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The battle for kerbside space: An evaluation of the competition between car-hailing and bus services

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ABSTRACT

The kerbside of today is a complex environment with a huge diversity of uses and highly dynamic patterns of use, including for parking, (un)loading, EV charging, and bus stops. The competition for kerbside space is to become more fierce with the rising of car-hailing services (CHS) and soon the connected and autonomous vehicles (CAVs). The kerbside is an often overlooked yet critical urban infrastructure which requires better understanding of its varies uses and functions. In this paper, we examine the competition between CHSs and traditional buses on the use of kerbside lanes. More specifically, we investigate the relationship between the mode share of car-hailing and bus services, network congestion and the performance of bus priority strategies along a real-life bus corridor and quantify their effects through simulation modelling of a set of future scenarios. The results show that the increasing penetration of car-hailing services will negatively impact network performance due to the growing number of kerbside stops, while increasing the share of public transport can help mitigate this loss and improve network resilience. Additionally, bus improvement policies, such as bus lanes and faster boarding techniques, can effectively prevent the adverse effects of car-hailing on network speed. These findings demonstrate the importance of managing kerbside space in a range of scenarios and offer valuable insights to authorities and researchers for policy-making and modelling.

1. Introduction

Urban centres worldwide are undergoing significant transformations in their transport landscapes, due to digital innovations and emerging mobility options, which, while improving urban livability and sustainability, also pose substantial challenges in urban space management (Najmi et al., 2021; Shafiei et al., 2023; Timmer et al., 2023). A critical challenge is the growing competition for kerbside space, an example of which is between traditional public transport and emerging services such as car-hailing services (CHSs) who compete for limited resources of urban infrastructure (Wu et al., 2022). This competition reduces urban transport efficiency, leading to a decrease in attracting passengers and revenue generation (Bi et al., 2021; Ngo et al., 2021; Yang et al., 2023).

The kerbside space, or the area adjacent to the pavement or sidewalk, has long been an important and contested space in urban

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areas (Pu et al., 2017). As cities have evolved and transport modes have diversified, the use of the kerbside has expanded beyond just parking. Nowadays, it serves a range of functions, including loading and unloading, e-vehicle charging, cycling infrastructure, bus stops, taxi and CHSs (as illustrated in Fig. 1). This multi-functionality of kerbside space has also led to heightened competition and a rise in rule-breaking instances, which in turn leads hazardous conditions and reduced accessibility for kerbside (Hao et al., 2023; Liu et al., 2022).

Moreover, it is expected that future changes in new vehicles and modes of transport will only greatly increase the demand for using kerbside space. For instance, in San Francisco, 15 % of all trips are now made by CHSs, leading to a significant increase in the volume of pick-up and drop-off traffic by the kerbside (Clewlow and Mishra, 2017). In England, the number of licensed car-hailing vehicles reached 256,600 in 2023, keeping an annual growth rate of over 10 % (Department for Transport, 2024). Additionally, the kerbside is seen as a crucial resource for supporting charging infrastructure as part of the electric vehicle revolution (Gu et al., 2023).

The diverse and the dynamic of use of kerbside space calls for further research to understand these interactions and to support urban planners and policymakers in providing guidance and strategies to better manage them (Ramirez-Rios et al., 2023). Among them is to better explore and quantify the competition between CHSs and traditional public transport. Traditionally, kerbside lanes served public transport, or other equivalent mass transit services. By contrast, significant individualised shifts to CHSs will damage network performance in some areas due to increased volumes of stopping (for pick-ups/dropping-offs) (Gragera and Albalate, 2016). CHSs are potentially competing for the same passengers who would previously or otherwise have used buses (Bi et al., 2021; Wang and Qi, 2025). These changes are happening and are eroding the benfits of public transport investments such as contactless and mobile bus ticketing and traffic signal priority. While CHSs and private vehicles can outcompete buses in the absence of regulated street space (Hampshire and Shoup, 2018), the detailed impacts and role of regulatory strategies on such competition remain poorly understood.

This study seeks to fill this critical gap through a microsimulation modelling of travel patterns along a busy urban corridor, in order to understand and quantify the trade-offs between the growths of different user classes given their different stopping behaviours We aim to uncover not just the existence of these trade-offs between public transport and CHSs at kerb space, but also quantifying their impacts on urban transport efficiency under various scenarios. Specifically, this study analysed the competition between public transport and CHSs by adopting a simulation-based analysis of various scenarios representing the potential development of these modes of transport. By integrating empirical data with advanced simulation techniques, our research offers comprehensive insights into how changes in transport mode usage influence overall network performance, thereby informing sustainable urban planning and policy-making.

The remainder of this paper is structured to first outline our main objectives and research questions in Section 2, followed by a

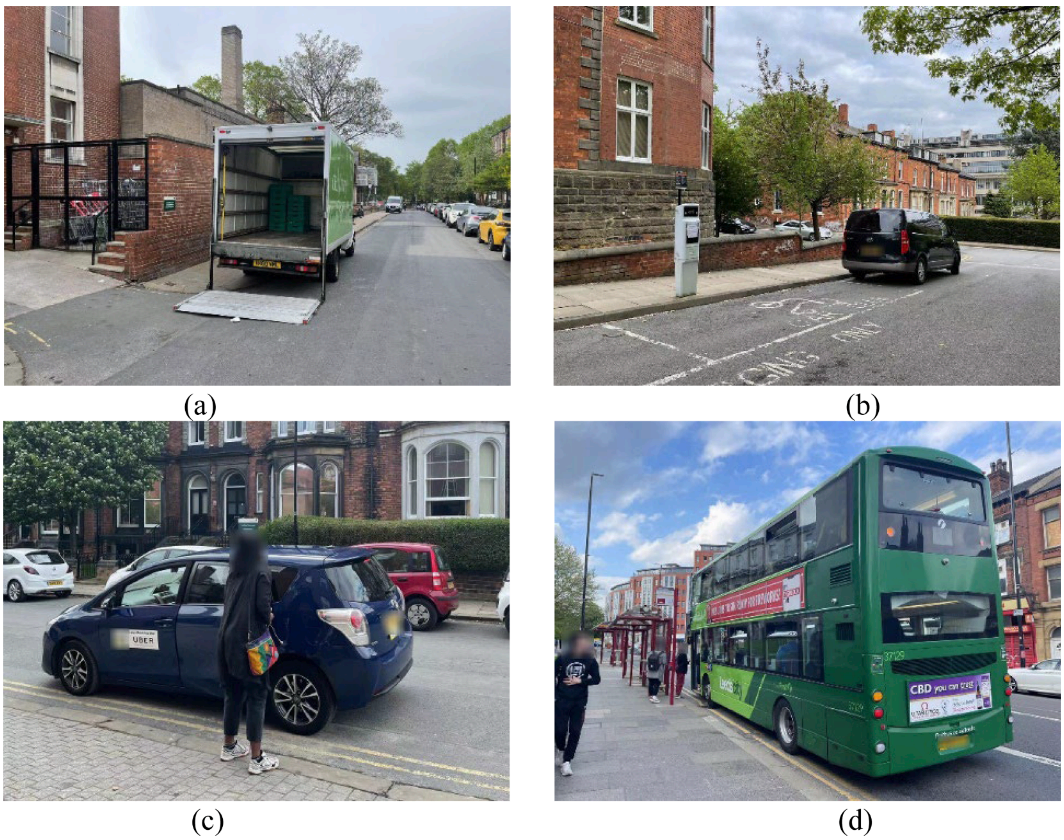

Fig. 1. The diverse uses of kerbside spaces: (a) goods delivery, (b) car parking and charging facilities, (c) pike-up/drop-off, and (d) bus stop.

review of relevant literature on kerbside management policies and findings of competition for kerbside spaces in Section 3. Section 4 describes the DRACULA-based simulation scenarios that support our study, and Section 5 presents the results. In Section 6, we discuss the implications of the competition between bus services and CHSs in using kerbside spaces. Finally, we provide concluding remarks in the last Section 7.

2. Research objectives

2.1. Main objectives

Given the complex challenges discussed in the introduction, such as the growing competition for kerbside space and the inefficiencies in urban road traffic, this study is motivated to thoroughly examine these matters under the increasing influence of digital innovations and mobility shifts.

The overarching objective of this study is to enhance the existing knowledge base by mapping out how technological advancements in transport, like CHSs, impact urban transport networks, particularly at the kerbside. This goal addresses the wider implications of evolving urban transport systems, considering the need for sustainable and efficient mobility solutions.

Complementing this broader perspective, the primary aim of this study is more focused. We seek to investigate the specific impact of various future mobility scenarios on urban transport networks, particularly examining the competitive use and management of kerbside space, i.e., the violated behaviour of kerbside parking on transport networks. This includes conducting a detailed simulation analysis of a transport corridor, which will incorporate public transport enhancement schemes, to model and examine the impact of different levels of technology/user interactions on public transport and network designs. In addition, we aim to explore how the transport network designs of a major city could be adapted to different transport infrastructures, such as additional bus lanes and faster boarding techniques. This focused investigation will allow us to analyse the impact of public transport improvement and priority on traffic performance. Moreover, this study is to contribute to the knowledge base regarding the future of transport networks, such as priority of bus lane and innovations of mobile tickets, and their interactions with changing transport modes, user behaviour and technology advancements.

The synergy between the overarching objective and the primary aim lies in how the detailed findings from the primary aim inform and contribute to the broader understanding of future urban mobility challenges and opportunities. While our study zeroes in on specific aspects like kerbside usage and public transport enhancements, the insights gained will have implications for the larger context of urban transport evolution. This approach enables us to address both the immediate, tangible impacts on urban transport and the broader, strategic considerations necessary for transitioning to a more connected, electric, and shared future.

2.2. Research questions

From these objectives, we derive specific research questions (RQ) that pinpoint the critical factors influencing urban transport dynamics, thereby guiding our simulation and analysis. These questions will be explored through scenarios designed in Section 4 and addressed in Section 5.

RQ 1: How does CHS penetration impact on the overall network velocity?

Is there an inverse relationship between the proliferation of car-hailing services (CHSs) and the mean velocity of the transport network? We aim to understand how an increase in CHS prevalence might affect the overall speed and efficiency of the network.

RQ 2: What is the impact of increased public transport utilisation on network efficacy?

How does escalating the utilisation of public transport, notably buses, influence the speed of the overall transport network? In our simulation, we examine the effects of varying mode shares among buses, private cars, CHSs, and taxis, with a particular focus on the operational dynamics of bus transport.

RQ 3: What are the effects of CHS penetration on bus velocity?

To what extent do CHS activities, including lane-changing and parking behaviours, adversely affect bus velocities? This question seeks to understand the specific challenges in maintaining efficient bus speeds in the face of increasing CHS activities.

RQ 4: How do bus improvement strategies affect overall network performance?

In scenarios with significant CHS utilisation, how might bus improvement strategies, such as reducing dwelling times and introducing dedicated lanes, inadvertently impact the performance of the entire transport network? This question explores the potential unintended consequences of strategies aimed at enhancing bus efficiency.

3. Literature review

We present in this section, the relevant literature that examines the relationship between public transport and CHS in their competition for kerbside space and effects on the urban transport system. The focus is on the past studies that analyse the impacts of CHSs on public transport and the overall road network, as well as the current regulations governing kerbside space management. Additionally, it explores the technologies currently used for kerbside parking management.

3.1. Impacts of car-hailing services on bus services and other urban transport

The emergence of CHSs have exerted a profound impact on urban transport systems. Extensive research demonstrates that these services have reshaped the travel behaviours of city dwellers, while simultaneously presenting new challenges for traffic congestion, the demand for urban space, and environmental sustainability (Tirachini, 2020; Wu and Xu, 2022). For instance, Wang and Yuan (2024) observed a significant increase in traffic flow in urban areas due to the rapid expansion of CHS, leading to debates on how traditional traffic control policies could mitigate their detrimental impacts on urban transport efficiency. Zhai et al. (2019) indicated a change in the travel mode preferences of urban residents, particularly among the youthful and educated populations. Furthermore, Zhong et al. (2020) discovered that CHS adversely affect private car usage in Chinese cities, with the impact varying over time and across different urban regions.

In multiple aspects such as market presence and operations, CHSs are in direct competition with public transport services, significantly influencing the latter. Studies from Indonesia (Irawan et al., 2020) and Ghana (Acheampong et al., 2020) indicate CHSs gradually replacing traditional taxis and public transport. Lehe and Pandey (2020) modelled demand curves to find that congestion might shift users from high-occupancy to low-occupancy modes, and further analysed the dynamic feedback and equilibrium states between average vehicle speed and public transport demand (Pandey and Lehe, 2023). Concurrently, Wu et al. (2020) observed that ride-hailing platforms' pricing mechanisms, influenced by regional disparities and temporal factors, lead to fluctuations in public transport demand across different areas and times. Liu et al. (2020) indicated that an increase in CHSs during subway disruptions could reduce the reliability of public transport.

These studies collectively highlight how CHSs are impacting public transport, whether by directly encroaching on the public transport market or by indirectly influencing commuters' preference for CHSs through their impact on the overall network's capacity. However, existing literature primarily investigates this competition at a macro level, focusing on overall demand and network perspectives. There is a dearth of research employing simulations based on the distinct operational characteristics and regulations of car-hailing and public buses to understand their micro-level competitive behaviours on the roads and analyse their implications.

3.2. Regulations of utilising the kerbside space

Regulations for managing access to the kerb currently allow for loading and unloading, as well as different uses of the kerb through stopping, waiting, and parking at various times of the day. These policies have been in place for a long time and have been designed to accommodate the needs of different stakeholders such as pedestrians, cyclists, public transit, and vehicles. It is important to acknowledge that the kerbside in urban areas have already posed more complex management challenges due to its dynamic patterns of use (Liu et al., 2023).

Cities worldwide have adopted various strategies to address this challenge. Recent international developments in kerbside space management provide insightful examples. Seattle, for instance, adopted "flex zones," a policy that adapts curb space usage according to the specific needs of each street corridor, thus enhancing the efficiency of various transportation modes including buses. This policy shift acknowledges the multifunctional nature of kerbside space, balancing the requirements of different users. San Francisco's approach to cyclist safety through 'parking-protected bike lanes' is another innovative use of kerbside space. Here, bike lanes are positioned between the sidewalk and parked cars, offering protection to cyclists and reorganizing the street layout to better accommodate different modes of transport (San Francisco Municipal Transportation Agency, 2020). Barcelona's strategy involves charging for kerbside parking and distinctly marking spaces for mixed-use or resident-only, effectively managing parking demand and ensuring optimised use of kerbside space (Albalate and Gragera, 2020). Finally, the London Borough of Lambeth's Kerbside Strategy aims to transform 25 % of kerbside space from vehicle parking to sustainable uses. This initiative prioritises active travel, social spaces, and climate resilience, showcasing a commitment to repurposing kerbside space for broader urban benefits beyond car parking (Lambeth Council, 2023).

The intense competition for kerb space comes as no surprise, given the limited availability of kerbside space, particularly in urban centres. Widespread non-compliance with traffic regulations, designed to manage street usage, has been observed (Marsden et al., 2019). For example, pavement parking impedes the use of bus stops and cycle lanes. In Manhattan, it has been observed that the occupation of kerb space by taxis and trucks often forces other users, such as buses, to travel in lanes designated for general traffic (King and Saldarriaga, 2018).

With the advent of new technologies and mobility services, the demand for kerb space is expected to increase significantly and the traditional kerbside management policies need to be re-evaluated to address current and future needs.

3.3. Techniques for managing the kerbside parking

Parking is one of the main demands on the use of kerb space. It has been argued that kerbside parking is often considered as an effective means to alleviate parking shortages in urban areas and reduce the need for suburban parking garages (Arnott and Rowse, 2009; Biswas et al., 2017; Brooke et al., 2019; Chen et al., 2016). Researchers have studied the capacity and location of kerbside parking, examining the influencing factors such as land use, car ownership, and seasonality, and have developed various modelling tools to investigate their correlations and impacts (Parmar et al., 2020; Zong and Wang, 2015). However, it has also become clear that the increasing kerbside parking may cause traffic congestion and heightened pollutant emissions due to the extra time and fuel spent searching for a parking space (Anderson and de Palma, 2004; Cao et al., 2017). In addition, the manoeuvring of vehicles in and out of parking spaces poses risks to road safety (Agbelie, 2020). In this regard, some researchers have modelled parking behaviours and developed advanced algorithms to guide the parking search process, such as Ji et al. (2015) employed the wavelet neural network model to predict available parking spaces.

Parking fees have also been explored as a means to regulate demand for kerbside parking. Gu et al. (2021) have shown that proactive pricing approaches that use predictive capabilities are more effective than feedback pricing approaches. Wang et al. (2020) have used field-collected panel data to investigate the time-varying effect of pricing on on-street parking characteristics, including parking duration and turnover, before and after implementing a new parking pricing policy in Nanning. Advanced parking pricing systems have been successfully implemented in the Netherlands and San Francisco, where they are shown to significantly reduce the searching and cruising times (Alemi et al., 2018; van Ommeren et al., 2012). A survey by Mo et al. (2021) has shown that higher parking prices can shorten the distance between parking lots and final destinations, freeing up more parking spaces and increasing overall parking satisfaction. Shoup (2023, 2021) suggests using kerbside spaces for market-priced parking to improve traffic flow and reduce pollution. This strategy can also turn the private cost of searching for parking into public revenue for better services.

The issue of kerbside parking has become increasingly problematic and difficult, leading to a rise in illegal parking and the scarcity of road space (Kurnicki, 2022). Such encroachment of kerbside space is at the expense of the rights of other road users. Studies by Marsden et al. (2020) and Wang et al. (2022) have noted that advanced mobility services such as car-hailing, door-to-door delivery, and demand-responsive buses will further increase the demand for kerb access. Based on an analysis of cases in Germany, Taylor (2021) suggested that the government should impose restrictions on the right to kerbside parking. However, Docherty et al. (2018) argued that restricting the free use of kerbs by car-hailing vehicles and taxis might potentially infringe on the interests of passengers who require door-to-door service.

In summary, current research predominantly focuses on the competition for kerbside space between emerging transportation modes under the shared economy paradigm, such as CHSs, and public transport. The general consensus acknowledges the existence of this competition, directing attention towards exploring various management strategies to address it. Additionally, existing studies tend to concentrate only on singular aspects of kerbside space competition, such as the impact on parking sources.

3.4. Research gaps

After reviewing existing research, we have identified several research gaps pertaining to the competition for kerbside space usage between car-hailing services and buses.

- Although the present of competition for kerbside space between emerging transport modes (e.g., CHSs) in the sharing economy and tranditional public transport is widely recognised, there is a stark lack of quantitative analysis detailing the nature of this clash and its consequential impacts. Existing studies typically acknowledge the issue only in broad terms, without offering the varying impact levels under different conditions. This oversight may potentially limit the precision needed for relevant model calibration and policy formulation.
- The current collection of research primarily focuses on improving the management of roadside parking in limited space, often neglecting to consider the wider consequences, such as how parking behaviours including lane changing and stopping affect the overall effectiveness of urban transport networks. This limited perspective fails to acknowledge how these behaviours impede the smooth flow of traffic and impact the effectiveness of various road users.
- There is a lack of empirical, dynamic analysis that effectively captures the transition from current states to future equilibria in predicting future traffic conditions, despite the existence of numerous theoretical models. Agent-based micro-simulations play a crucial role in this context, as they enable the modelling of gradual changes and interactions among various transport modes over time.

As competition for kerbside space intensifies, this study aims to fill the existing research gaps and achieve its set objectives. By utilising the reliable trend of future travel demands and considering different traffic management measures, we have constructed various potential scenarios from the present to the future. Employing the micro-simulation technology, this research simulates the competition for kerbside usage between CHSs and buses, providing a quantitative analysis of the overall network efficiency and the impact on all transport participants.

4. Microsimulation modelling

To attain the research objectives, this study employs an established transport microsimulation tool called DRACULA, developed in-house at the University of Leeds (Liu, 2010), to conduct a thorough analysis of the impact of car-hailing and bus services on kerbside parking behaviour in an urban road corridor. Through this microsimulation analysis, the study aims to provide a comprehensive understanding of the complex interactions between these factors and their effects on the overall transport network.

4.1. Case description

The Oakwood corridor, encompassing Roundhay Road and Easterly Road in the northeast of Leeds (as shown in Fig. 2), has been selected as the network model for this study due to its unique context and diverse infrastructure and transport services. Specifically, it presents three distinct transport characteristics: (1) a corridor network featuring high-quality bus services and a high level of public transport patronage; (2) a city centre network boasting a broad range of mobility options; and (3) a market town with narrow streets and limited bus-priority infrastructures. This corridor, a key component of urban transport infrastructure, connects city centres to their residential outskirts. It serves a dual purpose, accommodating both leisure and commuting needs, and epitomises the demand patterns and service capabilities typical in urban areas. Often a bottleneck for traffic congestion, this corridor mirrors the challenges faced by

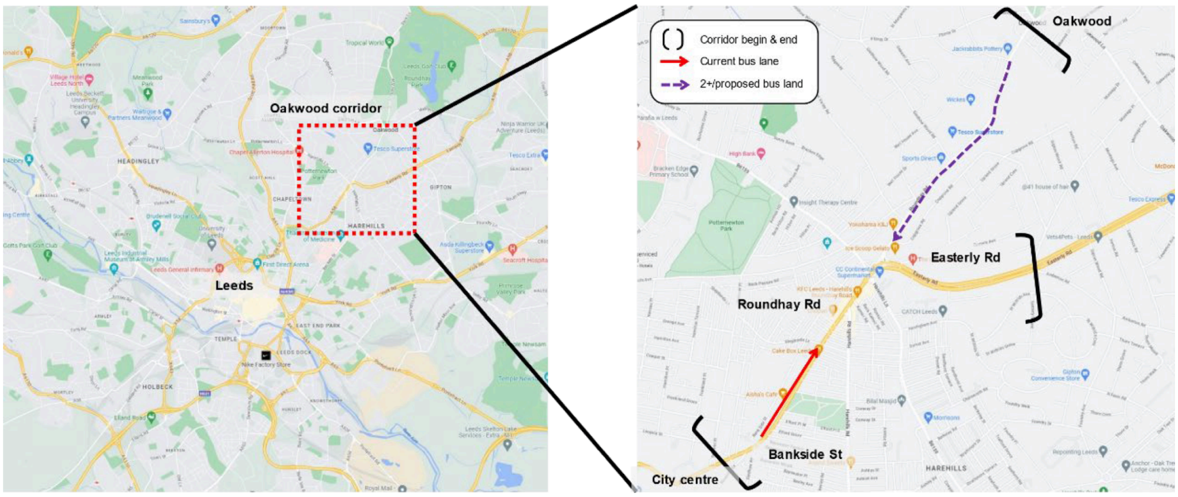

Fig. 2. The case study of Oakwood corridor in Leeds.

urban mobility systems.

The Oakwood corridor is one of the Connected Leeds Corridors,[1] with plans to convert a current 2+ lane in the north of Roundhay Road to an extended bus lane. The corridor is well-served, with 16 bus routes operating at frequencies ranging from one every eight to 45 min. Most parts of the corridor operate as two lanes in each direction, with a speed limit of 64 km/h (40 mph) in the outer region, and reduced to 48 km/h (30 mph) towards the city centre.

It is important to note the specific regulatory framework governing buses in the UK, which varies from regulations in other countries and can influence the number of buses operating in these corridors. In the UK, regulatory practices often shape minimum bus service availability and frequencies. This ensures that there is significant coverage, even in areas with lower population density. Our case study focuses on this corridor due to its representation of common urban transport issues. It provides a comprehensive understanding of how kerbside parking behaviour is impacted by various transport infrastructures and services, which makes the Oakwood corridor an ideal case study. We aim to derive insights applicable to various urban settings with similar traffic dynamics, enhancing understanding of urban mobility for improved traffic management and urban planning globally.

4.2. Building up a microsimulation network

To model the Oakwood corridor, a DRACULA microsimulation model was developed (see Fig. 3). The road network and the base traffic flow were extracted from a Leeds traffic model for the morning peak period between 08:00–09:00. Bus routes, stops, and frequency data were obtained online from the West Yorkshire Metro,[2] while passenger flow at bus stops was estimated from an earlier manual survey conducted at bus stops along Easterly Road. This forms the base-year model of the corridor and was calibrated against the full traffic network model of Leeds.

Parking demand, including the time and location, is randomly generated from the parking generation model. The regulation of parking for different kinds of vehicles will be introduced in detail in the next section. The traffic model is based on an explicit simulation of individual vehicles' car-following and lane-changing behaviours and a newly developed parking behaviour model, as illustrated in Fig. 4. Where parking is required, the vehicles would move the kerbside lane and stop at the locations and for the durations as generated above. Finally, the outputs of the simulation models will be analysed.

4.3. Base-year scenario design

The microsimulation model used in this study was calibrated against the Leeds traffic model and was found not to be overly congested as it uses the data from the survey in 2010. The base travel demand has a total of 6000 person-trips for the morning peak hour. This reflected a desire to have a relatively simple corridor for illustrative purposes but to test the sensitivity of the network under the more congested conditions which would be found closer to the city centre. The base-year mode shares of people who drive, take a taxi, or take buses were modelled as 75 %, 5 % and 20 %, respectively.

The 20 % of base passenger flows yields an average of 50 passengers per hour boarding flow at bus stops, which corresponds well with the earlier survey results on Easterly Road. The simulation assumes that passenger alighting coincides simultaneously with boarding and that bus dwell time is primarily dominated by passenger boarding. The bus dwell time is modelled as a function of the

[1] https://a58qtc.commonplace.is/.
[2] https://www.wymetro.com/buses.

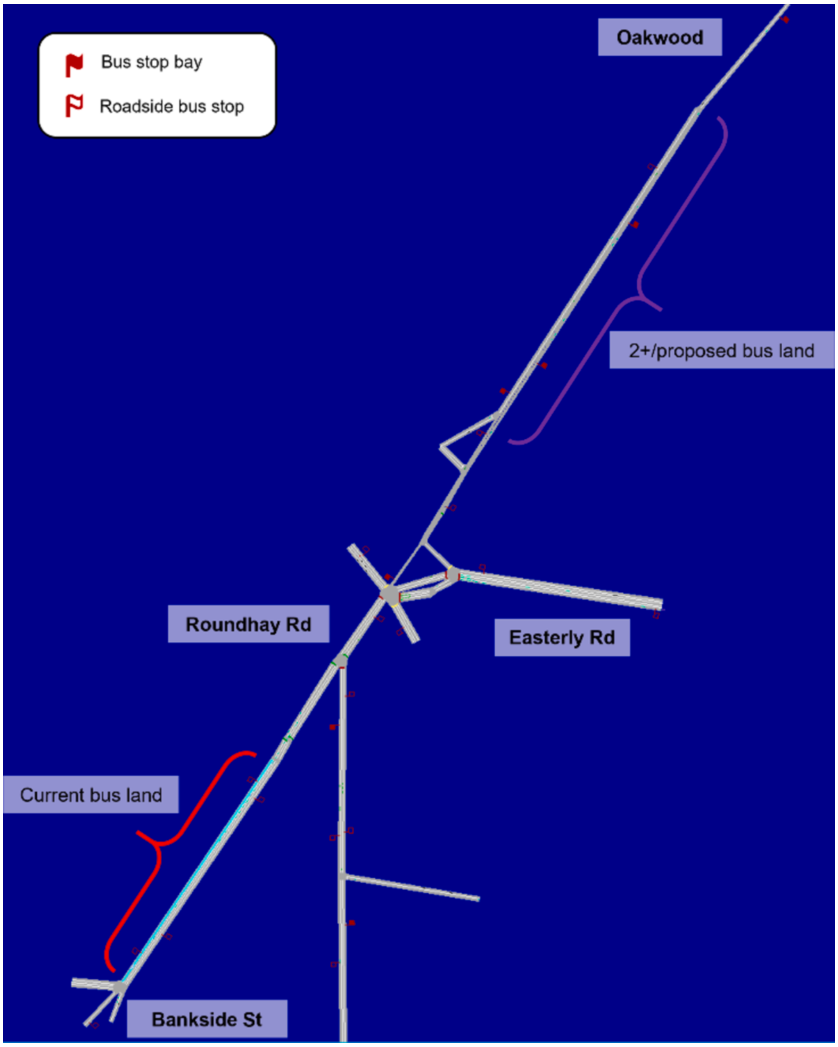

Fig. 3. The screenshot of DRACULA model showing the road infrastuctures and bus services within the Oakwood corridor in Leeds.

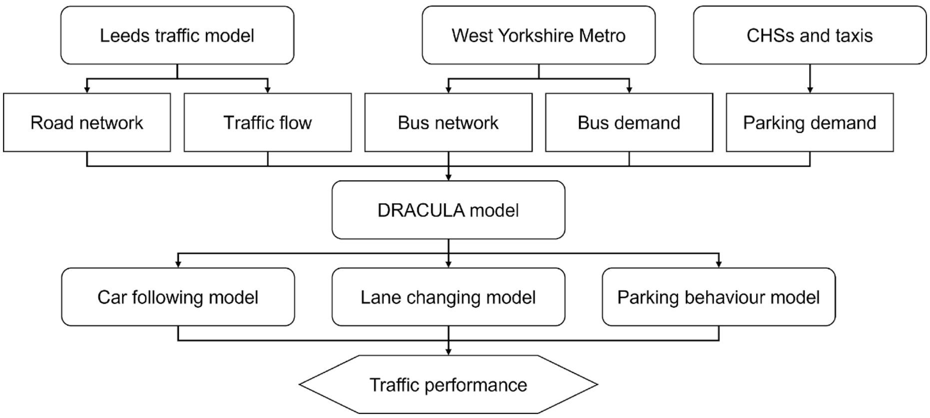

Fig. 4. The flow chart of the DRACULA simulation model.

number of waiting passengers, and the model uses a boarding time of 4 s per passenger on average for the entire simulation. A part of key parameters, related to the stopping behaviour of CHSs, taxis and buses, are listed in Table 1.

We used DRACULA defaults for general parameters like taxi stopping times (Liu, 2010). Bus-related parameters were derived from our earlier manual survey, ensuring real-world accuracy. We cross-validated these with parameters from studies by Fernández et al. (2009) and Tirachini (2013). For CHSs, assumptions were made based on their operational characteristics, particularly in relation to stopping times. These assumptions were informed by the streamlined boarding and alighting processes of CHSs, contrasting with traditional taxi services, as there is usually no need for discussing the destination or handling payment at the time of boarding or alighting.

For taxi and CHSs, the model assumes that they each stop once for either pick-up or drop-off of passengers, with a randomly generated stopping location. As with the general traffic regulations, taxis are allowed to drive in bus lanes, whilst CHSs are not. Both taxis and CHSs are allowed to stop in bus lanes for pick-up and drop-off, but not at bus stops. These assumptions for pick-up and drop-off represent areas with high demand where these services are most intensively used.

4.4. Simulation scenario designs

To accurately simulate future transport networks and their interactions with technology and road users, several key simulation variables can be manipulated, including the mode-share of transport (such as private cars, taxis, and CHSs) and public transport passenger demand, both currently and in the future. In addition, the simulation can incorporate innovative techniques and infrastructures in public transport systems, such as fast boarding techniques and bus lane policies. These variables are crucial to understanding the potential impacts of changes in transport infrastructure and technology on kerbside parking behaviour in urban areas.

4.4.1. Different share of mobility

In this section, we examine the dynamic interplay between CHVs and traditional transport modes by the network performance corresponding to the increase in CHV users. In this set of scenarios, we keep the total demand of 6000 trips and the 300 (5 %) taxi trips constant. We simulate scenarios where CHVs increasingly capture market share from buses and private vehicles. Fig. 5 illustrates the mode-share percentage in different simulation scenarios. We consider three situations where CHS users may switch from using only buses, private cars, or both. Each situation is simulated at different levels of CHS penetration, ranging from 5 % (300 trips) to 25 % (1500 trips) in increments of 300 trips. These scenarios are based on the observation that some cities have already reached a point where 15 % of trips are by CHSs, and this number is even higher in more central areas.

As presented in Table 2, we calculated the cross-elasticity of CHS demand with respect to time changes in private cars and buses (Dodgson, 1986; Wardman et al., 2018), where the own elasticity adopted the *meta*-analysis in UK (Wardman, 2012). As CHS penetration increases, the sensitivity to time changes for users shifting from private cars and buses is decreasing, particularly for those from buses. Hence, our scenario setup showcases a potential future where travellers increasingly rely on the CHS, even if we enhance the speed or reduce the travel time of other transport modes, especially buses (Tirachini, 2020).

4.4.2. Increasing CHS demand in the future

We plan to conduct a study to investigate the impact of the growth in CHS users on network performance. We analyse three potential future situations that reflect the growth of CHS users from 5 % to 25 % of total demand, as well as different bus demand scenarios.

- **Same bus demand** assumes that the public transport system would not be able to attract more passengers in the future, so the absolute number of bus trips would remain the same as the base-year scenario at 1200 passengers. The additional 1200 demand would then be added to the sum of private car and CHS trips.
- **Same bus-share** assumes that the future public transport system would have the same attractiveness as the current one, resulting in the same 20 % of total demand (1440 passengers) using buses.
- **Doubling bus demand** assumes that public transport demand would double to 2400 passengers, accounting for 33 % of total demand. This scenario is derived from Leeds City Council's target of achieving a doubling in bus use in the next decade. Private cars and CHSs would then share the remaining 62 % of total demand.

Table 1
Selected key parameters modelling the vehicles' stopping behaviour used in DRCULA.

Transport modes	Parameters	Default setting
CHSs	Stopping time	10 s per stopping
Taxis	Stopping time	30 s per stopping
Buses	Ticket-purchasing and boarding time	4 s per passenger
	Boarding time for season-ticket holders	1 s per passenger
	Time for door opening and closing	5 s per bus stop
	Percentage of passengers using fast-boarding	30 %

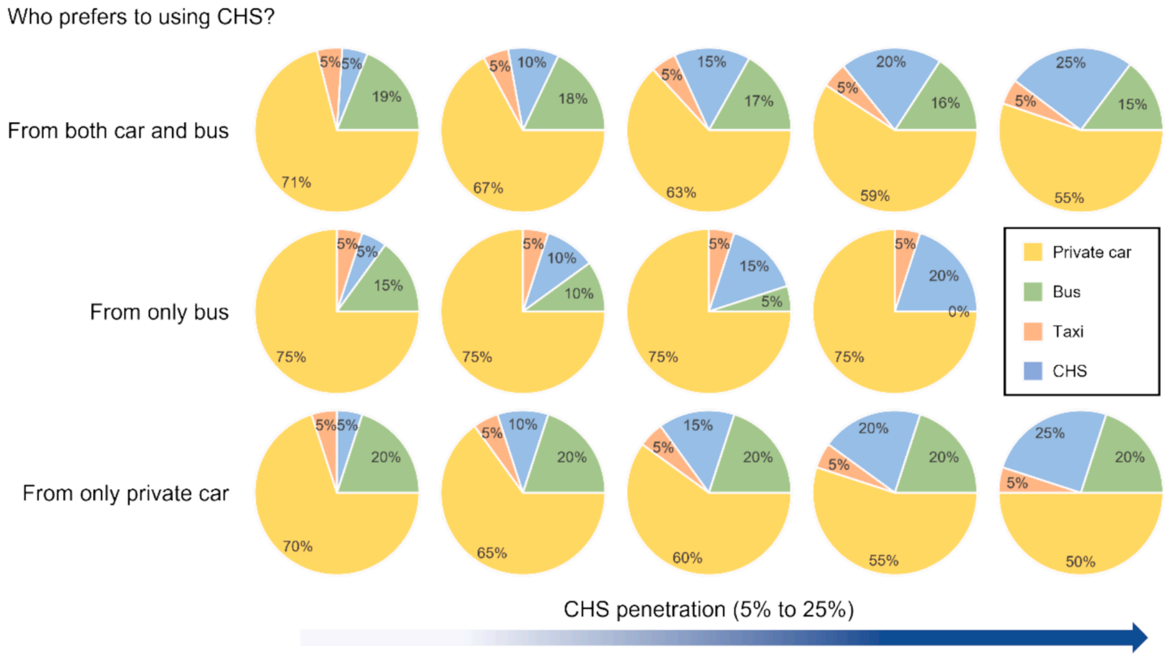

Fig. 5. The mode-shares of different simulating scenarios.

Table 2
The cross-elasticity of car-hailing demand with respect to time under different scenarios when assessing the shift from private cars or buses to CHSs.

Mode shift	From private car and bus		From private car	From bus
Mode affected	Private cars	Buses	Private cars	Buses
CHS penetration (%) 5	0.224	0.126	0.280	0.473
10	0.212	0.119	0.260	0.315
15	0.199	0.112	0.240	0.158
20	0.187	0.105	0.220	–
25	0.175	0.098	0.200	No scenario

Under the above situations, we design various scenarios with different growth rates for CHS trips from 0 % to 25 % of total demand. Thus, any change in the tested mode share in CHS or bus patronage would result in a different level of car traffic being simulated. Table 3 presents the share of mobility by transport modes that we tested in different simulation scenarios. Whilst the scenarios are not underpinned by a behavioural model, we consider them to be representative of a potential future, in which efforts to increase public transport use may or may not be successful.

4.4.3. *Bus improvement policy*

As part of the public transport improvement project in Leeds, we have investigated the potential impacts of a bus improvement policy on network performance. The policy would involve implementing an additional bus lane (indicated by the purple dash line in Fig. 2) and a faster boarding technique, reducing the average boarding time from 4 s to 2 s per passenger. The construction of the bus lane is part of the larger Connected Leeds Corridors project. Faster boarding technique refers to the reduction in the duration at passengers' boarding, achieved through fast payment systems (e.g. pre-paid tickets and tapping cards) or all-door boarding, directly enhancing the speed of public transport services. The faster boarding time is based on boarding time experiments conducted by First Bus in Bristol.

We have applied these innovations to the simulated scenarios presented earlier. These scenarios are presented in Table 4.The first

Table 3
Simulation scenarios (with a total of 7,200 trips and fixed 5% of taxis).

Situations	Bus patronage	Increasing CHS trips					
Same bus demand	17 % (1,200)	0 % (0)	5 % (360)	10 % (720)	15 % (1,080)	20 % (1,440)	25 % (1,800)
Same bus share	**20 %** (1,440)						
Doubling bus demand	33 % (2,400)						

group of scenarios is based on the current total demand and includes the base-year and "From only private car" scenarios. These are used to test the potential impact of implementing the bus improvement policy now. The other two groups of scenarios are designed to simulate the potential network performance under a future bus improvement policy. The "Doubling bus demand" scenario assumes that the bus improvement policy attracts more passengers, leading to a doubling of public transport demand to 2400 passengers, while the private car and CHS modes share the remaining 62 % of total demand. In contrast, the "Same bus-share" scenario assumes that the bus improvement policy has the same level of attractiveness as the current system, resulting in the same 20 % of total demand (1440 passengers) using buses.

5. Analysis of the simulation results

The section presents the analysis of the simulation results, and from which to draw insights into the potential effects of different scenarios on the performance of the transport network. Specifically, the results focus on three key areas: (i) the impact of different shares of mobility; (ii) the effects of increasing demand in the future; and (iii) the potential benefits of bus improvement policies. By analysing these scenarios, this study aims to identify the critical factors that will determine the success of the kerbside of the future.

5.1. Different share of mobility

Fig. 6 displays the variations in the average network speed (y-axis) in relation to the increasing proportion of CHSs (x-axis) in three simulated situations of different sources of CHS users. The base-year scenario, in which no CHSs are in use, is marked by a circle on the left. We included the greenhouse gas emission and the total queuing delay for our simulation scenarios in Figs. A1 and A2 for considering broader social benefits. These figures show trends completely opposite to those in Fig. 6, thus leading to consistent conclusions with our speed analysis.

Overall, the increased use of CHSs has resulted in a reduction in the average speed of the network, with the most significant reductions between 15 % and 20 % in CHS-shares. The scenario in which CHS users switched from buses (green dash-dot line with triangle dots) resulted in the most significant decrease in speed, with an average speed reduction of 47.3 % from 36.29 km/h to 19.12 km/h, while the reductions in "from car and bus (purple dashed line with circular dots)" and "from car (yellow solid line with square dots)" were 31.8 % and 13.7 %, respectively. The "from car" scenario differs from the base-year scenario in that only some private cars have been replaced with CHSs. It is reasonable to believe that the kerbside pick-up and drop-off activities of CHSs pose a threat to the entire corridor. Additionally, the more individuals use CHSs or drive private cars, the lower the average network speed.

In general, our results illustrate the broader effects of increased stopping behaviour on network performance. Illegal parking and additional freight and servicing demands that cannot be supported by existing or outdated infrastructure add to this pressure. The rise in short- and medium-term kerbside access uses could exacerbate this problem, endangering overall network efficiency unless proactive measures are taken. The government faces a challenge in balancing the benefits of ride-sharing services like CHSs with the potential harm they can cause to the network. While it is clear that CHSs are here to stay, their growth and increasing use must be managed to avoid damaging the overall performance of the network. The development of MaaS and Internet technology has driven the demand for CHSs, but promoting shared modes of transport could be a more sustainable way forward. Therefore, it is crucial for authorities to consider how to guide the development of CHSs and other ride-sharing methods to ensure a well-functioning and

Table 4
The selected scenarios for examining the impacts of bus improvement policy.

Scenarios	Basic network	Total demand	Mode-share			
			Private car	Taxi	CHS	Bus
Current demand	Base-year	6,000	75 %	5 %	0 %	20 %
	From only private car (Section 4.3.1)	6,000	70 %	5 %	5 %	20 %
			65 %		10 %	
			60 %		15 %	
			55 %		20 %	
			50 %		25 %	
Increased demand with same bus-share	Same bus-share (Section 4.3.2)	7,200 **(20 % ↑)**	75 %	5 %	0 %	20 % **(1,440)**
			70 %		5 %	
			65 %		10 %	
			60 %		15 %	
			55 %		20 %	
			50 %		25 %	
Increased demand with doubling bus demand	Doubling bus demand (Section 4.3.2)	7,200 **(20 % ↑)**	62 %	5 %	0 %	33 % **(2,400)**
			57 %		5 %	
			52 %		10 %	
			47 %		15 %	
			42 %		20 %	
			37 %		25 %	

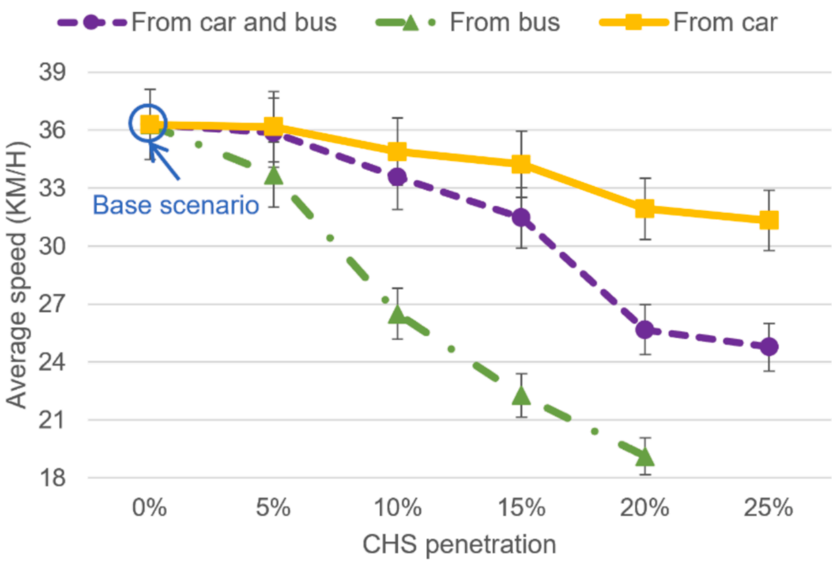

Fig. 6. Impact of increasing CHSs on the performance (average network speed) of the entire network for different sources of CHS users.

efficient transport network.

5.2. Increasing demand in the future

The simulation results for various scenarios with different shares of mobility are depicted in Fig. 7 and Fig. 8. Fig. 7 presents the average network speed concerning the increasing proportion of CHSs, with dotted, dashed and solid lines, coloured from light to dark, representing the three levels of bus patronage simulated, as per Table 2 (i.e., 17 %, 20 %, and 33 %). The average network speed in the base year is represented by a dotted line at the top of the figure.

The simulation reveals that increasing the bus mode share, at the expense of private car traffic, significantly enhances the network benefits for all users. For instance, an increase from 20 % to 33 % in bus patronage with no increase in CHSs (i.e., staying at 0 %) raises the average network speed from 21.2 km/h to 34.1 km/h. It is natural that, with fewer people driving or taking taxis or CHSs, the average traffic speed increases. The results demonstrate that increasing the bus mode share at the expense of private car traffic provides substantial network benefits to all users.

However, the increasing proportion of CHSs reduces overall network speed. This highlights the negative impact of individualised

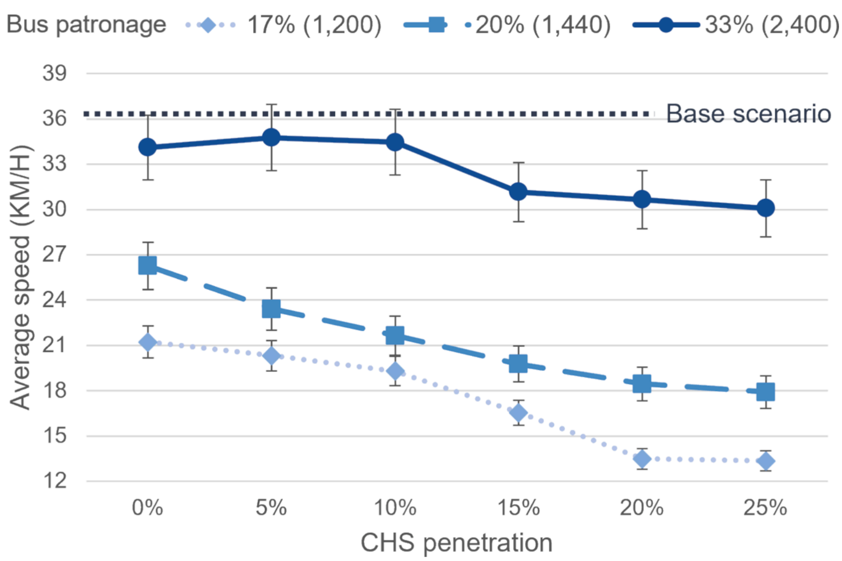

Fig. 7. Impact of increasing CHSs on the performance (average network speed) of the entire network for different levels of bus passenger demand (as a proportion of the total demand).

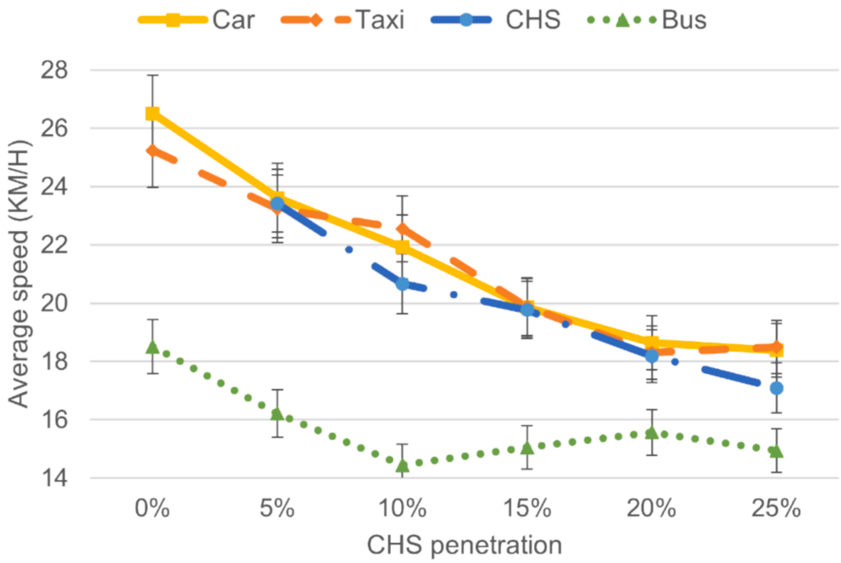

Fig. 8. Impact of increasing CHS on the average travel speed of different types of vehicles when the bus demand is at 20%.

vehicles on the collective benefit of public transport. It is worth noting that, at low bus patronage (i.e., at 17 %), the harm of increasing CHS penetration is more intense than at high bus patronage (i.e., at 33 %). At the high bus patronage of 33 %, the average speed remains a good running level (greater than 30 km/h), even though the values have dropped slightly by 17 % and 11.8 % compared to the base-year and 0 %-CHS scenarios, respectively.

In contrast, the network's performance deteriorated significantly, to an average speed below 15 km/h when 25 % CHSs and 17 % bus users were present. Although the exact effects may vary slightly between scenarios, a 5 % increase in CHS results in a 7 %, 6 %, and 2 % reduction in average speed for 17 %, 20 %, and 33 % of bus-share respectively, due to the additional stopping behaviour and their impact on other traffic.

Overall, the simulation results show that a shift towards public transport, particularly buses, can provide significant network benefits to all users by increasing the average traffic speed. It is suggested that there is a need to prioritise and promote the use of public transport, particularly buses, as an effective means of reducing traffic congestion and improving network speeds.

Fig. 8 provides a breakdown of the effects on different modes of transport for the scenario with 20 % bus patronage. It is worth noting that the average speeds of buses have taken into account bus dwell time, which explains why they are significantly lower than those of the other three vehicle types. Buses are represented by green dashed lines with triangles, CHS by blue dotted lines with circles, taxis by orange dashed lines with diamonds, and cars by solid yellow lines with squares.

The result of Fig. 8 indicates that the negative impacts of increasing CHS mode share on the average speeds of different modes of

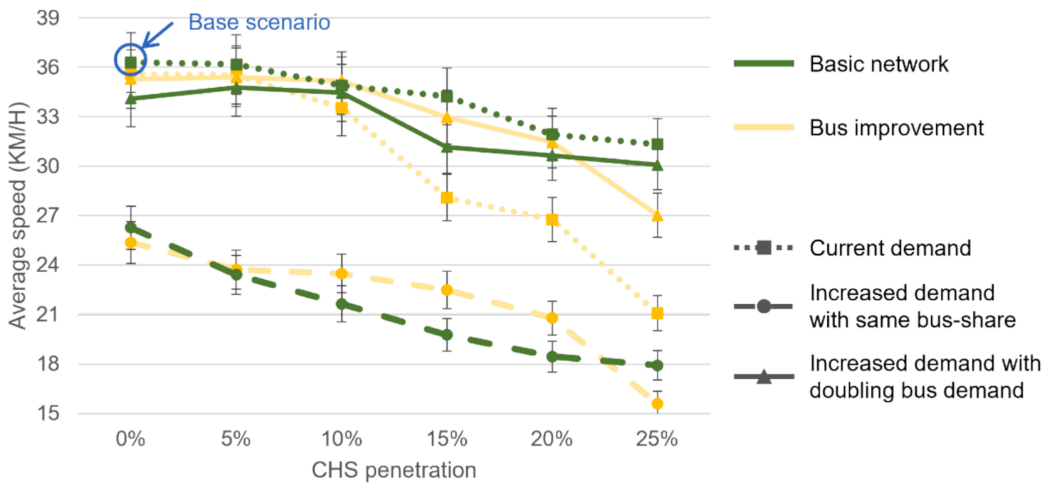

Fig. 9. Effect of reducing average boarding time per passenger and adding extra bus lane on network performance (with total demand of 7,200 and 6,000 trips).

transport become more significant as the CHS proportion increases. It shows that the decrease in average speed of buses is much more severe than that of cars and taxis, which can be attributed to the kerbside parking by CHSs, leading to increased waiting times and therefore forcing buses to stop or to change lanes. As a result, the average travel speed of buses declines by roughly 22 % with an increase in CHS penetration from 0 % to 10 %, whereas the decline is about 17 % and 10 % for cars and taxis, respectively. However, at higher levels of CHSs, the average speeds of both cars and CHSs decline and approach the bus speed. It is worth noting that while individual users still benefit from taking CHS over the bus, the collective user benefit of the bus is compromised, highlighting the trade-off between individual and collective benefits.

5.3. Bus improvement policies

Given the importance of bus boarding time to the performance of buses along the network, Fig. 9 illustrates the impact of halving bus boarding times through the implementation of contactless and mobile ticketing solutions and off-bus payment options in conjunction with bus priority policies such as the bus lane. While bus improvement policies are generally viewed as a useful means to enhance the public transport system and the network as a whole, the findings in Fig. 9 paint a different picture.

In the current scenario (represented by the dotted lines), implementing bus improvements (in light yellow) leads to slower network speeds compared to the basic network (in dark green). We speculate that transforming a regular lane into a bus lane leaves only one lane available for private cars and CHSs, resulting in increased traffic flow and congestion on the remaining lanes. Additionally, as the CHS usage increases, the differences in average speeds between the basic and bus improvement networks become more pronounced. The result concludes that CHSs stopping at kerbs for pick-up and drop-off negatively impact the smooth running of all road users. Segregated bus lanes and CHS violations of bus lanes exacerbate this effect. While our findings suggest this outcome, it is important to note that the impact of bus improvements on network speed can vary based on specific kerbside space management policies. For instance, strict regulations for car-hailing in bus lanes, as seen in some areas of London, can influence these dynamics significantly. This highlights the necessity of considering comprehensive management strategies for vehicles like CHS when implementing infrastructure improvements aimed at enhancing public transport services.

In a more congested future (with a 20 % increase in total demand), the effects of the bus improvement policy can contribute to a faster average speed by a 3.5 % uplift if the improvements are successful in doubling bus demand (solid line). If the future bus system can attract more passengers but keep the same mode-share at 20 % (dash line), there will be a minor decrease in average network speed. When there are more CHSs in the corridor (from 0 % to 20 %), the bus improvement policy benefits the running speed in both situations. However, the upgrade in average speed is eroded by the growth of CHSs at 25 %. Not only does the kerbside parking of CHSs block the kerb lane, but the more frequent lane-changing behaviour it results in also interferes with the movement of cars in other lanes.

The findings in the simulation reveal that bus improvement policies are an effective strategy to respond to future growth in transport demand. However, improvement to bus lanes will certainly cost the interests of other stakeholders. Therefore, such upgrades for the bus priority strategy need to be carefully considered in sections where they can move smoothly. In another context, the negative impact of high CHS penetration on bus priority cannot be neglected. In order to deal with the continued increase in CHS, appropriate management of the right to use the kerb for CHS is needed.

6. Discussion and implications

The urban kerbside presents a multifaceted and strictly regulated milieu, mandated to support diverse activities and dynamic usage patterns. While general compliance is noted, acute demand for kerb access precipitates non-adherent behaviours, engendering a range of adverse effects: from hazardous conditions for pedestrians and cyclists to compromised public transport efficiency. Enhanced enforcement remains challenging owing to the considerable financial, legal, and socio-political implications. Concurrently, the kerbside is undergoing a transitional phase wherein demand is surging due to diversifying uses and intensifying activities.

This dual complexity underscores the urgent need for an adaptive street management strategy that addresses the current intricacies and anticipates the gradual shift towards shared and automated mobility systems, lest the conditions continue to degrade. In addressing *RQ 4*, our findings suggest that certain bus improvement strategies, while seemingly advantageous, could paradoxically reduce the overall speed of the transport network, particularly in scenarios with high CHS utilisation. However, it is essential to recognise that well-implemented bus improvement strategies pose the potential to encourage a greater shift of passengers towards public transport, thereby reducing reliance on private cars and CHSs. This shift can help mitigate congestion issues brought about by high CHS penetration.

Building on this need for adaptability, our study delineates the benefits and drawbacks of different transport modes in this complex kerbside environment. Answering *RQ 2*, the study findings highlight the considerable advantages of greater public transport use for bus passengers and all network users.

By contrast, increased CHS usage, as our findings indicate, may have a negative impact on overall network performance, particularly in areas with frequent kerbside stops. This echoes our concerns of *RQ 1* and *3* regarding network velocity and adverse effects on bus speed. It could be suggested that sharing vehicles may reduce the number of stopping events for CHSs, but this might only be effective if the origins or destinations of travellers are the same. However, recent research suggests that there are challenges to promoting significant changes in sharing behaviours (Government Office for Science, 2019). Alternatively, managing drop-off and pick-up behaviours in dedicated bays away from the traffic stream might be a better solution (International Transport Forum, 2018). This would necessitate regulatory modifications and create additional demands on kerb space, although parking spaces could be repurposed.

In this context, the policy implications are multi-faceted, demanding refined approaches. Improving bus speeds is critical for enhancing public transport's appeal in congested conditions. This must be balanced with the growing prevalence of CHS and the needs of private vehicle users. The concept of non-car lanes emerges as a potential solution. Their effectiveness, however, is contingent upon the level of CHS penetration and the specific urban context. This necessitates broader regulatory strategies that might combine restrictions on CHS with incentives for public transport usage, aiming for a balanced and sustainable urban mobility landscape. These policy discussions, rooted in the empirical evidence from our study, are critical for shaping future urban planning and moving towards sustainable transport goals.

The adoption of CHSs like Uber has the potential to disrupt the transport industry. However, current regulations allow for taxis and CHSs to stop almost anywhere for pick-ups and drop-offs, excluding bus stops, clearways, and school zones. Section 5 of the study has shown that even low levels of penetration by these services can negatively impact overall network performance. The concentration of demand in both time and space requires careful management to avoid socio-economic consequences. Integrating these services as feeder systems for mass public transport will require better management of the interface with bus stops.

The adoption of spatially-bounded pick-up and drop-off rules and the provision of dedicated off-street facilities may become necessary beyond a certain penetration of shared vehicles. In some on-demand bus services in the UK, passengers must make their way to designated "virtual bus stops" to minimise the route distance and the number of stops. In other countries like Brazil, CHSs must share information about pick-ups and drop-offs as part of their operating license, acknowledging the private value derived from public kerbside use.

The study highlights the need to address several regulatory issues that stem from the mismatch between current regulations and the evolving behaviours and business models that influence street use. Urgent consideration is required, particularly with regards to how taxis and CHSs access busy kerbside spaces and the provision and management of deliveries and services. The development of an integrated, intelligent, and dynamically managed kerbside will necessitate the sharing of data and communication across various user groups, vehicles, and infrastructure.

7. Conclusion

In the era of upgrading transport modes, where the benefits are often couched in terms of genuinely door-to-door journeys, urban kerbside becomes a more scarce and valuable resource. It is used by everyone, including pedestrians, passengers and kerbside shops. Like all such resources, kerbside space will need to be carefully managed in order to maximise the benefits of all users operating in congested urban areas. However, the competition at kerbside spaces for parking by all types of vehicles is growing, and the popularity of CHSs aggravates the conflicts in using kerb spaces even further. To the best of our knowledge, it is still unclear how the future network will perform with the competition of car-hailing bus services at the kerbside.

This study initiated the exploration of imagining and designing the kerbside of the future. It recognised that the CHSs and a series of associated technological developments offer opportunities to reduce or resolve some of the current problems of the transport system. However, left to develop organically, the kerbside risks becoming a yet more congested and contested asset. The project aims to produce a picture that identifies the essential aspects of kerbside reform and the key aspects that need to be altered through the transition to the next generation of transport modes.

Our research indicates that the presence of CHS negatively impacts network performance, mainly because of the disruptive lane-changing and stopping behaviours observed during pickups and drop-offs. This adverse effect is somewhat mitigated when CHSs primarily attract users who would otherwise rely on private cars, rather than diverting riders from buses. In scenarios where the CHS share remains relatively low (as in our case study, below 15 %), the system shows a certain resilience to the negative impacts of CHS growth (*RQ1*). Our research demonstrates the positive impact of increased bus usage in addressing the challenges posed by growing CHS activities, thereby alleviating congestion problems (*RQ2*). CHS activities, especially those that intrude into bus lanes, significantly reduce the travel speeds for all road users, with the impact being most evident on buses (*RQ3*). However, as the road network becomes more congested due to CHS behaviours, taxis, which also have access to bus lanes, may exhibit a relative advantage. This suggests that as CHS share increases, policymakers may need to pay closer attention to the competition between taxis and CHS (Luo et al., 2024). While strategies that prioritise buses over other road users can offer some benefits, they may become counterproductive as CHS penetration increases, potentially worsening the overall situation (*RQ4*). The insufficient roadway for buses to navigate around stopped CHS vehicles worsens delays, emphasising the necessity for comprehensive strategies that also resolve CHS behaviours. Our research supports the detailed examination of the effects of the battle between CHS and bus for kerbside space on urban transport systems, offering substantial empirical evidence that enhances our comprehension of the complex interactions among various transport methods. This study not only confirms established patterns, but also provides refined dynamics into how different transport policies can have varying impacts on future urban mobility.

Through simulations of various potential future scenarios, including the different mode-shares, increased total network demand, and improvements in bus lanes and faster boarding techniques. The study underscored the importance of the bus, or other equivalent mass transit corridor solutions, in improving overall network performance. Large-scale sharing of vehicle assets is critical. By contrast, significant individualised shifts to CHSs would damage network performance in some areas due to increased volumes of stopping. Similar criticisms might be levelled at light goods vehicles where the volumes requiring kerb access far exceed the capacity that has been planned for and where stopping behaviours can block routes. Further work is recommended to understand these issues and manage them better, which is urgent. These changes are now eroding the benefits of other investments such as contactless and mobile bus ticketing and bus lane priority.

Our simulation-based tool proves to be highly useful and valuable for guiding urban transport policy. By captures the intricate interactions between various modes of transport and the urban traffic network under different CHS penetration levels, our micro-simulation model enables policymakers to conduct a thorough analysis of the current situation before developing policies. This dynamic modelling approach allows for the testing of various hypothetical scenarios, such as increased CHS presence or enhancements to bus services, providing a clear framework for better-informed decision-making. Moreover, the tool is valuable not only for initial policy formulation but also for evaluating and refining policies across multiple scenarios after implementation, ensuring that decisions are both adaptive to changing urban dynamics and grounded in empirical evidence. This contribution to the literature underscores the importance of data-driven approaches in anticipating and addressing future urban transport challenges.

In considering the transferability of our findings from the studied urban corridor to other urban settings, it is essential to acknowledge the common structural and operational similarities that exist across different urban landscapes. While each urban area has its unique characteristics, the fundamental dynamics of kerbside space competition, especially with the rise of CHSs, are likely to be mirrored in many cities globally. Our study's insights into the effects of various transport modalities and kerbside management strategies offer valuable lessons for broader application. Urban planners and policymakers in other cities can draw upon our findings to anticipate and mitigate similar challenges, adapting the strategies to their specific contexts. The generalizability of our results is particularly relevant for cities undergoing rapid transport modal transformations or experiencing increasing pressures on kerbside space utilisation. By applying the principles and understandings gained from our case study, other urban areas can proactively address the complexities of modern urban transport, leading to more efficient, equitable, and sustainable urban environments.

In conclusion, our study contributes to understanding the competition for kerbside space in the context of evolving urban transport dynamics. However, a promising avenue for future research is the development of dynamic models that explicitly capture the feedback loop between bus demand and average speed. Such models would offer a more comprehensive view of potential equilibria under varying regulatory and demand scenarios, further enriching our understanding of urban transport systems. Moreover, our analysis did not account for more complex demand scenarios and was limited to specific urban settings. Future research should expand to include a wider range of demand scenarios, possibly incorporating broader economic theories to understand the intermodal cross-elasticity in urban transport (Wardman et al., 2018). Our study does not focus on the formulation of specific policies or methods (such as parking fees, etc.); therefore, the analysis needs to incorporate results from simulations executed under a broader range of scenarios and additional policies. Additionally, given the early stage of this simulation-based research, emphasis should be placed not on the absolute value of the scenarios' result but rather on the broader implications of the displacement of communal transport services by individualised vehicles. To thoroughly comprehend the potential issues, it is imperative to extend the investigation across various locales and times, integrating more authentic behavioural assumptions. The study underscores the urgency of proactive measures to mitigate the repercussions associated with the initial, low adoption rates of CHSs. Finally, our current scenarios focus more on bus improvement strategies. Future research should pay more attention to restrictive policies for car-hailing services and discuss their broader socio-economic benefits.

CRediT authorship contribution statement

Tianli Tang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Ronghui Liu:** Writing – review & editing, Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Greg Marsden:** Writing – original draft, Validation, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Ziyuan Gu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Formal analysis. **Xiao Fu:** Writing – review & editing, Writing – original draft, Validation, Funding acquisition.

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.

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Appendix A

Figs. A1 and A2.

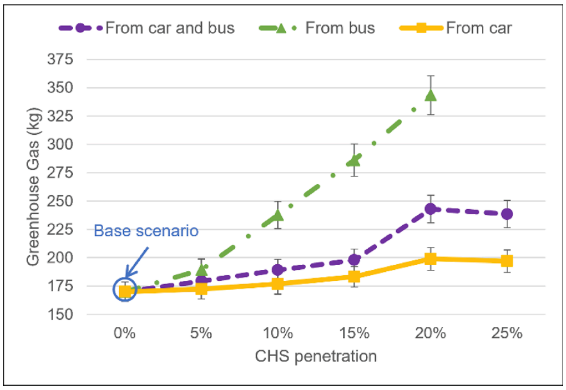

Fig. A1. Impact of increasing CHSs on the greenhouse gas emissions of the entire network for different sources of CHS users.

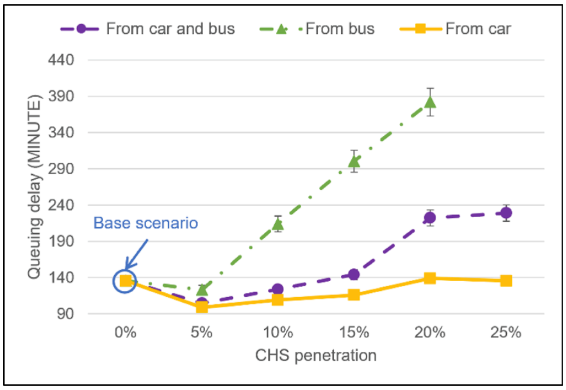

Fig. A2. Impact of increasing CHSs on the total queuing delay in the network for different sources of CHS users.

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