) and the three that were least successful (Hammersmith Grove, Saltram Cresecent (a) and Meymott Street). We utilised OpenStreetMap (OpenStreetMap contributors, 2023) and Google Street View (Google, 2023) to assess the infrastructure against the principles

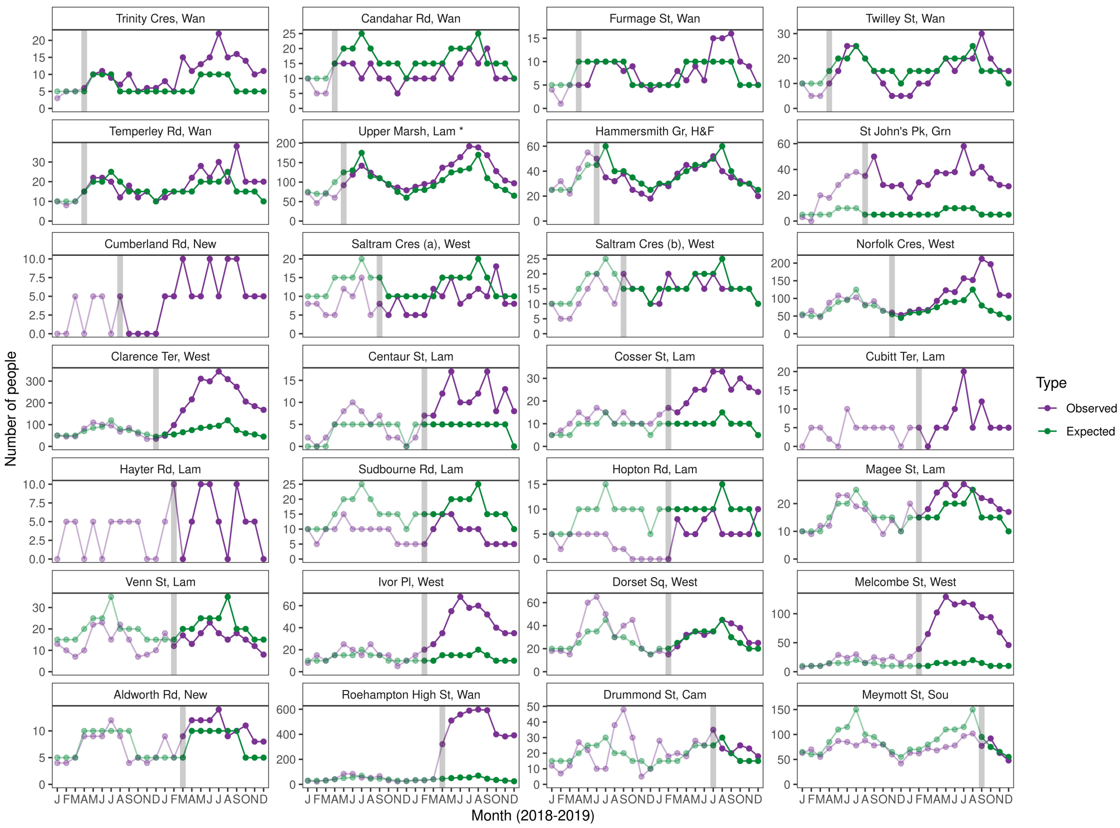

FIGURE 4.6: Monthly variation in total observed and expected number of unique Strava users cycling contraflow on each existing one-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line).

of coherence, directness, safety, comfort, attractiveness and accessibility for all and the specific design guidance for contraflow infrastructure (DfT, 2020). Data to support the qualitative assessment, such as before and after street images, can be found at: https://publichealthdatageek.github.io/qualitative_assessment_intro.html

4.4.3.4.1 "Successful" contraflow introduction

Our analysis identified three roads where there were considerable increases in contraflow cycling trips and people after the introduction of contraflow cycling: Clarence Terrace, Melcombe Street and Roehampton High Street. These roads had low levels of illegal contraflow cycling prior to implementation.

1. Clarence Terrace

Clarence Terrace is a short, straight 20mph street (67m) that forms part of the London Cycling Network and is close to Cycleway 27 (part of London's strategic cycling network). Cycling contraflow takes cyclists away from central London towards the suburbs, green space such as Regent's Park and attractions such as London Zoo. Contraflow cyclists are protected on entry by a traffic island and then use a mandatory cycle lane that is distanced from motor vehicles using cross-hatched paint. It is well lit, has a good surface, clear views, only one side junction and motor vehicles cannot park on the contraflow side. Traffic congestion could reduce its appeal. Overall this appears to be good infrastructure that meets national guidance.

2. Melcombe Street

Melcombe Street is in close proximity to Clarence Terrace and is similarly straight, short in length with good quality surface, clear views and a 20mph speed limit. It has similar connectivity with a protected entrance and subsequent mandatory cycle lane that is distanced from motor vehicles with no same-side parking and road reallocation to raise the quality of the infrastructure. Again this appears to be good infrastructure that meets national guidance.

3. Roehampton High Street

Cycling contraflow on Roehampton High Street connects inner London areas with affluent suburbs. It facilitates cycling in large green spaces such as Richmond Park. The road is 330m in length, has a 20mph speed limit with multiple small side junctions and has many shops and amenities. It is well lit with a variegated surface (asphalt and pave) and has sections of parking on the contraflow nearside. The entrance is protected with a traffic island and set back side junction, and highlighted with green asphalt whilst the exit has a mandatory cycle lane. The rest of the length is not protected but has multiple cyclists signs and paint. In places it is narrow and there would be difficulty in a contraflow cyclist passing a vehicle travelling in the opposite direction. Overall this appears to be satisfactory infrastructure that meets guidance. However, it is likely to be less accessible for some cyclists and has a higher risk of conflict with motor vehicles.

4.4.3.4.2 "Unsuccessful" contraflow introduction

Three streets experienced a fall in mean contraflow counts after contraflow implementation: Hammersmith Grove, Saltram Crescent (a) and Meymott Street; with the former two having observed counts lower than expected.

1. Hammersmith Grove

The Hammersmith Grove contraflow is around 100m in length and whilst the road surface is good, it is near amenities, well lit and has a 20mph speed limit, there are numerous issues that are apparent when looking at the Google Street View images. There is no protected entrance with no indication that cyclists can cycle contraflow until a painted signage on the tarmac some metres from the junction. Multiple large planters, which support road reallocation for pedestrians and cycle parking, interfere with the contraflow cyclists' road visuals and there are numerous parking spaces on both sides of the road, all of which encourage motor vehicles to drive down the centre of the road. Unfortunately, these factors make the road very unappealing and inaccessible for many. It appears that this infrastructure does not meet design standards.

2. Saltram Crescent (a)

Saltram Crescent appears to be a residential road in contrast to all the other ones we have examined so far, and appears to connect two cycle routes and facilitate travel towards central London. It is a 20mph curved road with parking on both sides. There is a short section of mandatory cycle lane at the entrance but during the study period there was no protection and the junction was extremely wide. It may be that this entrance has discouraged contraflow cycling. The entrance has now been upgraded with protection and it would be interesting to examine the current contraflow counts.

3. Meymott Street

Meymott Street is a short section of straight road that connects cyclists to multiple cycle routes. Contraflow cycling was legally allowed towards the end of the study period but examining Google Street View images there are no indications that any infrastructure changes have occurred on the ground that facilitate or indicate it is allowed which could clearly explain why the counts are low.

4.4.4 Two-way streets converted to one-way with contraflow cycling

4.4.4.1 Total trip counts

We will now examine the 14 two-way streets that were converted to one-way with the addition of contraflow cycling. Figure 4.7 shows the monthly variation in total observed and expected number of Strava trips before and after implementation. It shows that these streets tend to have higher volumes of cyclists than the road segments that were existing one-way streets (compare with Figure 4.3) although this may be an artefact of the study period. As these roads were two-way initially, we would expect the cycling volumes to be similar before and after contraflow implementation. This holds true for some e.g. Thurland Road, Nuttall Street and Lower Addison Gardens whose observed counts are very similar to the count expected should the usage reflect the wider change in Strava counts across Inner London roads. It also holds true for others even though their observed counts are lower e.g. Glasshouse Street and Laystall Street or higher e.g. Giffin Street than the expected counts. However, for Tanner Street, Old Jamaica Road and Ivor Place there appears to be an increase in trip counts after the implementation whilst Harrowby Street and Burwood Place experience reductions in cycling trips prior to any implementation. Again these findings suggest that local factors may be influencing cycling volumes on these different roads.

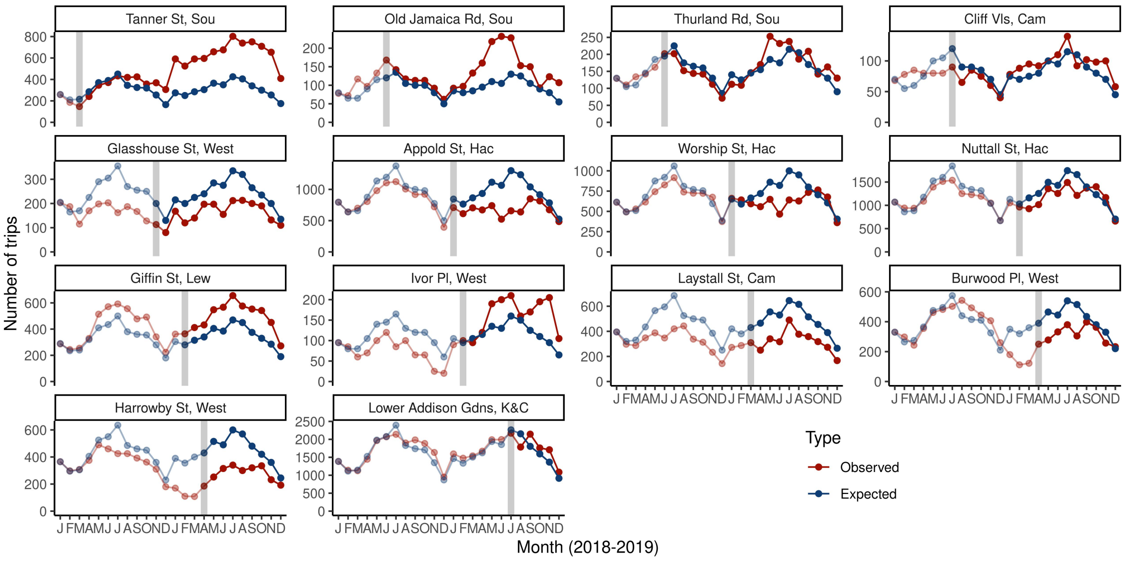

FIGURE 4.7: Monthly variation in total observed and expected total Strava trip counts on each existing twp-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

4.4.4.2 Contraflow trip counts

Examining the cyclist direction shows that Tanner Street, Worship Street and Ivor Place experience more than a ten percent increase (110%, 50% and 11%) in mean observed contraflow counts following implementation (Figure 4.8). Old Jamaica Road also appears to have had an increase, but the mean count only increases by 1%. The observed contraflow trip counts for Tanner Street, Ivor Place and Old Jamaica Road are higher than expected. Two streets show more than a ten percent fall in mean observed contraflow counts and both have lower than expected counts. Harrowby Street shows the greatest fall (25%) with Appold Street demonstrating the second greatest fall (15%). Examining the relative levels of contraflow cycling compared to with flow cycling (Figure 4.9), we can see for many roads the level is stable, which is in contrast to what we saw with existing one-way streets where there is more point to point variation (Figure 4.5). However, the proportion of contraflow cycling has dropped post implementation on five roads (30% fall on Old Jamaica Road and Ivor Place and around 20% on Harrowby Street, Giffin Street and Thurland Road) whereas only one road experienced an increase in contraflow proportion of 20% (Worship Street). This may suggest that converting two-way to one-way with contraflow cycling attracts cyclists to travel with flow. Overall this inconsistency in the way counts change after implementation suggest that local factors are important in influencing cycling.

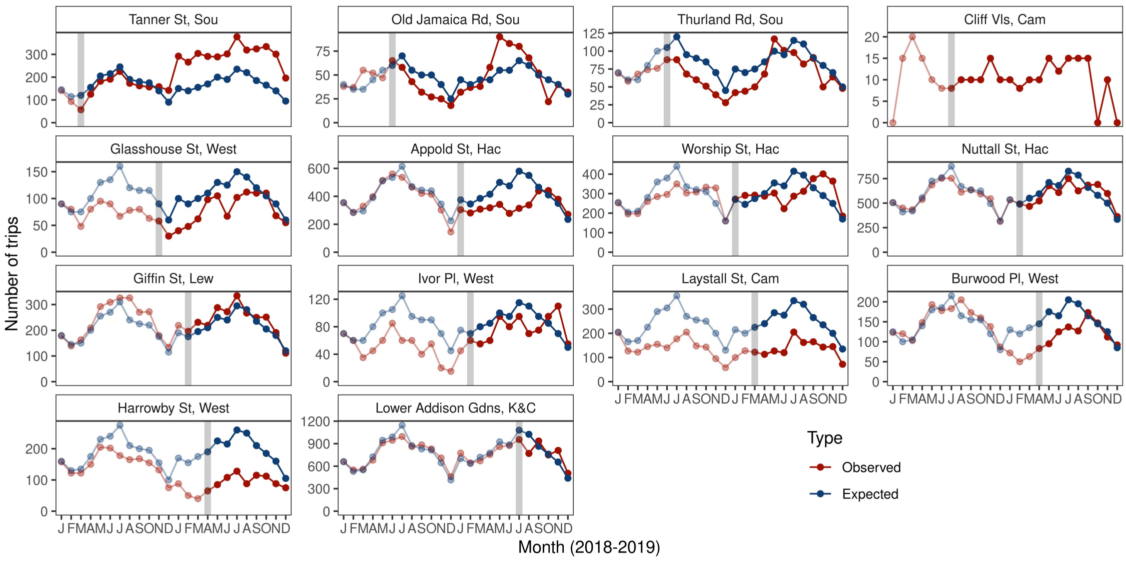

FIGURE 4.8: Monthly variation in observed and expected contraflow Strava trip counts on each former two-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

Examination of contraflow cycling trips by purpose shows that these roads are overwhelmingly used for commuting trips (Appendix B.4, Figure B.2). Where we have seen increases in contraflow cycle trips after implementation, we can see that increases in commuting trips are driving this pattern (Tanner Street, Old Jamaica Road and Ivor Place)

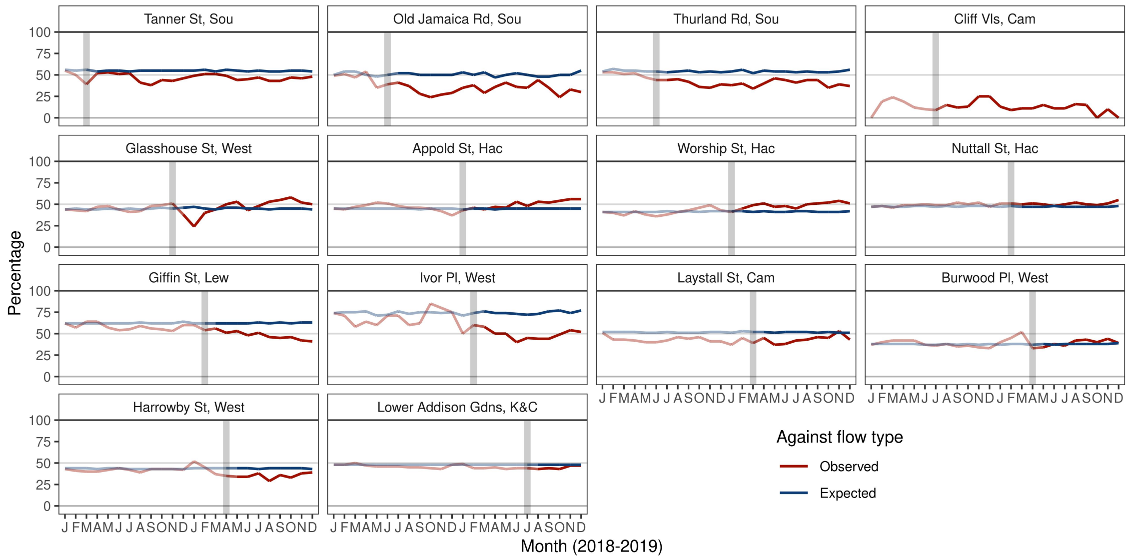

FIGURE 4.9: Monthly variation in observed and expected contraflow Strava trip counts as a percentage of all trips on each former two-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

4.4.4.3 Contraflow unique people counts

The patterns seen for contraflow people counts (Figure 4.10) tend to mirror those seen for contraflow trip counts. We can see that for Tanner Street, Old Jamaica Road and Ivor Place there are increases in the mean number of people cycling contraflow after implementation (91%, 33% and 30%). Harrowby Street and Burwood Place who had 25% and 5% reductions in contraflow trip counts have contrasting changes in people counts: Harrowby Street has a drop in people counts of 10% whilst Burwood Place has an increase of 12% post-implementation.

4.4.4.4 Examining the factors that may contribute to successful contraflow implementation

As before, we selected two-way streets where implementing a one-way street with contraflow cycling has been successful and unsuccessful to examine factors that may be contributing to these outcomes. Data to support the qualitative assessment, such as maps and before and after street images, can be found at: https://publichealthdatageek.github.io/qualitative_assessment_intro.html

4.4.4.4.1 "Successful" contraflow introduction

Our analysis identified three roads where contraflow cycling trips and people increased after implementation: Tanner Street, Old Jamaica Road and Ivor Place.

1. Tanner Street

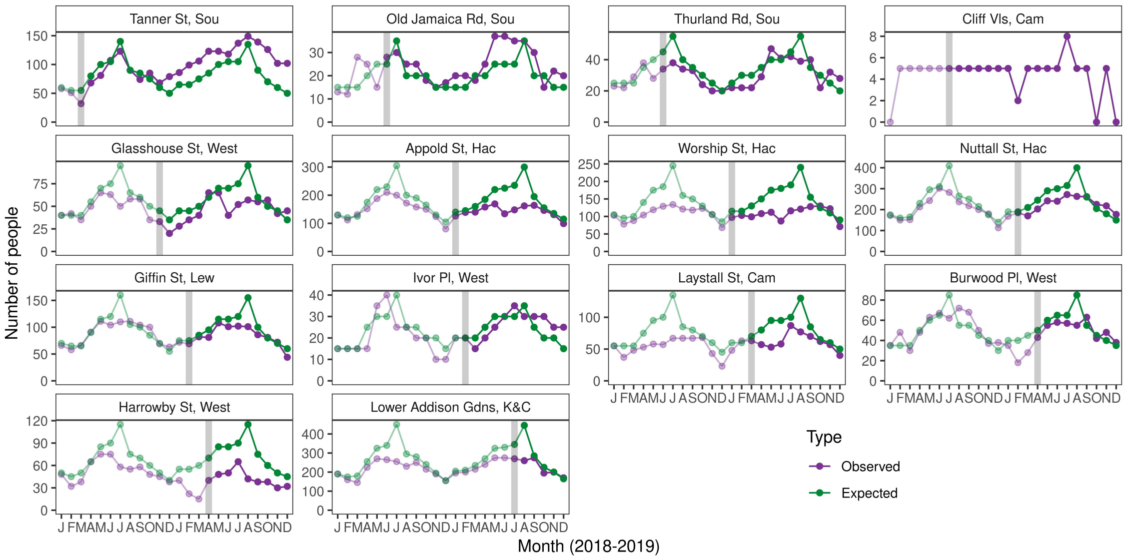

FIGURE 4.10: Monthly variation in total observed and expected number of unique Strava users cycling contraflow on each former two-way road segment before (pale colours) and after (darker colours) contraflow introduction (month of transition shown as vertical grey line).

Tanner Street is a long section (280m) of 20mph road that is part of Cycleway 14 (part of the strategic cycling network) and provides connections to other cycle routes. The contraflow entrance is very well protected with a wide entrance and bidirectional cycleway. There are some painted cycle lanes and traffic islands and the surface is good quality and well lit. There is on-road parking but not on the contraflow side. There are sections where the road narrows that may reduce its appeal but overall this has many positive aspects that makes it good infrastructure that appears to be compliant with design guidance. There appeared to be a delay between the contraflow start date and cycling volume increasing. This appears to be because the construction of the infrastructure took a long time and although people were legally allowed to cycle contraflow it was not desirable until building work on Tanner Street and Cycleway 14 was complete in Autumn 2018 (Mayor of London, 2018).

2. Old Jamaica Road

This 137m long 20mph residential road has no protection for contraflow cyclists at the entrance but does have short advisory cycle lane sections. It leads to a school as well as linking other cycle ways and the strategic cycling network. The surface is good and there is street lighting. There is parking allowed on both sides of the road but the road is wide. Assuming motor vehicle speed and flow is low, this could be satisfactory infrastructure compliant with design guidance but it could be improved with protection at the entrance.

3. Ivor Place

This is a very short (34m) residential contraflow that has no protection for contraflow cyclists. There is a short mandatory cycle lane at the exit and parking is allowed on the non-contraflow side. It is located close to other cycleways and amenities with a good surface and lighting. It appears to be satisfactory infrastructure compliant with design guidance but it could be improved with protection at the entrance.

4.4.4.4.2 "Unsuccessful" contraflow introduction

Two roads were identified as experiencing falls in contraflow cycling after contraflow implementation.

1. Harrowby Street

This short (74m), 20mph contraflow section is on good tarmac and well lit. The entrance is protected by a traffic island and there is an advisory contraflow cycle lane along its length. The road is wide with parking on the non-contraflow side. This appears to be good infrastructure that is compliant with design guidance.

3. Burwood Place

This is a very short (36m) contraflow segment with protection at the entrance with a traffic island and an advisory cycle lane. The road is narrowed at the exit which could bring the cyclist into conflict with oncoming vehicles but overall it appears to be satisfactory and compliant with design guidance.

These roads appear to be compliant with design guidance, are adjacent to each other and form part of Cycleway 27. Therefore, it seems surprising that they have been unsuccessful so far. One explanation is that Cycleway 27 is not complete. Currently, these roads form the eastern end of the west section. There is a significant distance (approximately 2km) between these roads and the next section of the eastern Cycleway 27, which is not finished yet.

4.5 Discussion

4.5.1 Key findings

Our findings suggest that implementing contraflow cycling can increase contraflow cycling volume and attract more people to cycle on such infrastructure. The 28 existing one-way streets where contraflow cycling was introduced tended to be longer, have fewer junctions and opportunities for parallel cycling such as on the highway and a cycle track than the 14 two-way streets that were converted to one-way with contraflow cycling. In our study, for the existing one-way streets that had more than 100 Strava cycling trips per month, eight out of twelve demonstrated increases in contraflow cycling trips and seven experienced increases in the number of unique people cycling contraflow, all of which exceeded counts expected after contraflow implementation. Three also experienced increases in the relative volume of contraflow cycling and individuals compared with with-flow cycling. Illegal contraflow cycling varied. Some streets had high levels that suggest previous unmet demand. Others had low levels of illegal contraflow then high levels of legal contraflow cycling suggesting that introducing the infrastructure itself did increase contraflow cycling.

Despite expecting little change in contraflow cycling when two-ways streets are converted to one-way streets with contraflow cycling, three out of 14 streets experienced more than ten percent increases in mean contraflow cycling volumes, all of which had more observed counts than expected. Furthermore, two streets showed more than a ten percent fall and observed counts were lower than expected. Relative contraflow counts fell on two streets that experienced increased contraflow volumes, suggesting these roads attracted with-flow cycling. However, for most streets we did not see any impact of introducing contraflow cycling.

Local context was important in determining apparent success of implementation. Connectivity of the roads to existing cycle routes and facilitating travel to and from places of interest including green spaces was important consistent with Beecham et al. (2023). Contraflow infrastructure factors identified as important for implementations include protected entrances to the contraflow, limited on-road parking, unobscured vision and distance or separation from with-flow motor vehicles. External factors such as local construction work, infrastructure construction or delays in implementation affected success.

4.5.2 Interpretation of findings and contextualisation within the literature

Our findings that contraflow cycling volumes and users can increase when contraflow cycling is introduced on existing one-way streets is consistent with the current evidence base (Ryley and Davies, 1998; Bjørnskau et al., 2012; Burkin, 2019; Pritchard et al., 2019). We also found some evidence that contraflow cycling volume can increase more than with-flow cycling on these streets which is again consistent with previous studies (Ryley and Davies, 1998; Bjørnskau et al., 2012). However, our findings that contraflow cycling can increase on converted two-way streets is a new finding as we have not found any research that examines this type of intervention. In particular our discovery that conversion of two-way streets may increase with-flow cycling suggests that cycling on these new one-way streets is more attractive than when they were two-way streets.

Looking at the literature it is unsurprising that we have found inconsistent associations between contraflow implementation and cycling volume on our study roads and that local contextual factors seem to be very important. Whilst individual studies have found that painted cycle lanes can increase cycling participation (e.g. Parker et al. (2013)), systematic reviews have concluded that there is insufficient high quality evidence that cycle lanes or separated cycle tracks influence counts (Mulvaney et al., 2015; Stappers et al., 2018;

Molenberg et al., 2019). However, when implemented as part of a wider programme to promote cycling (e.g. Goodman et al. (2013)) or within a cycle-friendly environment (e.g. Hull and O'Holleran (2014); Aldred et al. (2019)), they appear to have a positive effect on cycling volume. This could be explained by infrastructure delivering certain functions that result in increased cycling: improved accessibility and connectivity; traffic and personal safety; and cycling experience (Panter et al., 2019). Panter et al. (2019) found that even in unsupportive contexts, for example, car dominated areas, infrastructure that delivered such functions could be successful. This could also explain why car-dominated Roehampton High Street that had lower physical quality and high potential for conflict but good connectivity was successful whereas others such as Harrowby Street and Ivor, Place where the physical infrastructure was good but in an unsupportive context due to no onward connectivity and busy roads, were less successful.

4.5.3 Strengths and limitations

Our study is the first large data analysis of changes in contraflow cycling trips and users after the introduction of contraflow cycling on one-way streets or converted two-ways streets. We used 28 one-way streets and 14 former two-ways streets. Examining change on former two-way roads has not been performed before to the best of our knowledge. We examined twenty-four months of count data with a minimum of three months before and after implementation for each road studied. We generated expected counts to adjust for the number of strava users, strava trips, seasonality and time of year to examine whether changes in observed counts could be explained by these factors or whether such changes could be associated with contraflow implementation.

Our approach is not without limitations. The Strava Metro dataset makes it hard to generalise our findings to all cyclists. We know that it only contains data on people over 18 and that women, commuters and older age groups are under-represented (Lee and Sener, 2021). Strava users may not behave in the same way as other people who cycle. For example, Garber et al. (2019) found that fitness app users were more likely to illegally cycle contraflow than non-app users whilst Dunleavy (2015) found 95% of Strava users would cycle illegally contraflow rather than divert around a one-way street. Strava users motivations to cycle can be different, focussing on activity tracking, performance management and competition (Williams, 2013). We could have tried to mitigate this by comparing Strava Metro counts to manual cycle counts, although this may not address all these issues as manual counts may not have age-gender breakdowns.

We had assumed the road segment dataset was accurate (limitations are discussed in Tait et al. (2023)). However, it became clear that the contraflow had not been physically introduced on Meymott Street and there may have been delays in implementation on others. As we only qualitatively assessed 12 of the 42 intervention roads, there may be others affected by these factors and we may have erroneously concluded that there was no association between contraflow implementation and cycling volume.

Our methods have some limitations. For example, our expected counts were generated using Strava counts on inner London roads after excluding streets that people were unlikely to cycle on (e.g. gravel surfaces) and that were not comparable to our intervention (e.g through parks as none of our roads went through parks). However, this is unlikely to be fully comparable to our intervention roads, although one would hope the large volume of data would minimise any errors introduced by this broad approach. Whilst our expected counts would adjust for some factors - seasonality, time of year, number of Strava Metro users and number of Strava Metro counts, we have not taken into account other factors that influence cycling volume such as motor vehicle volume, road speed and traffic congestion. Whilst we have considered other aspects such as infrastructure quality and proximity to cycling routes we did not examine wider improvements to routes or other interventions such as cycle promotion, cycle parking etc that can also impact cycling participation.

Our qualitative assessment was subjective as there is no standard for contraflow implementation - there is advice and guidance. It was also desktop based and limited by the data available. Data on road width, average road speeds and motor vehicle volumes coupled with an on-site visit would have improved the assessment process.

4.5.4 Implications for policy and future research

Increasing the number of roads with contraflow cycling could increase cycling volumes and address key barriers to cycling participation. Safety and infrastructure are reported as the greatest barriers whilst quality infrastructure is the greatest enabler (Pearson et al., 2022) with people preferring separate infrastructure on low speed and low traffic volume roads (Misra et al., 2015; Misra, 2016). We have previously demonstrated that introducing contraflow cycling is safe and improves the safety on former two-way streets in particular (Tait et al., 2023). This, in combination with carefully designed contraflow infrastructure that delivers improved connectivity, accessibility and the cycling experience, preferably in supportive context such as other cycling infrastructure, speed reduction and cycle promoting activities, should deliver greater cycling participation at lower cost than other types of cycling infrastructure (Steer Davies Gleave, 2016; Taylor and Hiblin, 2017). We echo our earlier call for UK transport authorities to review their one-way streets with a view to introducing contraflow cycling (Tait et al., 2023). In 2016, Lambeth Council did just that and identified that only three of their 67 one-way streets were considered not suitable for such a change (Steer Davies Gleave, 2016). We also call on UK transport authorities to consider two-way streets that could be reconfigured and encourage national governments to consider legislation making contraflow cycling mandatory on one-way streets unless exceptional circumstances exist (Tait et al., 2023).

This quantitative and qualitative research on cycling infrastructure is important as it can guide evidence-based decision making by policy-makers as to what type of infrastructure is effective in increasing cycling participation in what circumstances and thus maximise limited active travel resources. It also highlights the importance of the context in which such infrastructure is introduced as a factor influencing success. This research has demonstrated that transport authorities could use Strava Metro counts to identify one-way streets with high levels of illegal contraflow cycling that would benefit from contraflow implementation.

Research on cycling volume is particularly important as such data is used to underpin questions that policy-makers are interested in such as how much cycling, who is cycling and where they are cycling (Handy et al., 2014). However, cycling volumes are also used as a measure of exposure and are vital for calculating crash rates involving cyclists (e.g. Vanparijs et al., 2015; Dozza, 2017), examining safety risk (Strauss et al., 2015; Ferster et al., 2021) and thus reducing risks to cyclists.

Future research could focus on detailed examination of the 42 roads to establish more clearly the factors for successful implementation of contraflows complemented with interviews with key stakeholders such as Transport for London, London Cycling Campaign and transport authorities. Such examination could include triangulation with other datasets such as public bike sharing scheme that have previously been used to assess bikeability (Beecham et al., 2023), gendered cycling behaviour (Beecham and Wood, 2014) and inclusivity (Lovelace et al., 2020). The method to generate the expected counts could be improved by using Bayesian techniques to generate more localised expected counts (Sahu, 2022). Finally, examining whether there is route substitution onto contraflow infrastructure could improve the case for more investment in such infrastructure but would probably need a mixed-method approach due to the local factors we have highlighted that make such infrastructure successful or not.

4.6 Conclusion

This is the first large-scale analysis of the impact on cycling volumes of introducing contraflow cycling on one-way streets. We have demonstrated that contraflow can be associated with increases in the number of trips and individuals cycling when implemented on existing one-way streets measured using crowd-sourced data. We have also shown that on two-way streets, introducing a one-way street with such infrastructure can also be associated with increases in cycling trips and individuals as well as possibly encouraging more people to cycle with-flow. Local context appears to be important in determining success of these implementations and qualitative assessment indicated connectivity, protective entrances, minimal on-road parking, clear vision and distance or separation from motor vehicles were positive influencing factors. Transport authorities should examine their one-way streets and consider converting these and two-way streets to one-way with contraflow cycling as such roads have previously been demonstrated to be safe (Tait et al., 2023), now shown to encourage cycling participation and represent a low-cost intervention compared to segregated cycle lanes or junction remodelling (Taylor and Hiblin, 2017). Legislative change to make one-way streets contraflow by default would facilitate faster implementation of such infrastructure. Further research could explore in more detail the aspects of contraflow implementation that are necessary for success, improve methods to use crowd-sourced data to generate cycling volume counts and examine the effect of such infrastructure on route choice.

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Strava Metro data:

This report includes aggregated and de-identified data from Strava Metro.

OpenStreetMap data:

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Chapter 5

Discussion

5.1 Overview

In this chapter the key findings for each of the research questions are presented. The body of research is then considered in terms of the original aim by discussing infrastructure evaluation, addressing the research gaps and generating evidence for policy-makers. Limitations of the research are then presented followed by policy recommendations and proposed areas for future research. The section finishes with the Conclusion.

5.2 Key findings

This thesis sought to evaluate the impact of cycling infrastructure using large observational datasets. To do this, three research questions were developed. This section presents the key findings for each research question.

5.2.1 RQ1: What cycling infrastructure exists in London?

This question was explored in Chapter 2 in the paper *"Is cycling infrastructure in London safe and equitable? Evidence from the cycling infrastructure database"*. This was the first analysis of the London cycling infrastructure database (CID) and analysed cycling infrastructure provision and cycle lane quality. It demonstrated that the quantity and quality of infrastructure was not equal across London. People living in outer London had less infrastructure that provided safe space for cycling than inner London. This pattern persisted when adjusted for area and population but was inverted when adjusted for commuter cycling. Traffic calming was the most common infrastructure and found in 58,585 locations. Just six percent of on-road cycle lane length was physically segregated from motor traffic. Estimated mean compliance with national design guidance (DfT, 2020a) for protection of cyclists in cycle lanes from motor vehicle traffic based on segregation and road speed limits was 22%. This varied by location with 64% of inner London boroughs exceeding the mean compliance compared to just 16% of outer London boroughs. Estimated compliance was higher than perhaps the low levels of physical segregation would predict. This was due to low road speed limits making non-physical separation acceptable i.e. compliance was achieved automatically rather than through deliberately-designed infrastructure.

5.2.2 RQ2: What is the impact of introducing contraflow cycling on one-way streets on cyclist safety in London?

This question was considered in Chapter 3 in the paper *"Contraflows and cycling safety: Evidence from 22 years of data involving 508 one-way streets"*. This paper compared pedal cyclist crashes before and after contraflow cycling introduction on inner London roads to see if there was any change in crash or casualty rates. Five hundred and eight road segments were identified with contraflow cycling introduced during the 22 years preceding the COVID-19 pandemic. Of the 473 road segments with a documented contraflow start date, 306 (65%) had pedal cycle crashes within 10m whilst 167 (35%) had none. In total there were 1498 pedal cyclist crashes: 788 before, 703 after and 7 following contraflow cycling removal. Over 92% of crashes occurred close to junctions or roundabouts.

Crash rates calculated using raw numbers suggested that introducing contraflow cycling increased pedal cyclist crashes. However, when the rate was adjusted using cordon cycling count data to take into account the significant changes in cycling volume over the 22 years, there was no difference in overall crash rates before or after contraflow cycling was introduced. Factors associated with increasing the crash rate were the cyclist changing direction (i.e. turning) or the presence of a junction or roundabout within 10m (both double the crash rate). Converting two-way streets to one-way with contraflow cycling (or to a bus lane with contraflow cycling) was associated with a reduction in the crash rate by over a third. The crash rate was identical irrespective of whether the cyclists were cycling with flow, illegally contraflow or legally contraflow. Following contraflow introduction, turning cyclists experienced lower crash rates. The casualty analysis demonstrated that there was no difference in the fatal, severely or slightly injured cyclist casualty rates when contraflows were introduced once cordon cycling volume and injury severity reporting changes were taken into account.

5.2.3 RQ3: What is the impact of introducing contraflow cycling on one-way streets on cycling participation in London?

This question was examined in Chapter 4 in the paper *"Build it but will they come? Exploring the impact of introducing contraflow cycling on cycling volumes with crowd-sourced data"*. Using the primary database of roads with contraflow cycling in inner London developed for RQ2, it examined whether the volume of pedal cyclists changes when contraflow cycling is introduced and the quality of the contraflow infrastructure.

It demonstrated that allowing contraflow cycling increased contraflow cycling volume and attracted more people to cycle on such infrastructure on some roads. The number of trips and unique individuals increased on around two-thirds of existing one-way streets (with high Strava usage) with the volume exceeding that expected based on the global change in cycling volume. Some had increases in the relative volume of contraflow cycling compared to with-flow cycling. Several streets had high levels of illegal contraflow cycling pre-implementation that suggested previous unmet demand. Others had low levels of illegal contraflow then high levels of legal contraflow cycling suggesting that the infrastructure introduction *itself* did increase contraflow cycling. Despite expecting no change in contraflow cycling when two-ways streets were converted to one-way with contraflow cycling, a fifth experienced over a ten percent increase in contraflow cycling volumes above what would be expected. Relative contraflow counts fell on two streets that experienced increased contraflow volumes, suggesting these roads attracted with-flow cycling. However, for most streets we did not see any impact of introducing contraflow cycling.

Certain contraflow infrastructure factors were identified as important in whether cycling volumes increased after introduction. These included protected entrances, limited on-road parking, unobscured vision and distance or separation from with-flow motor vehicles. Local context also appeared to be important in determining success such as connectivity to cycle routes and facilitating travel to and from places of interest. External factors such as infrastructure construction, other construction work or delays in implementation appeared to influence cycling volume.

5.3 Interpretation and contextualisation of the thesis

The aim of this thesis was to contribute original research evaluating the effect of cycling infrastructure on cyclist safety and participation using large, observational datasets to address research gaps in this field and generate evidence that can influence policy and have real-world impact.

5.3.1 Evaluating infrastructure

Paper 1 used a new database for London containing 234,251 cycling infrastructure objects to examine common evaluation questions such as what type, how much and where infrastructure is located. It also compared the provision of infrastructure that aimed to promote safe cycling space between areas, taking into account factors such as cycling volume, population size and area to make fairer comparisons, before evaluating the quality of infrastructure against a criteria. These comparative and evaluative approaches could be considered a form of benchmarking which is of particular interest to policy-makers (Bowerman et al., 2002; Northcott and Llewellyn, 2005; Papaioannou et al., 2006).

However, such approaches can be misleading. Paper 1 identified that just six percent of on-road cycle lane length in London was physically segregated (fully or partially) but this resulted in 22% compliance with national design standards. The global reductions in road speed limits to 20mph that have occurred across London (see Appendix C, Figure C.1) will mean that such compliance will automatically increase without any improvements in segregation from motor vehicles. So although cyclist crashes, casualties and participation may improve as speed reduction is effective (Mulvaney et al., 2015; Phillips et al., 2018), cycling safety perceptions will not improve as the infrastructure present is not segregated and, as established in the Introduction, segregation is vital to increase such perceptions (Steer Davies Gleave, 2012; Misra et al., 2015; TfL, 2017; DfT, 2020c). Furthermore, recent research has shown that 20mph speed limits have minimal impact on such perceptions (Williams et al., 2022). However, policy-makers may see that compliance with design standards has increased and believe that the infrastructure is of appropriate quality and consequently will improve cycling safety and participation.

Papers 2 and 3 used large quantities of observational data at a city-wide level over many years to evaluate whether a particular type of cycling infrastructure altered cycling crashes and volumes. This type of question is extremely important as it determines what is effective and therefore what should be prioritised and funded by policy-makers (Evaluation Task Force, 2023a; Evaluation Task Force, 2023b). The quantitative approaches taken in Papers 2 and 3 are essential and appropriate to answering such questions. The qualitative examination undertaken in Paper 3 is useful as it teases out the context in which interventions may work and why, what on paper seem to be good implementations, may not work in practice.

However, using observational data that may be new (such as the contraflow cycling infrastructure) or under-explored (e.g. Strava Metro data) and deriving data such as crash or casualty rates using denominators that are imperfect can be challenging. In particularly, this data is subject to uncertainty. Some of these uncertainties were known and quantified or accounted for whilst others could only be acknowledged. The research presented in this thesis communicates these uncertainties so that the quality and application of the evidence can be assessed by readers and others.

5.3.2 Addressing research gaps

This research has addressed some specific research gaps and issues identified with the cycling infrastructure evidence base as outlined in the Introduction. Firstly, it is the first description and analysis of the CID, a new city-wide cycling infrastructure database for London, and therefore totally original. Secondly, it examines the impact of contraflow cycling infrastructure on safety and participation. Such research has not been performed before in the UK nor at this scale anywhere else in the world. Thirdly, it addresses historical issues with methods used for evaluating cycling infrastructure. Specifically it uses large volumes of high quality data, involving multiple locations, across multiple years using a before and after implementation approach. Fourthly, it considers uncertainty and other factors that may influence findings and actions these by calculating confidence intervals and adjusting for confounders. Finally, it considers the context in which infrastructure is implemented that can influence success.

5.3.3 Generating evidence

This research has demonstrated that infrastructure datasets when combined with geographical and demographic data, can generate new insights into cycling infrastructure quantity and quality and be used to compare administrative units. It has also demonstrated that infrastructure datasets can be combined with other data to estimate compliance with design standards and evaluate the effect of infrastructure on cyclist crashes and volumes.

This body of research has provided evidence that introducing contraflow cycling on one-way streets is safe and has no significant impact on cyclist crashes or casualties. In particular, that such an implementation is safer than when the roads were previously two-way for motor vehicles. These findings are contrary to widely-held beliefs (e.g. Ryley and Davies (1998); Police Scotland (2021)) and demonstrate that customs and practices in cycling infrastructure may not be evidence-based but can become ingrained and hinder the development of cycling networks and routes. This highlights the importance of high quality data and research to examine where evidence is poor or lacking to inform policy. This research has also provided evidence that contraflow cycling infrastructure can increase cycling on some streets but this may be subject to local context.

5.4 Limitations

There are limitations in all the research carried out as part of this thesis. Limitations of the research conducted for each paper are presented in the relevant chapters (2 to 4). However, there are some more general limitations of the research as a whole and these are discussed below.

5.4.1 Data

The first category of limitations relate to the data. A key principle was to use data of the highest quality for the research, however, all the data sources have issues. For example, the population and commuting cycling estimates used in Paper 1 were based on 2011 Census data so were not contemporaneous whilst the Strava data used in Paper 3 was not representative of all people who cycle. Crashes involving cyclists (Paper 2) are known to be under-reported (e.g. Ward et al., 2005; Jeffrey et al., 2009) with particular issues with geospatial location, vehicle direction (Anderson, 2003; Imprialou and Quddus, 2019) and casualty severity reporting (DfT, 2020b) whilst the cycle counts used as the denominator in the crash and casualty rates calculations lacked spatio-temporal coverage and granularity.

Infrastructure, the focus of this research, was not immune to data issues. Paper 1 explored the London CID. The data for this was traditionally surveyed on-site over a 33 month period but was not updated subsequently. It was missing key data items such as cycle lane width or implementation date that limited the evaluation. The Traffic Regulation Order (TRO) data for roads implementing contraflow cycling (Papers 2 and 3) was incomplete, particularly around contraflow start dates, and sometimes these dates were inaccurate. TRO did not have data on the length or precise location of additional infrastructure such as segregated, mandatory or advisory cycle lanes that would have generated further insight regarding effectiveness of infrastructure.

There were also missing or inaccessible datasets that limited the research. For example, in Paper 1, compliance of cycle lanes with national design standards had to be estimated because there is no local data for motor vehicle volume or actual road speeds (see Appendix A, Figure A.1). If that data had been available then compliance could have been determined more precisely. As it was, compliance could not be estimated in 21% of road length because there was no open road speed limit data for these roads. Frustratingly, actual speed and road speed limit data was available but *not accessible* to researchers.

Mitigations for these issues included validating data using multiple data sources; for example using OpenStreetMap, Google Street View and the CID to identify contraflow cycling locations; using the highest quality data available, for example, official datasets such as census data and road traffic crash data; using large volumes of data with multiple data points in time and space; estimating uncertainty around crash and casualty rates using bootstrapping; and highlighting these issues in the relevant papers and chapters of this thesis.

5.4.2 Methods

The second category of limitations relates to the methods. An uncontrolled before and after method was utilised for Papers 2 and 3. As discussed in the Introduction, this is not the highest quality methodological approach for examining effectiveness of cycling infrastructure. Other study designs such as a randomised controlled trial would be superior but these are costly, complex and difficult to implement for exposure to interventions such as infrastructure (Ogilvie et al., 2020). The methods could have been improved by using a controlled design thus allowing both a before and after comparison and a control-intervention comparison (Lopez Bernal et al., 2018). However, this may have been difficult due to 'contamination' from nearby infrastructure, challenges in identifying 'suitable' controls and the unit of analysis being the road. Nevertheless, whilst the before and after study design does not allow causation to be drawn from the findings, true causation should only be determined from amalgamation of a large body of evidence that includes multiple studies that utilise diverse methods and perspectives (Lesko et al., 2020).

This research contributes significantly to the very small body of evidence on the safety and participation of contraflow cycling.

Most of the data utilised had a spatial attribute and were points (e.g. location of a crash) or lines (e.g. a cycle lane or road). Whilst the CID (Paper 1) had very specific information on how this was collected (TfL, 2019), the other data sources were less accurate. For example, in OpenStreetMap users contribute data (Basiri et al., 2019) whilst the collection methods and accuracy of GB road crash data has changed over time (Anderson, 2003; DfT, 2005; DfT, 2011). To overcome potential location inaccuracies, spatial buffering was utilised where the spatial data is enlarged, in this case symmetrically, around the point or line, giving uncertainty to the exact location. This technique was also employed when joining spatial data together, for example to link cycle lanes to road speed limits (Paper 1) or crashes to roads (Paper 2). However, this approach does have its limitations. The buffer could include or exclude the true location depending on the accuracy of the original data and joining buffered data could result in inaccurate joins, for example, attributing a crash to the wrong road at a junction.

Various approaches were used to mitigate this issue. Firstly, the size of the buffer required for each data type was estimated using the best data and evidence available. For example, national design guidance for road lane width (Highways England, 2020), spatial accuracy research of OpenStreetMap (Haklay, 2010) and location reporting guidance for crashes (DfT, 2005; DfT, 2011). Starting with these estimates, buffer size sensitivity testing was used to examine potential inaccurate joins before settling on conservative sizes to minimise this risk. This generated additional work to link unsuccessfully joined data but this was preferable to inaccuracy. The joins were validated using multiple methods such as visualisation on maps and comparing road names.

5.4.3 Confounders

Confounders could have affected the associations seen between infrastructure and cycling participation and safety. Some known confounders were included in the data analysis. For example, knowledge that temporal cycling patterns could have influenced exposure to infrastructure and therefore crash rates meant that in Paper 2 the crash rates were adjusted to take cycling volume into account using the best open data available. Similarly, recognising that Strava cycling volume can fluctuate due to changes in the number of trips or users and depend on the time of year, expected counts using global changes were calculated in Paper 3. In Paper 2, cyclist casualty rates were adjusted to take into account changes in injury severity reporting. However, there are many other known confounders that exist that were not factored into the analysis.

A key confounder not included was motor vehicles. The main reason for not including these is the lack of data relating to the volume of motor vehicles. Such data does not exist for every road in London. Even when it exists for some roads, it is only available for short time periods once a year and it may not be accessible to researchers. The second reason for not including motor vehicles is that different aspects of such vehicles have independent impacts on crash risk (e.g. volume versus flow) that are not necessarily linear (e.g. Tasic et al., 2017). Furthermore, motor vehicles are not homogeneous. There are multiple different: classes (motorcycles to heavy good vehicles); sizes (city cars to 4x4); volumes and vehicle mix that differ depending on the road, location and time of day; and speeds (acceleration ability and likely average speed). Therefore, any adjustment based solely on motor vehicle volume data, if such data existed at any level that would be helpful, without consideration of these other factors (again if granular data existed) would be an oversimplification of complex dynamics.

Whilst changes in cyclist volume was included in the analysis, the adjustment made the assumption that as cycling volume increases, the number of crashes involving cyclists also increases i.e. a positive linear relationship. This is unlikely to be the case (Elvik, 2009). Multiple studies demonstrate a 'safety in numbers' effect where as the number of cyclists increases then safety also increases (although the reverse may be true where as safety increases the numbers of cyclists increase) (Elvik and Goel, 2019). This effect is usually seen as a negative, non-linear, exponentially decreasing correlation (e.g. Tasic et al., 2017; Aldred et al., 2018). However, the safety in numbers effect seems to be stronger at a macro e.g. country (Drbohlav and Kocourek, 2018) or city-wide (e.g. Tasic et al., 2017) level rather than a micro e.g. infrastructure level (Elvik and Goel, 2019). This may mean it is less likely to affect this research. Firstly, as the research involves specific sections of contraflow infrastructure i.e. it is at a micro-level and secondly, because the cycling volume may not reach the numbers on this type of infrastructure where safety is influenced.

Other known confounders that were not adjusted for in the crash quantitative analysis (Paper 2) include daylight, weather, road surface quality, width, speed limit and average road speed, mainly due to a lack of data and difficulties attributing these factors as contributing to crashes or influencing participation. However, some of these were included in the quantitative and qualitative analysis of the successful and unsuccessful contraflow implementations (Paper 3).

There was no adjustment for demographic aspects such as age, sex or socio-economic status. Whilst this data may be available in the road traffic crash datasets, subgroup analysis of this type is likely to have resulted in extremely small numbers of crashes involving contraflows. Strava Metro data does contain sex and age data but at an aggregated level and small numbers are rounded down to zero for rarer characteristics due to its privacy process, particularly affecting women and older people.

Finally, there was no adjustment for behavioural aspects by cyclists or motor vehicle drivers. This is principally because the data used did not contain information on these aspects.

Some of these known confounders could be better explored using other research methods. For example, surveys for demographic details or behavioural factors, individual crash analysis for causative factors and modelling techniques to explore factors affecting crashes or improve estimation of cycling or motor vehicle volumes.

There are potentially unknown confounders that may be difficult to measure or include in the analysis that could be influencing findings, particularly around aspects such as the local wider context and environment in which infrastructure is implemented (Panter et al., 2019). Potential factors that are not known confounders but could be include: connectedness (Beecham et al., 2023); distribution of employment (e.g. Beecham and Slingsby, 2019; Beecham et al., 2023); distribution of amenities (e.g. Jarvis, 2005); social geography such as gentrification, class or ethnic diversity (e.g. Davidson and Wyly, 2012; Watt, 2013) and the development of infrastructure within an area.

5.4.4 Generalisability

This thesis has focussed on London out of necessity due to it having a large volume of infrastructure and cyclists that enable the research questions to be examined. This means the findings may not be generalisable to other UK locations, particularly because other places have not had the leadership, funding and specific transport authority that has placed such a focus on increasing cycling. Furthermore other locations will have diverse and different contexts that may make their cycling infrastructure implementations more or less successful. However, these findings are likely to be generalisable to large cities and urban areas, particularly those that are moving forward with transport devolution such as Greater Manchester, West Yorkshire and West Midlands and have been identified as having high active travel capability.

5.4.5 Using spatial data

Spatial data was utilised throughout this thesis and included borough boundaries and areas, population size, cycling infrastructure location, cordon cycling volumes and road-level cycling crashes and volumes. Using spatial data comes with numerous issues (e.g. Stewart Fotheringham and Rogerson, 1993; Loidl, 2019; Brunsdon and Comber, 2021). In this thesis it was frequently aggregated to city, borough or road levels. This aggregated data enables comparison but loses granularity and can fail to capture the diversity within smaller spatial units (spatial heterogeneity). For example, aggregated cycling volume data suggests that cycling volume is the same across a particular area or along a road but this may not be the case (Loidl, 2019). Two specific issues are introduced when using such aggregated spatial data (Stewart Fotheringham and Rogerson, 1993). Firstly, aggregation levels can be fixed and artificial, therefore, they may not capture other factors that may be influencing the outcomes of interest. For example, the physical location of cycling infrastructure is specifically influenced by where roads are located. Secondly, factors in one location can influence outcomes in another, for example, building high quality infrastructure in a particular location can result in route substitution onto that new infrastructure and reduction in use of other infrastructure.

5.5 Policy recommendations

Accurate data on the location, type and characteristics of physical cycling infrastructure is vital for evaluating such infrastructure and for research, policy and planning. Therefore, one policy recommendation to national governments is that open inventories of cycling infrastructure be considered a critical infrastructure asset in a similar way to other transport assets (Hall, 2019; Schooling et al., 2020) and that open data on all new cycling infrastructure be electronically captured using the CID specifications developed (TfL, 2020) in conjunction with national design guidance (DfT, 2020a) and include date of infrastructure implementation and two-dimensional geometry. Since publication of Paper 1, the creation of the Active Travel Infrastructure Platform to support assessment for government funding (Carlino et al., 2023; ATE, 2023) and progress towards digital Traffic Regulation Orders (Galea et al., 2018; Lokat, 2019; DfT, 2022) means that there are significant developments in this area, however, it remains to be seen how much of this data will available to researchers.

The second policy recommendation to national government builds on this theme. Data on road speed limits, actual road speeds, motor vehicle volumes and cycling volumes must be made available to researchers at a high spatio-temporal level of coverage and granularity (preferably individual roads). Official data at this level already exists for road speed limits and actual road speeds but was inaccessible to researchers until recently (OS, 2023). Emerging sources can provide data on traffic volumes (Williams et al., 2015; e.g. TomTom, 2023) and were used particularly during the COVID-19 pandemic (Google, 2022; ONS, 2022). Such resources are being explored by government departments (Hemmings and Goves, 2016; ONS, 2023) but academics need to have access to such data to evaluate infrastructure to inform governments. Whilst Strava Metro provides granular cycling volume data, it is limited to the previous 5 years and large downloads such as an entire region or country are not possible. Governments can influence access to such data.

The third policy recommendation to the UK national governments is that they legislate to mandate contraflow cycling on one-way streets unless exceptional conditions exist. Such legislation already exists in Belgium (Depoortere, 2019) and France (CanalDuMidiBike, 2017). It would encourage, simplify and expedite the process undertaken by local highways authorities to convert existing one-way streets.

The fourth policy recommendation concerns cycling infrastructure. National cycling infrastructure design guidance and funding requirements should be reviewed to ensure that infrastructure that meets design guidance but is unlikely to achieve desired outcomes such protecting cyclists or increasing cycling participation is reviewed. This would mean blanket changes to speed limits that could increase infrastructure compliance with design standards but that are likely to be ineffective are identified and considered for further additional infrastructure intervention. Contraflow cycling infrastructure design guidance should be strengthened to protect contraflow cyclists at junctions as these locations and turning cyclists were associated with higher crash rates. Previous guidance recommended protection at both entry and exit of contraflows (DfT, 2008) whilst recent guidance only recommends it at the entrance (DfT, 2020a).

There are specific recommendations for local government and highway authorities. Firstly, that all highway authorities review their one-way streets with a view to allowing contraflow cycling as this is a low-cost, effective intervention that can increase the quality of cycling networks and routes. Strava Metro data could be used to identify locations of high illegal contraflow cycling suggesting potential roads for implementation. Secondly, that they should consider whether any two-way streets have the potential to be converted to one-way with contraflow cycling since this results is associated with greater safety improvements. Thirdly, TRO data (historical and future) and cycling infrastructure consultation and implementation data should be made openly available to researchers. The data should include details of the type of infrastructure (including aspects such as segregation, colour etc), its location and date of implementation. Finally, local governments should make other data that they collect openly available such as cycling surveys.

5.6 Future research

Future research could calibrate the Strava Metro cycling volumes against manual cyclist counts to estimate the proportion of cyclists in London that record their activity on Strava. This could be used to generate more accurate cycling volumes, in particular by improving accuracy through examination of spatio-temporal differences between the proportions. More accurate cycling volumes could be used to improve estimation of the expected number of cyclists on contraflows. These cycling volumes could also be used as an better denominator for cyclist crash and casualty rates, potentially re-evaluating the safety of contraflow cycling or evaluating other cycling infrastructure interventions.

Another area of future research is to examine contraflow infrastructure route substitution. This is where cyclists deviate from their original route to use infrastructure. Traditionally it has been measured through participant recall (e.g. Vasilev et al., 2018) or manual observations (e.g. Parker et al., 2013) but now it is mainly examined using GPS data (Pritchard, 2018). There is very little research on route substitution involving contraflows (Pritchard et al., 2019). There is the potential to use large observational datasets combining origin-destination data, contraflow infrastructure data and crowd-sourced cycling volumes with routing algorithms to examine this question.

Building on the existing qualitative assessment of contraflow cycling infrastructure, images of pre and post intervention contraflow infrastructure could be viewed by a variety of people to understand their perspective of such infrastructure, particularly in terms of safety. Participants could include cyclists, non-cyclists, highway engineers, active travel inspectors and cycle campaigners. Furthermore, women, children, older people, minoritised ethnicities, disabled or impaired people could offer insights on contraflow infrastructure and how it would impact them and make cycling more accessible to all.

5.7 Summary of Discussion

In this chapter the key findings for each of the research questions was presented. The research was interpreted and contextualised in terms of the original aim by discussing infrastructure evaluation, addressing the research gaps and generating evidence for policy-makers. Limitations of the research categorised as data, methods, confounders, generalisability and use of spatial data were discussed. Key policy recommendations were presented and future areas of research proposed. The final Conclusions are presented in Chapter 6.

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Chapter 6

Conclusion

This thesis has evaluated cycling infrastructure in London using large observational data with a particular focus on cyclist safety and participation. It has discovered that there is no evidence that contraflow cycling in unsafe in the UK, contrary to widely-held beliefs, and that it can increase cycling participation. However, it has also shown that cycling infrastructure is not distributed equally across London and may not be of the quality that provides safe space for cycling or that appeals to everyone.

Ambitions for active travel to be the default choice for short urban journeys to reap the individual and population benefits will not be achieved without high-quality infrastructure that is safe, coherent, direct, comfortable, attractive and enables all to cycle. Making large datasets available to researchers could improve evaluation of cycling infrastructure in particular by knowing where, when and what infrastructure is implemented and improving estimates of cycling volumes across entire areas and time periods. However, researchers need to be aware of the limitations of such data and the methods used to evaluate infrastructure. Further research could improve such evaluation by examining route substitution, improving denominators and incorporating qualitative assessments.

The research has already had an impact through presentation of the contraflow cycling findings to influential UK government departments such as Active Travel England, the Department for Transport, Public Health Scotland and local government such as the Urban Transport Group.

Appendix A

Supplementary materials for Paper 1 (chapter 2)

A.1 Supplementary materials: Additional method details

A.1.1 Datasets importation

R version 4.1.0 was used for data importation and analysis (R Core Team, 2021). The CID data was imported into R using the function read_sf and the longitude and latitude was converted into geometrical shapes (Pebesma, 2018) as part of the CycleInfLon package (Tait and Lovelace, 2019). Other data was imported into R using the following approaches: ONS Boundary data using st_read; commuting cycling data was obtained from the Propensity to Cycle Tool using the pct R package (Lovelace and Hama, 2021); and OpenStreetMap data was imported using osmextract (Gilardi and Lovelace, 2021).

A.1.2 Spatial data cleansing and manipulation

We transformed all spatial data into the British National Grid geography (ONS, 2020a). The function *st_intersection* was used to spatially limit all data to within the outermost boundary of London.

We examined the borough for every CID observation and cross-referenced it with ONS borough data. Where CID infrastructure crossed a borough boundary into another borough we split the infrastructure into two segments. When an observation did not have a borough coded or there was a mismatch between the pre-coded and cross-referenced borough, these were corrected as follows. Two ASL were assigned to the borough location where the Traffic signal for that ASL was located (one was NA, one reassigned). The length of the 29 Crossings that had no borough assigned was measured. Crossings were allocated to the borough that contained 60% or more of the length (n = 26). For three crossings where the length was between 40 and 60% in two boroughs, new crossing observations were created so that each borough could be represented. A further three crossings that had a coded borough were reassigned to a new borough (these were originally multi-crossing observations where the process of dividing into single crossings meant the original borough was no longer correct).

Cycle lanes and tracks and restricted routes in the CID can cross multiple borough boundaries as well as cross into Local Authorities outside London. Of the 24,622 cycle lane and track observations that had a coded borough, 72 were segmented by borough boundaries creating an additional 72 observations. 354 observations had no borough assigned and segmentation of these resulted in an additional 267 observations. Segmentation of restricted routes with a borough created an additional three observations whilst segmentation of those without a borough created a further 18 observations.

CID point observations that had their borough relabelled were: traffic calming (138), cycle parking (37), restricted points (2) and cycle signals (2). Eight signage observations were removed as they were outside London boundaries and 398 were relabelled to the correct boroughs.

All CID line asset observations were examined to identify whether they contained more than one observation by examining the type of geometry in the observation (i.e. single line string versus multilinestrings). No ASL observations contained more than one observation. 1,422 crossing observations contained a single linestring i.e. one crossing. 265 crossing observations contained multilinestrings i.e. more than one crossing. For these 265 observations, new crossing observations were created so that each crossing observation contained a single crossing. Some cycle lanes and tracks and restricted routes also contained more than one observation however as these were considered in terms of length rather than count in the analysis then it was unnecessary to ensure that each observation only contained one observation. Line assets were measured using the function *st_length*.

A.1.3 On-road cycle lane separation from motor vehicles

Assignment of the 'highest' level of separation from motor vehicles was achieved by creating multiple columns each representing a numeric value for the level of separation (10,000 for full, 1,000 for stepped etc down to 1 for advisory). These columns were summed. If the sum was greater than 10,000 then the asset was assigned to full segregation, if between 1,000 and 10,000 then assigned to stepped etc.

A.1.4 Estimating On-road cycle lane compliance with national design standards

We utilised the following approach to obtain the road speed limits for highways that cyclists may be using from OpenStreetMap data. Using the variable "highway", OpenStreetMap observations that had the following values were kept: primary, residential, trunk, trunk_link, service, unclassified, tertiary, secondary, tertiary_link, secondary_link, primary_link, and living_street. Other values such as motorway, escalator, proposed, bridleway and footway were dropped. We examined the "maxspeed" variable and dropped observations coded as "NA", "national", "signal" and "variable" leaving 71,660 observations. Values for "maxspeed" were processed to obtain the speed limit in numeric mph grouped into 10 mph increments.

Each OpenStreetMap observation had a 9.65 m spatial buffer applied. Spatial joins were utilised to identify cycle lanes contained within or touching these buffered OpenStreetMap observations.

Compliance was estimated using logical code that compared the highest degree of cycle separation and the road speed limit against the criteria defined in Figure A.1 resulting in an output of Compliant (True), Not compliant (False) or Unknown.

LTN 1/20 level of protection appropriate for most people cycling on highways dependent on speed limit and motor vehicle traffic flow [a]			**Criteria used for CID compliance based on available data**	**Estimated LTN 1/20 Compliance [c]**
Protection	**Maximum speed limit**	**Maximum Motor Traffic Flow (Passenger Car Units per 24 hours [b])**		
Fully kerbed cycle track	Any	Any	Fully segregated AND any speed limit or speed limit unknown	Compliant
Stepped cycle track or light segregation	30mph	Any	Stepped or part-segregated AND speed limit 30mph or less	
Mandatory or advisory cycle lane	20mph [d]	5000 PCU per 24 hours AND 500 PCU in peak hour [e]	Mandatory or advisory cycle lane AND speed limit 20mph or less	
Mixed traffic	20mph [d]	2500 PCU per 24 hours AND 250 PCU in peak hour	No separation	Not compliant
-	-	-	Cycle lane fails any of the above tests	Not compliant
-	-	-	Not fully segregated AND no associated speed limit data	Unknown

[a] Derived from Figure 4.1, page 33, LTN 1/20 Cycle Infrastructure Design (DfT, 2020a)
[b] PCU is Passenger car unit and this is used to standardise for vehicles of different classes (Kimber et al., 1985). In London, buses have a PCU value of 2, cars 1 and bicycles 0.2 (page 67, TfL, 2010).
[c] Peak hour motor traffic flow should be no more than 10% of the 24-hour flow
[d] If the 85^{th} percentile speed is more than 10% above the speed limit then 30 mph protection should be applied. However, there is no granular open data availble so when estimating compliance it is assumed this threshold is not breached.
[e] There is no open data available with detailed motor vehicle flow across all London road network, so compliance is estimated without Motor Traffic Flow

Figure A.1: Estimating CID on-road cycle lane compliance with UK Cycle Infrastructure Design guidance (LTN 1/20)

A.1.5 Other data cleansing and manipulation

All datasets with borough names were recoded to ensure that the names matched for when the datasets were joined.

A.1.6 Visualisation

The *ggplot2* R package was used to generate all maps, bar charts, and density plots (Wickham and RStudio, 2019). We facilitated data visualisation using The London Squared dataset that represents boroughs as squares in a simplified spatial arrangement (After the Flood, 2019b; After the Flood, 2019a) and geographical borough boundaries clipped to the mean high water mark with the River Thames as a key visual landmark (ONS, 2020b).

A.2 Supplementary materials: Table S1 Unique variables for each CID dataset (TfL, 2020)

TABLE A.1: Unique variables for each CID dataset (TfL (2020))

Variable name	Variable label	Description
Advanced Stop Lines		
ASL_FDR	Feeder Lane	True = Feeder lane present False = No feeder lane present (may be gate)
ASL_FDRLFT	Feeder Lane on Left	True = Feeder lane is aligned left next to kerb False = Feeder lane is not aligned left next to kerb
ASL_FDCENT	Feeder Lane in Centre	True = Feeder lane is in the centre of the ASL False = Feeder lane is not in the centre of the ASL
ASL_FDRIGH	Feeder Lane on Right	True = Feeder lane is aligned to far side of lane False = Feeder lane is not aligned to far side of lane
ASL_SHARED	Shared Nearside Lane	True = Shared nearside lane False = Not a shared nearside lane
ASL_COLOUR	Colour	Colour of advanced stop line - None, Green, Red, Blue, Buff/Yellow, Other

Variable name	Variable label	Description
Crossings		
CRS_SIGNAL	Signal-Controlled Crossing	True = Controlled
		False = Uncontrolled (e.g. zebra)
CRS_SEGREG	Segregated Cycles and Pedestrians	True = Cyclists segregated
		False = Shared with other users (e.g. pedestrians or horses)
CRS_CYGAP	Cycle Gap	True = Crossing includes gap in island or kerb allowing cyclists only (NOT a refuge)
		False = Crossing does not include gap in island or kerb
CRS_PEDEST	Pedestrian-Only Crossing	True = Cyclists must dismount to use
		False = Not a pedestrian-only crossing
CRS_LEVEL	Level Crossing	True = Crossing or rail/tram tracks on cycle lane/track
		False = Not a level crossing
Cycle lanes and tracks		
CLT_CARR	On-Carriageway (if true) or Off-Carriageway (if false)	True = On-carriageway
		False = Off-carriageway
CLT_SEGREG	Segregated Lane/Track	True = Fully segregated lane (i.e. On carriageway) / track (i.e. Off carriageway)
		False = Not fully segregated
CLT_STEPP	Stepped Lane/Track	True = Stepped lane/track
		False = Not a stepped lane/track
CLT_PARSEG	Partially Segregated Lane/Track	True = Partially or light segregated lane/track
		False = Not a partially or light segregated lane/track
CLT_SHARED	Shared Lane or Footway	True = Shared lane (eg bus lane)
		False = Shared footway or track
CLT_MANDAT	Mandatory Cycle Lane	True = Mandatory lane
		False = Not a mandatory lane
CLT_ADVIS	Advisory Cycle Lane	True = Advisory lane

Variable name	Variable label	Description
		False = Not an advisory lane
CLT_PRIORI	Cycle Lane/Track Priority	True = Cycles have priority, other traffic has to give way False = Cycles do not have priority
CLT_CONTRA	Contraflow Lane/Track	True = Contraflow lane/track (NOT if bi-directional) False = With flow
CLT_BIDIRE	Bi-directional	True = Two-way flow on lane/track/path False = Single direction lane/track/path
CLT_CBYPAS	Cycle Bypass	True = Bypass allowing turn without stopping at traffic signals False = Not a cycle bypass
CLT_BBYPAS	Continuous Cycle Facilities at Bus Stop	True = Cycle track carries on through the bus stop area False = Not a continuous cycle facility
CLT_PARKR	Park Route	True = Road/lane/track through park False = Not a park route
CLT_WATERR	Waterside Route	True = Route beside river, canal or other watercourse False = Not a waterside route
CLT_PTIME	Part-time (if true) or Full-time (if false)	True = Part-time False = Full-time
CLT_ACCESS	Access Times	Times route is accessible (either exact times or description)
CLT_COLOUR	Colour	Colour of lane/track - Limited to only the following entries: None, Green, Red, Blue, Buff/Yellow, Other
Cycle Parking		
PRK_CARR	Carriageway	True = On carriageway False = Off carriageway
PRK_COVER	Covered	True = Covered or sheltered (including partial shelter) False = No cover
PRK_SECURE	Secure	True = Locked compound with shared or combination lock provided by operator False = Not a locked compound
PRK_LOCKER	Locker	True = Locker using own or integral lock False = No locker present

Variable name	Variable label	Description
PRK_SHEFF	Sheffield Stand	True = Sheffield stand (including TfL type) or variant False = Not a sheffield stand
PRK_MSTAND	“M” stand	True = “M” stand (stand that resembles a letter M) False = Not an “M” stand
PRK_PSTAND	“P” stand	True = P, flag or pennant stand (stand that resembles a letter P) False = Not a “P” stand
PRK_HOOP	Cyclehoop	True = Cyclehoop False = Not a cyclehoop
PRK_POST	Post	True = Post False = Not a post
PRK_BUTERF	Butterfly	True = Butterfly/wheelbender False = Not a butterfly/wheelbender
PRK_WHEEL	Wheel Rack	True = Wheel rack or slot False = Not a wheel rack or slot
PRK_HANGAR	Bike Hangar	True = Bike hangar False = Not a bike hangar
PRK_TIER	Two Tier	True = Multi tiered cycle parking False = Not a multi tiered cycle parking
PRK_OTHER	Other	True = Other or unknown type of cycle parking False = Not an unknown type of cycle parking
PRK_PROVIS	Provision	Number of stands or discrete units
PRK_CPT	Capacity	Number of bikes that can be parked without difficulty
Restricted Points		
RST_STEPS	Steps	True = This feature is only relevant where steps link routes where cycling is permitted. False = No steps
RST_LIFT	Lift	True = This feature is only relevant where a lift links routes where cycling is permitted. False = No lift

Variable name	Variable label	Description
Restricted Routes		
RES_PEDEST	Pedestrian-Only Route	True = Pedestrian-only route linking cycle routes False = Not a pedestrian-only route
RES_BRIDGE	Pedestrian Bridge	True = Route includes a pedestrian bridge False = Route does not include a pedestrian bridge
RES_TUNNEL	Pedestrian Tunnel	True = Route includes a pedestrian tunnel/subway False = Route does not include a pedestrian tunnel/subway
RES_STEPS	Steps	True = Route includes steps to/from a particular cycle route which form part of a linear link route False = No steps
RES_LIFT	Lift	True = Route includes lift to/from a particular cycle route which forms part of a linear link route False = No lift
Signage		
SS_ROAD	Road Marking (if true) or Sign Face (if false)	True = Road marking or symbol False = Sign face
SS_PATCH	Coloured Patch on Surface	True = Marking/symbol on coloured background patch False = No colour
SS_COLOUR	Colour of Patch	Colour of road marking patch
SS_FACING	Facing Off-side	True = Facing oncoming traffic but on off-side (i.e. right) False = Not facing oncoming traffic
SS_NOCYC	No Cycling	True = Sign prohibiting cycling (No Cycling) False = Sign not prohibiting cycling
SS_NOVEH	No Vehicles	True = No vehicles except pedal cycles pushed False = Sign not prohibiting vehicles

Variable name	Variable label	Description
SS_CIRC	Circular Sign (if true) or Rectangular Sign (if false)	True = Circular False = Rectangular
SS_EXEMPT	Exemption	True = Exemption text present (i.e. "Except cycles") False = No exemption text
SS_NOLEFT	No Left Turn Exception	True = Banned left turn with exception False = No banned left turn
SS_NORIGH	No Right Turn Exception	True = Banned right turn with exception False = No banned right turn
SS_LEFT	Compulsory Turn Left Exception	True = All traffic must turn left with exception False = No compulsory left turn
SS_RIGHT	Compulsory Turn Right exception	True = All traffic must turn right with exception False = No compulsory right turn
SS_NOEXCE	No Straight Ahead Exception	True = Banned straight ahead movement with exception False = Straight ahead movement not banned
SS_DISMOU	Cyclists Dismount	True = Cyclist dismount sign False = Not a dismount sign
SS_END	End of Route	True = End of route sign False = Not an end of route sign
SS_CYCSMB	Cycle Symbol	True = Cycle symbol or marker False = Cycle symbol or market not present
SS_PEDSMB	Pedestrian Symbol	True = Pedestrian symbol False = Pedestrian symbol not present
SS_BUSSMB	Bus Symbol	True = Bus symbol False = Bus symbol not present
SS_SMB	Other Vehicle Symbol	True = Taxi/Motorcycle/Horse symbol False = Taxi/Motorcycle/Horse symbol not present
SS_LNSIGN	Delineating Line on Sign	True = Delineating line False = Delineating sign not present
SS_ARROW	Direction Arrow	True = Contraflow or one-way False = Not contraflow or one-way
SS_NRCOL	Number in a Box	True = Yes a number in a box is present

Variable name	Variable label	Description
		False = Number is box isn't present
SS_NCN	National Cycle Network	True = National Cycle Network sign, symbol or sticker False = Not a National Cycle Network sign, symbol or sticker
SS_LCN	London Cycle Network	True = London Cycle Network sign or symbol False = Not a London Cycle Network sign or symbol
SS_SUPERH	Cycle Superhighway	True = Cycle Superhighway sign, symbol or marker (NOT totem) False = Not a Cycle Superhighway sign, symbol or marker
SS_QUIETW	Quietway	True = Quietway sign or symbol False = Not a Quietway sign or symbol
SS_GREENW	Greenway	True = Greenway sign, symbol or marker False = Not a Greenway sign, symbol or marker
SS_ROUTEN	Route Number	Number of route
SS_DESTN	Destination	True = Direction sign False = Advisory sign
SS_ACCESS	Access Times	Times route is accessible (either exact times or description)
SS_NAME	TSRGD Sign Number	Sign number, e.g. 956.1, 953.1A,
Cyclist Signals		
SIG_HEAD	Cycle Signal Head	True = Cycle symbol on signal (as a light or set of lights with symbols) False = No cycle symbol on signal
SIG_SEPARA	Separate Stage for Cyclists	True = Separate stage for cyclists False = No separate stage for cyclists
SIG_EARLY	Early Release	True = Early release for cyclists False = No early release for cyclists
SIG_TWOSTG	Two Stage Turn	True = Two stage right turn (where signed) False = No two stage right turn (where signed)
SIG_GATE	Cycle/Bus Gate	True = Cycle/bus gate allowing cycles to get ahead of general traffic

Variable name	Variable label	Description
		False = Not a cycle/bus gate
Traffic Calming		
TRF_RAISED	Raised Table	True = Raised table at junction False = Not a raised table
TRF_ENTRY	Side Road Entry Treatment	True = Side road entry treatment (raised in some way including continuous footway) False = Not a side road entry treatment
TRF_CUSHI	Speed Cushions	True = Speed cushions in line across road False = Not a speed cushions in line across road
TRF_HUMP	Speed Hump	True = Speed hump False = Not a speed hump
TRF_SINUSO	Sinusoidal	True = Hump or cushion is sinusoidal False = Not a sinusoidal hump or cushion
TRF_BARIER	Barrier	True = Barrier that cyclists can pass False = No barrier
TRF_NAROW	Carriageway Narrowing	True = Chicane, narrowing, build-out or other horizontal deflection to traffic flow False = No carriageway narrowing
TRF_CALM	Other	True = Other traffic calming measure False = No 'other' type of traffic calming

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Appendix B

Appendices to Paper 3 (chapter 4)

B.1 Strava edge data dictionary (Strava Metro, 2023)

Definitions:

- "Trip" counts indicate the number of bicycle or pedestrian trips on that edge during the given timeframe.
- "People" counts indicate the number of unique people who completed a bicycle or pedestrian trip on that edge during the given timeframe. For instance, 10 people may have completed 30 trips on an edge during the timeframe.
- "Forward" indicates trips travelling in the direction the street was digitized into OSM (from the first point of the line to the last point of the line).
- "Reverse" indicates trips travelling in the opposite direction the street was digitized into OSM (does not indicate wrong-way travel).

The exported Street (edge) level data contains the following columns:

- edge_UID – the identifier for the street block
- activity_type – the type of activity, e.g. (ride, walk)
- year-month-date-hour – one row per aggregated time frame in ISO 8601 format (YYYY-MM-DD-HOUR). In this format an hour value of 5 represents data between 5:00 am and 6:00 am local time as the field is formatted to the local time zone of the data export.
- osm_reference_id – refers to the OpenStreetMap (OSM) Way ID associated with that particular edge. In OSM, a way normally represents a linear feature on the ground such as a road, trail, or bike path. Due to the way edges are created for Strava Metro, many edges can have the same osm_reference_id.

For each row, the following count columns are provided:

Trip counts:

- forward_trip_count, reverse_trip_count
- forward_commute_trip_count, reverse_commute_trip_count forward_leisure_trip_count, reverse_leisure_trip_count
- total_trip_count, ride_count (meaning traditional bikes), ebike_ride_count (from Strava activities listed as ebike rides)

People counts:

- forward_people_count, reverse_people_count

People counts by Gender:

- forward_male_people_count, reverse_male_people_count forward_female_people_count, reverse_female_people_count forward_unspecified_people_count, reverse_unspecified_people_c

People counts by Age:

- forward_18_34_people_count, reverse_18_34_people_count
- forward_35_54_people_count, reverse_35_54_people_count
- forward_55_64_people_count, reverse_55_64_people_count
- forward_65_plus_people_count, reverse_65_plus_people_count

Average Speed:

- forward_average_speed, reverse_average_speed (metres per second)

B.2 Exclusion criteria for OpenStreetMap highways

We started with the OSM lines dataset. We removed any non-highways OSM lines that were coded as: “dam”, “lock_gate”, “gate”, “handrail” or “fence”.

We removed any highways that were coded as:

- Footway
- Steps

- Elevator
- Track (this is off road, mainly for agricultural vehicles)
- Proposed (as this means they have not been built)
- Construction (as this means they are under construction)
- Bridleways (as this as usually off road tracks for horse riders)

We removed any highways where the surface was coded as:

- Gravel, fine gravel, grit or loose-surface
- Dirt
- Grass or grass-paver

B.3 Roads with contraflow cycling introduced April 2018 to October 2019

The below tables list the one-way and two-streets that introduced contraflow cycling. The contraflow start date and notice ID come from the Traffic Regulation Orders that legally allowed the contraflow cycling. The actual orders can be accessed by appending the notice ID to https://www.thegazette.co.uk/notice/ , for example, https://www.thegazette.co.uk/notice/2999427 is the TRO for Trinity Crescent, Candahar Road, Furmage Street, Twilley Street and Temperley Road. More details such as the description of the contraflow spatial extent and actual spatial data can be accessed via the full dataset available from (Tait, 2022).

Saltram Crescent only appears once in Table B.1 as both sections had the same contraflow start date.

TABLE B.1: Existing one-way roads with contraflow cycling introduced

Road name	Borough	TRO contraflow start date	TRO notice ID
Trinity Crescent	Wandsworth	06 April 2018	2999427
Candahar Road	Wandsworth	06 April 2018	2999427
Furmage Street	Wandsworth	06 April 2018	2999427
Twilley Street	Wandsworth	06 April 2018	2999427
Temperley Road	Wandsworth	06 April 2018	2999427
Upper Marsh	Lambeth	29 May 2018	2824241
Hammersmith Grove	Hammersmith and Fulham	11 June 2018	3035229

Road name	Borough	TRO contraflow start date	TRO notice ID
St John's Park	Greenwich	06 August 2018	3080077
Cumberland Road	Newham	16 August 2018	2846585
Saltram Crescent	Westminster	11 September 2018	3048578
Norfolk Crescent	Westminster	19 November 2018	2745411
Clarence Terrace	Westminster	10 December 2018	2659170
Centaur Street	Lambeth	11 February 2019	3104035
Cosser Street	Lambeth	11 February 2019	3104035
Cubitt Terrace	Lambeth	11 February 2019	3104035
Hayter Road	Lambeth	11 February 2019	3104035
Sudbourne Road	Lambeth	11 February 2019	3104035
Hopton Road	Lambeth	11 February 2019	3104035
Magee Street	Lambeth	11 February 2019	3104035
Venn Street	Lambeth	11 February 2019	3104035
Ivor Place	Westminster	24 February 2019	2648991
Dorset Square	Westminster	24 February 2019	2648991
Melcombe Street	Westminster	24 February 2019	2648991
Aldworth Road	Newham	25 March 2019	2846585
Roehampton High Street	Wandsworth	13 April 2019	2918580
Drummond Street	Camden	01 July 2019	3268444
Meymott Street	Southwark	16 September 2019	3260316

Table B.2: Former two-way roads converted to one-way with contraflow cycling

Road name	Borough	TRO contraflow start date	TRO notice ID
Tanner Street	Southwark	05 March 2018	2918355
Old Jamaica Road	Southwark	01 June 2018	3034235
Thurland Road	Southwark	01 June 2018	3034235
Cliff Villas	Camden	30 July 2018	2984851
Glasshouse Street	Westminster	12 November 2018	3148658
Appold Street	Hackney	21 January 2019	3153817
Worship Street	Hackney	21 January 2019	3153817
Nuttall Street	Hackney	11 February 2019	3206808
Giffin Street	Lewisham	18 February 2019	3186754
Ivor Place	Westminster	24 February 2019	2648991
Laystall Street	Camden	11 March 2019	3139336
Burwood Place	Westminster	01 April 2019	3085582
Harrowby Street	Westminster	01 April 2019	3085582

Road name	Borough	TRO contraflow start date	TRO notice ID
Lower Addison Gardens	Kensington and Chelsea	15 July 2019	3153789

B.4 Additional figures

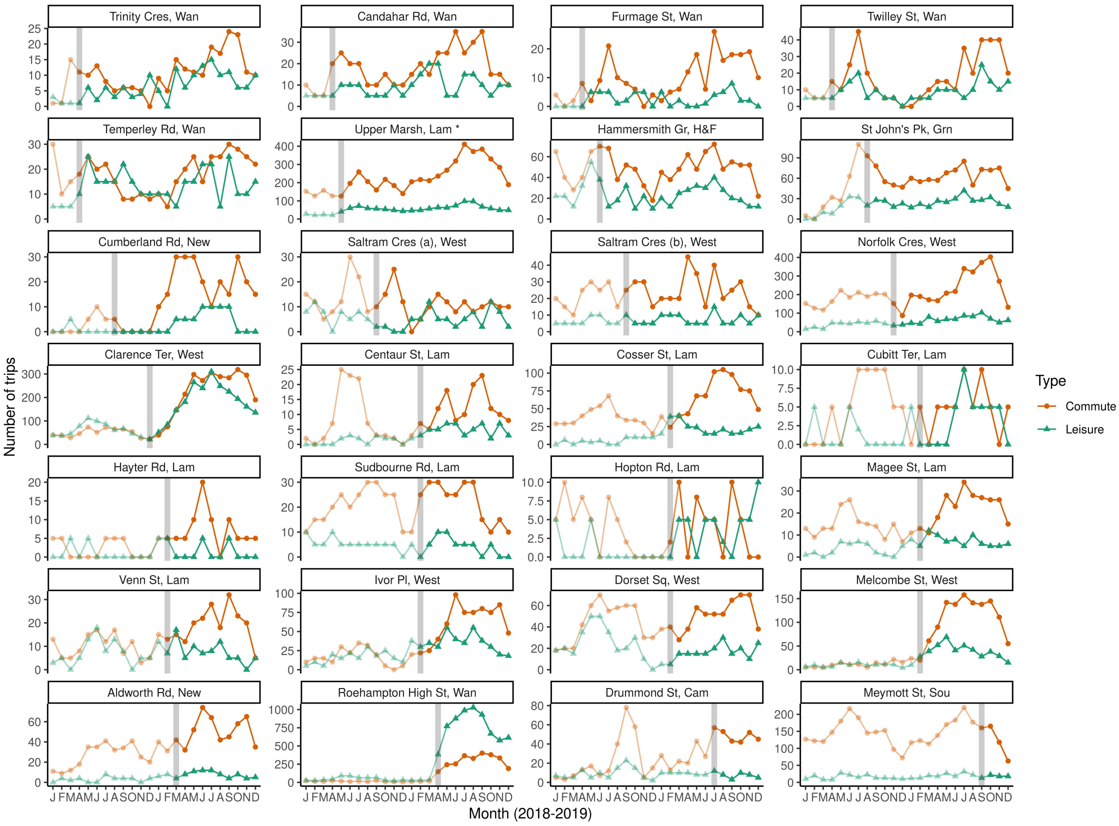

FIGURE B.1: Monthly variation in observed commute and leisure contraflow Strava trip counts on each former one-way road segments before (pale colours)and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

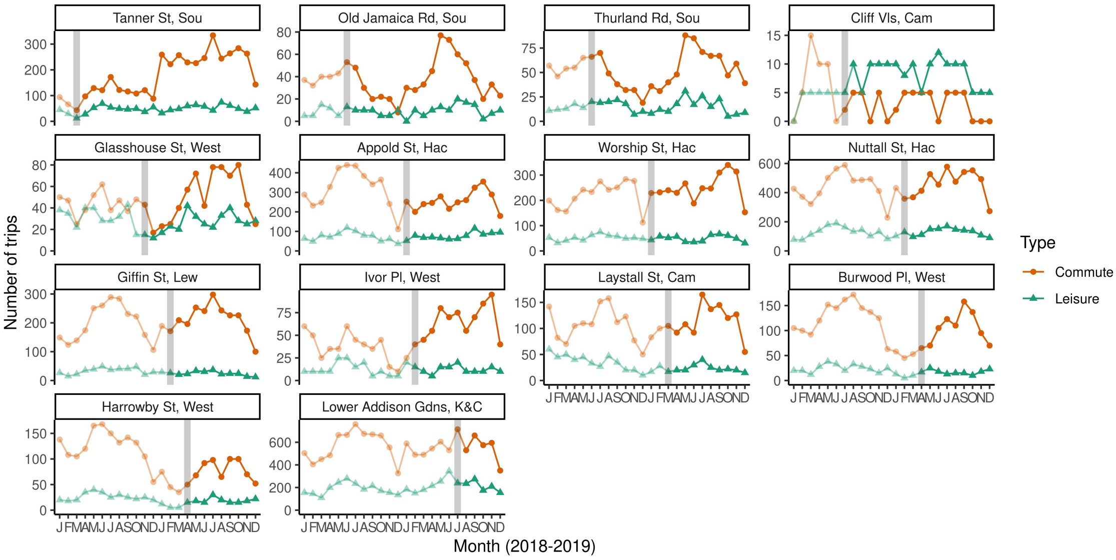

FIGURE B.2: Monthly variation in observed commute and leisure contraflow Strava trip counts on each former two-way road segments before (pale colours)and after (darker colours) contraflow introduction (month of transition shown as vertical grey line)

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Appendix C

Appendices to Discussion

C.1 Additional figure

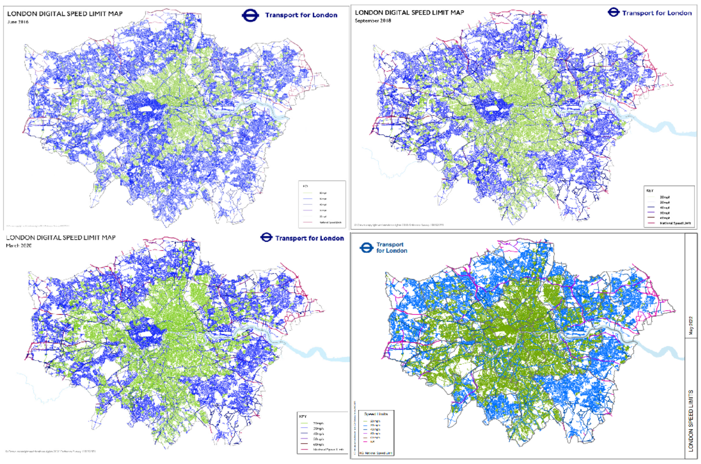

FIGURE C.1: London road speed limits 2016, 2018, 2020 and 2022 with 20mph roads coloured green (Mapping London 2020 & TfL 2022)

Mapping London 2020. Speed Limit Map. Available from: http://mappinglondon.co.uk/2017/speed-limit-map/?utm_source=dlvr.it&utm_medium=twitter

TfL 2022. London speed limits May 2022. Available from: https://content.tfl.gov.uk/london-digital-speed-limit-map.pdf