On-demand ridesharing operation: matching, pricing, and routing

Ze Zhou
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Abstract

Excessive private vehicles in densely populated cities, together with the increasing need for mobility, have been constantly challenging the existing transportation systems. Fortunately, mobility on-demand services, such as ride-hailing and ridesharing, are becoming a growing trend in megacities due to their convenience and cost-effectiveness. These services are envisioned as enablers of a shift from car ownership to vehicle usage. Nonetheless, the impact of mobility on-demand service on transport systems is complicated and largely depends on governance and operation strategies. Accordingly, this dissertation aims at developing novel management strategies, involving matching, pricing, and routing, to improve ridesharing system efficiency. Meanwhile, the impact of such methods on urban transportation systems is evaluated.

Firstly, an innovative strategy is proposed to integrate vehicle assignment with the prediction of time-dependent link travel times. We unify the assignment and routing problem into a linear integer problem where k-shortest paths are provided to reduce congestion. The results indicate that the proposed strategy can significantly improve ridesharing system performance, such as reducing the passengers’ waiting and travel times, by mitigating congestion effects arising from ridesharing fleets. Additionally, we account for traveller’s modal choice and ridesharing pricing fairness. A novel discounting method is designed based on the proposed fairness principles. Moreover, computationally efficient optimisation models are constructed accounting for co-existing ride-hailing and ridesharing services. The real travel dataset is utilised to assess the proposed method. The results indicate that the proposed optimisation strategy, considering traveller behaviour and fairness, can significantly improve fleet performance while maintaining fair service quality. Lastly, we present a simulation-based service assessment framework to test online ridesharing strategies with shared autonomous vehicles. Individual socio-demographic features are considered in generating future demand for SAVs. Travellers’ mode choices are explicitly modelled, and advanced ridesharing strategies, involving optimal matching and pricing, are tested in a mixed-traffic urban network, with both private cars and shared autonomous vehicles. Compared to rule-based methods, optimal matching and fairness pricing combined method can greatly improve both fleet performance and transportation efficiency.

In summary, this dissertation reveals that dynamic ridesharing offers a promising pathway toward achieving more sustainable mobility, provided it is properly managed.

Keywords Dynamic ridesharing, Ridepooling, Congestion, Vehicle assignment and routing, Pricing, Fairness, Traffic simulation


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From April 2019 to February 2024, five years have passed in the blink of an eye. However, numerous things happened during this peculiar period. My honeymoon with Finland was short-lived, as the unprecedented pandemic swept across the world in early 2020. Fortunately, my actual honeymoon took place in the summer of that same year. Due to COVID, remote work became a norm during the early stages of my PhD. Who knows how cheerful I felt when I was allowed to work from home. Most of the time, I was coding in my spacious living room, bathing in warm sunshine with a cup of coffee. However, this idyllic scenario does not last long until the winter of Finland comes by and greets me from November to March. To be honest, as a child growing up in the south of China, I was excited to see the heavy snowstorm turning the world into a white, icy, and desolate wilderness. Yet, after five years of struggling with long-time darkness and never-ending snowfall, my perspective has shifted. I now empathize with Finns as a devotee of summer.

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Espoo, May 2, 2024,

Ze Zhou
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This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.


**Publication II** Ze Zhou; Roncoli, Claudio; Sipetas Charalampos. Optimal matching for coexisting ride-hailing and ridesharing services considering pricing fairness and user choices. *Transportation Research Part C: Emerging Technologies*, 2023.

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Publication II: “Optimal matching for coexisting ride-hailing and ridesharing services considering pricing fairness and user choices”

Ze Zhou: Conceptualisation, Methodology, Software, Validation, Formal analysis, Writing – original draft, Visualisation. Claudio Roncoli: Conceptualisation, Methodology, Writing – review editing, Supervision, Funding acquisition. Charalampos Sipetas: Conceptualisation, Methodology, Writing – review Editing.

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Abbreviations

**AV** Autonomous vehicles

**BPR** Bureau of public roads

**DARP** Dial-a-Ride problem

**DRS** Dynamic ridesharing

**ILP** Integer linear program

**MoD** Mobility on demand

**SAV** Shared autonomous vehicles

**TNC** Transportation Network Companies

**VMT** Vehicle miles travelled
1. Introduction

1.1 Research background and challenges

In the last decade (2010-2020), the prevalence of smartphones has unexpectedly shifted the way urban inhabitants travel. In many major cities, it is ubiquitous for travellers to hail a car via mobility applications offered by Transportation Network Companies (TNCs), such as Uber (globally), Lyft (in the U.S.), DiDi (in China), Ola (in India, U.K., and Australia), and Bolt (in Europe) (Gurumurthy and Kockelman, 2022). Spurred by the development of TNCs’ mobility services, innovative transportation concepts, such as shared mobility and on-demand mobility, have grown rapidly. Particularly, shared mobility, including carsharing, ridesharing, and bikesharing, involves short-term shared use of a vehicle for a trip. Shared mobility provides a more sustainable mobility solution by enhancing transportation accessibility and reducing vehicle ownership (Shaheen et al., 2015). On the other hand, Mobility on Demand (MoD), also known as demand-responsive mobility, is a concept where consumers can access mobility and goods on demand by dispatching or utilising shared mobility (Shaheen et al., 2017).

This dissertation primarily focuses on the discussion of two types of MoD services: ride-hailing and ridesharing. Ridehailing is defined as a traveller who requests a trip through a mobile application and is matched with a freelance or professional driver who is willing to satisfy the trip request (Tirachini, 2020). Ridehailing trips are solo trips without detours. As pointed by Beojone and Geroliminis (2021), the effect of ridehailing service on traffic congestion depends on how it is replacing conventional travel modes. If ridehailing competes with public transportation, the influences on congestion may be significant. A recent study by Agarwal et al. (2023) indicates that ridehailing vehicles are replacing public transit and are contributing significantly to congestion in Indian cities. On the other hand, ridesharing, or ride-pooling, refers to assigning multiple travel requests to a single vehicle such that passengers can share the trip cost at
the expense of potentially experiencing longer travel times. Ridesharing is a promising approach to address the low occupancy rate and notorious congestion issues arose from the increasing ridehailing trips. Specifically, dynamic ridesharing (DRS) allows new travel requests to be combined and assigned to an en-route vehicle as long as it is not fully occupied. Intuitively, DRS is capable of increasing the average vehicle occupancy and reducing the number of vehicles travelling. Therefore DRS is commonly advertised as a promising method to reduce congestion and enhance the sustainability of mobility. Nonetheless, the effect of DRS on congestion is a controversial topic and may depend on operational strategies (Zhou and Roncoli, 2022) and trip density (Alisoltani et al., 2021). Gaining a deeper understanding of the impacts of DRS is also one of the research objectives of this thesis.

On the other hand, the practice of ridesharing, such as UberPool, has not achieved widespread success. In fact, it is not widely available in many metropolitan areas and European cities, particularly those with populations of fewer than 100,000 (Walls, 2020). A recent study by De et al. (de Ruijter et al., 2024) reveals that MoD services thrive on socio-economic inequality. Additionally, safety concerns and discomfort due to sharing further hinder the widespread adoption of such services. To make ridesharing more appealing, this thesis focuses on designing innovative operational methods to attract ridesharing users.

Following the automation megatrend, substantial research and development in autonomous vehicle (AV) technology has been accelerated over the last decade. For instance, Waymo, an American autonomous driving technology company, started in 2020 to offer mobility services to the public without having drivers in the vehicle (Waymo, 2024). AV is a disruptive technology and has the potential to become a major catalyst for urban transformation (Duarte and Ratti, 2018). Compared to human drivers, AVs are envisioned to connect with traffic management system. Besides, AVs’ ability to follow optimal routes with self-adjustments in real-time (Claudel and Ratti, 2015) has great potential to reduce network congestion and the associated emissions (Taiebat et al., 2018). Furthermore, company-owned shared AVs (SAVs) are commonly reckoned as a promising application considering the purchase fee of AVs would be expensive in the early days of implementation (Gurumurthy et al., 2019). It is worth mentioning that the term “shared” in SAV emphasises the fact that an AV is intended for short-term use rather than individual ownership. SAVs are allowed to perform solo trips. For travellers, SAVs are expected to save them money and time (Chen and Kockelman, 2016). For companies, although the purchase cost is high, SAVs offer savings by eliminating the need for driver salaries and opening up more possibilities in performing complicated operation tasks, such as rerouting and reassignment. In the passenger transportation domain, SAVs are reckoned as a promising tool to improve mobility...
and fight private car ownership (Loeb and Kockelman, 2019).

The implementation of DRS in SAVs is expected to be a cost-effective alternative for automobile travel, and central urban regions are likely to have abundant shareable trips (Tachet et al., 2017). Given the reliability and flexibility enabled by the SAVs, the inherent challenges in DRS, such as the requirement of updating vehicle route frequently, can be overcome (Zhang et al., 2015). Meanwhile, safety and privacy concerns, as well as discomfort due to sharing, could potentially be alleviated with the advent of advanced connected and automated vehicles. Furthermore, the DRS-enabled SAV fleet has significant potential to reduce Vehicle Miles Traveled (VMT), thereby offsetting the possible detours incurred by its convenience (Loeb and Kockelman, 2019).

The integration of SAVs and DRS presents both opportunities and challenges in research. Firstly, DRS is inherently dynamic and flexible, requiring updating vehicle schedules frequently. Secondly, the operation of DRS involves routing, matching, and pricing. These processes are further complicated by the spatial-temporal varied supply, demand, and traffic conditions. Thirdly, addressing large-scale demand requires scalable models and algorithms to ensure practical feasibility. Lastly, conventional traffic simulators are unable to capture the details of SAVs. In order to accurately assess the impacts and performance of MoD systems, especially in the presence of SAVs, a detailed simulation framework of MoD coupled with advanced traffic simulators is indispensable.

MoD service operators need to cope with the potential congestion effect and aim at improving the system performance through effective DRS operational strategies. This dissertation aims to develop novel MoD DRS operational strategies and analyze their impacts on the urban transportation systems and passengers’ travel experience. The research problems and corresponding objectives are discussed in detail in Chapter 3.

1.2 Structure of the dissertation

The remainder of this dissertation is structured as follows. Chapter 2 reviews the relevant literature and identifies research gaps. The corresponding research questions and objectives are formulated in Chapter 3. Chapter 4 describes the proposed methodologies associated with each research question. In Chapter 5, we summarise the primary contributions of this dissertation, by elaborating on each publication. Finally, Chapter 6 concludes the dissertation by summarising the outcomes and discussing the future research directions.
2. Literature review and research gap

In the early history of ridesharing, it was characterised by saving energy and reducing travel expenses. The first organized ridesharing was conducted in the U.S. in order to conserve fuel during WWII (Chan and Shaheen, 2012). In the 1970s, the oil crisis further prompted the development of ridesharing methods and practices. In the 1990s, ridesharing started to gain momentum as travellers in the United States wished to gain access to High-Occupancy Vehicle lanes or reduced tolls (Furuhata et al., 2013). Entering the 21st century, the environment and urban traffic situation have deteriorated due to excessive urbanisation, accompanied by a growing number of private cars, and low car occupancy. Ridesharing, as a promising way to increase car occupancy and alleviate congestion by serving the heavy demand with a reduced number of vehicles (Agatz et al., 2012), has generated much interest in both academia and transportation industry.

Theoretically, the DRS-enabled MoD operational problem, involving vehicle assignment and routing, can be broadly categorised as a stochastic dynamic vehicle routing problem (SDVRP) or a dynamic pickup and delivery problem (Hyland and Mahmassani, 2020). Specifically, vehicle route design is close to the Dial-a-Ride problem (DARP), a variation of the vehicle routing problem (Ho et al., 2018). Unlike conventional optimisation problems, where a set of decision variables are solved and determined at a time, the MoD fleet operator needs to constantly update the vehicle schedules as new travellers enter and pool with on-board passengers.

In this chapter, keywords such as dynamic ridesharing, ridepooling, shared-taxis, mobility on-demand, pricing, vehicle assignment and matching, congestion, vehicle routing, and shared automated fleet management are used to collect relevant studies, mostly on Elsevier journals. Nonetheless, we have to admit that there is an enormous amount of literature in this field. Due to limited time and energy, only the most relevant studies are selected based on the author’s preferences and experiences. In the following sections, the DRS and SAV-relevant literature for the main concepts discussed in this dissertation is presented. First, state-of-the-art routing
and matching strategies for large-scale DRS are discussed. Second, DRS pricing methods and passengers’ travel behaviours are analyzed. Lastly, DRS-enabled SAV fleet simulation-based studies are summarised.

2.1 Large-scale ridesharing matching and routing

As mentioned above, the DRS-enabled MoD operational problem is essentially a variant of the well-known vehicle routing problem or dynamic pickup and delivery problem with time windows, which are both difficult to solve. The efficient operation of DRS fleets with city-scale demand and supply is even more challenging, as the large-scale problem needs to be solved in real-time. By utilising the Markov Decision Process model, Hyland and Mahmassani (2020) presented a mathematical model for the DRS operational problem. However, due to the curses of dimensionality, it is unlikely to determine an optimal policy (Powell, 2011). Hence, it is necessary to adopt heuristic methods to solve the DRS operational problem. It is a common practice to formulate a static optimisation problem and solve it locally without considering its downstream effects on the following decision epochs.

Ma et al. (2013) proposed an efficient candidate taxi searching and a scheduling algorithm to speed up the insertion of new request origin-destination (OD). Moreover, Santi et al. (2014) introduced an innovative shareability network method to handle the large-scale taxi sharing problem. Based on Santi et al. (2014)’s work, Alonso-Mora et al. (2017) introduced a 4-step algorithm that guarantees anytime optimality when coping with high-capacity ridesharing issues; this is achieved by constructing a request-trip-vehicle graph and solving the following integer linear program (ILP). The results optimistically show that 3000 four-seat vehicles can cover 98% of the total taxi trips in Manhattan, with around 3 minutes waiting time and 2 minutes delay. Furthermore, Simonetto et al. (2019) argued that assigning at most one traveller to a vehicle at each optimisation epoch can significantly improve computational efficiency. The simulation results indicate that one-to-one match can achieve a similar service quality as the ones by Alonso-Mora et al. (2017) with a considerably lower computational burden.

In order to simplify the DRS operation, all the aforementioned studies consider either static or historical travel time among different ODs. However, a great number of DRS vehicles will inevitably incur traffic congestion in an urban network. To investigate the impact of DRS on traffic congestion, it is necessary to account for dynamic travel times. Meanwhile, DRS service is susceptible to changes of travel times and schedules, whereas congestion worsens the situation as it increases the unreliability of the system. Therefore, effective DRS matching and routing methods should
account for dynamic travel times and overall traffic patterns to increase the reliability of ridesharing services. Fortunately, some recent studies on DRS started to relax the assumptions of constant travel times to incorporate more accurate but sophisticated traffic flow models.

To begin with, the well-known Bureau of Public Roads (BPR) function, which maps the traffic volumes to the link travel time, is a popular option due to its simplicity. Salazar et al. (2019) proposed a congestion-aware routing scheme for autonomous MoD systems, utilising a piecewise approximation of the BPR function to reduce the computational complexity. However, the model leaves aside the ridesharing service. Correa et al. (2019) employed BPR functions to evaluate the travel delay on road segments, developing a congestion-aware activity-based ridesharing method. Furthermore, Liang et al. (2020) proposed an integer non-linear programming model, where congestion is captured via BPR, to optimise the automated taxis' routes. Nonetheless, the BPR-based methods are less accurate and unable to depict more sophisticated congestion patterns, such as spillback, traffic waves, and queues at intersections (Boyles et al., 2021).

On the other hand, traffic can be modelled at a finer resolution using dynamic models, which enables more precise and realistic travel time predictions. With this purpose, Levin et al. (2017) designed an event-based simulation framework for SAVs and employed the cell transmission model to simulate the traffic. The simulation results show that SAVS significantly increase congestion due to the empty repositioning. However, heuristic ridesharing methods are used without optimising the operation of the ridesharing service. Levin (2017) investigated the SAV routing problem by developing a linear program based on DARP and the link transmission model. A similar work has been conducted by Venkatraman and Levin (2021), where the cell transmission model is utilised to model the traffic flow. Nevertheless, both Levin (2017) and Venkatraman and Levin (2021) do not consider ridesharing. Although Venkatraman and Levin (2021) claimed that the proposed method can be extended to include ridesharing, the authors emphasized that such extension would further complicate the model, thereby making it hard to solve large-scale problems. Seo and Asakura (2021) formulated a linear programming problem to jointly optimise fleet size, road network design, and parking lot deployment of an SAV system. However, the method is designed for long-term strategic planning of SAV systems and thus is not applicable for real-time DRS operation.

To address the DRS matching and routing problem while considering traffic congestion, two similar works are identified and compared. First, Liang et al. (2020) developed a framework to integrate vehicle assignment and routing considering endogenous congestion, purely caused by SAVs fleet, in the presence of ridesharing. Nonetheless, as mentioned before, the BPR-based models cannot capture complex traffic conditions. Besides,
the model is not suitable for real-time usage, due to the computational complexity. Second, Alisoltani et al. (2021) investigated whether dynamic ride-sharing services can reduce urban traffic congestion. They design a ridesharing system to provide real-time services and employ a trip-based Macroscopic Fundamental Diagram model to reproduce the evolution of traffic conditions. Results indicate that DRS can significantly reduce traffic congestion when the demand density is high. Despite the proposed method is utilised to assess the impacts of DRS on traffic congestion, it is unanswered whether the method applies to real-time high-capacity DRS operations. Besides, the Macroscopic Fundamental Diagram, being a spatially aggregated model, is unable to depict link-and-intersection-level traffic conditions.

2.2 Ridesharing pricing, traveller fairness and mode choice

Dynamic pricing refers to the adjustment of prices by the service provider in real-time to react to changes in supply and demand (Banerjee et al., 2016). In DRS, dynamic pricing is commonly adopted as a tool to maintain demand-supply market equilibrium (Liu and Li, 2017; Ke et al., 2020; Zhang and Nie, 2021). However, dynamic pricing has been criticised for its nontransparent fare structure, which might confuse and even annoy ridesharing travellers (Tervo and Väyrynen, 2022). In contrast, Haliem et al. (2021) introduced a model-free demand-aware DRS framework that unifies vehicle-traveller matching, pricing, and routing. Specifically, the ridesharing price is calculated via a formulation that considers, total trip distance, number of co-riders, and traveller’s waiting time. Besides, the framework allows travellers to accept or reject ride offers based on their preferences. However, only heuristic algorithms are employed for DRS matching.

Other studies introduced the concept of stable matches in shared rides and set prices to attain such a stable state. Instead of aiming for profit, the service provider is usually assumed to be a public transportation agency and is designed to share the trip cost among travellers. For instance, Lu and Quadrifoglio (2019) formulated the sustainable ridesharing service design as a fair cost allocation problem using cooperative game theory. Foti et al. (2021) proposed the fairness concept in ridesharing, which involves finding the Nash equilibrium in a ridesharing scheme. They found that the system optimal assignment is close to the fairness-aware assignment plan. Similarly, Fielbaum et al. (2022) aimed to form a stable match. They developed three different protocols to split the cost of a ridesharing trip such that the optimal solution is also an equilibrium. In these papers, the concept of fairness corresponds to stable matching or equilibrium. However, in this thesis, ridesharing fairness is defined from a different
perspective. Specifically, ridesharing fairness is introduced to address passengers’ concerns about trip fare. Ridesharing fairness can be viewed as a scale that balances between the disutilities experienced by passengers and the monetary compensation they receive. In other words, the more discomfort a passenger experiences, such as longer detours or sharing with more co-riders, the lower the fare. Conversely, if a ridesharing user experiences a longer detour but pays relatively more than their co-rider, this unfair treatment could lead to potential loss of future consumers.

Additionally, the cost-sharing mechanism design is commonly used to set prices in public transit and on-demand systems. For instance, Chau et al. (2020) argued that ridesharing is essentially a decentralised decision-making paradigm, where travellers are self-interested and only motivated by individual payments. Therefore, the ridesharing cost should be shared fairly between travellers. They introduce several fair cost-sharing mechanisms and analyze the corresponding stable matching results. The results indicate that the induced social costs of fair matching are as comparably low as the social optimal outcomes. Furuhata et al. (2014) designed cost-sharing mechanisms to update ridesharing fares in demand-responsive transport systems so that all travellers are treated fairly. Furthermore, Hu et al. (2021) extended Furuhata et al. (2014)’s mechanisms by including driver’s costs and providing incentives to encourage travellers to submit their trip requests as early as possible. However, such methods are not designed for real-time DRS service, which requires a computationally efficient solution for handling large-scale supply and demand.

Instead of investigating pricing and matching separately, Özkan (2020) suggested that joint optimisation of the pricing and matching in ridesharing can significantly improve the system performance. Similarly, Liu et al. (2021) argued that the pricing and matching problems are coupled because the travellers are sensible to service quality and prices. They further propose a framework for jointly optimising the matching and pricing in MoD systems with shared rides. Although the operational challenges are amplified due to mixed service types, ride-hailing and ridesharing, as well as travellers’ mode choices, an efficient method for solving the coupled problem both in sequence and in batches is developed. Still, the traceability of the proposed method is challenged when the number of ridesharing travellers is greater than two. Besides, Kucharski and Cats (2020) developed an efficient algorithm for ridesharing matching. The algorithm is capable of identifying shared rides from large-scale demand but not apply to real-time DRS pricing. Jiao and Ramezani (2022) designed a dynamic discounting strategy to incentivise travellers to choose ridesharing trips. However, they assume that partially occupied vehicles are excluded from assignment and that a maximum of two travellers share a trip. To account for the traveller’s preferences, Azadeh et al. (2022) introduced a framework for a choice-driven DARP incorporating the optimised price of service alter-
natives and travellers’ mode choices. The generalised DARP is formulated as a mixed integer problem and a customised algorithm is proposed to solve it. Nonetheless, the computational efficiency of the proposed model is questionable when dealing with large-scale problems.

In this respect, there is a similar study by Paul et al. (2023). They developed an assignment strategy that accounts for traveller delay and delay acceptance. Travellers are offered personalized discounts to incentivize them to participate in shared trips. Nonetheless, only trip delay is considered for discounting. We take into account a more comprehensive set of factors, including the number of co-riders and shared distance.

2.3 Shared autonomous vehicle enabled ridesharing fleet simulation

As mentioned previously, ridesharing in human-driven vehicles has been studied for many decades. More recent ridesharing studies have shifted from static ridesharing to real-time DRS, and from conventional vehicles to SAVs. For instance, Gurumurthy and Kockelman (2020) conducted a stated-preference survey to investigate Americans’ willingness to use AV for DRS. The essence of the DRS remains unchanged, but SAVs are envisioned to be more flexible and reliable in performing DRS.

Optimisation-based research (Alonso-Mora et al., 2017; Simonetto et al., 2019; Santi et al., 2014) has emphasized the operation of DRS to improve performance metrics. Agatz et al. (2011) introduced an optimisation-based method to assess the potential of DRS using real travel data in Atlanta. They found that using optimisation-based methods instead of simple heuristic rules could substantially improve the performance of DRS. On the other hand, simulation-based studies have attempted to use real travel demand data to capture more realistic travel behaviours and their impact (Gurumurthy et al., 2019). Fagnant and Kockelman (2018) used agent-based simulation to investigate the impacts of DRS-enabled SAVs. The results indicate that DRS is critical in reducing empty vehicle miles travelled due to relocation. However, previous studies usually lack realistic traffic flow models or even assume constant speed. Ignoring the endogenous congestion effects and travellers’ mode choices may yield over-optimistic results (Gurumurthy et al., 2019). Besides, SAVs have different driving patterns when considering traffic congestion.

Recent studies tend to employ more realistic traffic models to investigate the impact of SAVs. Dandl et al. (2017) employed a microscopic tool to precisely depict link-level dynamic travel times and to investigate the operation of autonomous taxi systems without ridesharing. Levin et al. (2017) proposed an event-based framework for simulating SAVs using the cell transmission model. Private vehicles and SAV scenarios are designed to evaluate the effects of the SAV fleet. Surprisingly, the results show
that SAV scenarios lead to increased congestion, primarily due to empty repositioning. While DRS contributes to congestion reduction, its impact is only comparable to private vehicle scenarios. But this might be because only a simple heuristic-based ridesharing method was employed. Further improvements are anticipated with the deployment of a more effective DRS method (Agatz et al., 2011). A stream of works utilised the agent-based simulator MATsim, which employs a queue-based approach to model traffic dynamics (Horni et al., 2016): Fagnant and Kockelman (2018) showed that DRS is critical to reduce the vehicle-miles travelled, thereby traffic congestion, demonstrating the benefits brought by DRS-enabled SAVs; Lokhandwala and Cai (2018) compared the performance of traditional taxis with DRS-enabled SAVs, indicating that DRS can significantly increase vehicle occupancy and reduce carbon emissions; Gurumurthy et al. (2019) quantified the benefits and costs of DRS-enabled SAVs in Austin, Texas, demonstrating that, in the presence of both private AVs and SAVs, DRS is beneficial to the transport system when road pricing is enforced during peak hours. Vosooghi et al. (2019) simulated SAVs in a multimodal dynamic demand system to evaluate the performance of the SAV fleet, concluding that ridesharing and vehicle relocation can greatly improve the system performance.

2.4 Research gaps

According to the literature review and state-of-the-art studies which have been presented, three research gaps are identified as follows:

- **Research gap 1 (RG1):** Model and optimise the large-scale dynamic ridesharing operation in real-time while considering endogenous congestion. Previous studies on DRS optimisation either overlook the congestion effects incurred by vehicle fleet (Santi et al., 2014; Alonso-Mora et al., 2017; Simonetto et al., 2019) or formulate a congestion-aware framework that is computationally intensive and thus not viable for peak-hour demand (Levin, 2017; Liang et al., 2020). Therefore, it is imperative to develop an efficient routing and matching method for the DRS system.

- **Research gap 2 (RG2):** Model and optimise dynamic ridesharing pricing and matching accounting for traveller’s mode choice. In literature where system efficiency and profit are generally emphasised, ridesharing travellers are usually assumed to accept any ride the platform offers. However, this is a strong assumption considering that travellers in reality can decline a ride offer and turn to other modes if, e.g., the price is inappropriate. If we relax this assumption, then it is critical to present ridesharing users with a customer-centred fare plan, which accounts for
their detours and other ridesharing effects. However, most studies in existing literature have focused on maximising only the platform profit when it comes to pricing, thus ignoring fairness from the traveller’s viewpoint. To summarise, there are no studies dealing with the design of a fairness-aware pricing scheme while accounting for travellers’ mode choice in terms of DRS matching and assignment.

• **Research gap 3 (RG3):** Combining optimisation- and simulation-based methods to analyse DRS-SAV service performance and its impact on traffic. Most existing studies about SAVs and DRS either emphasise traffic simulation or fleet operation. The operation optimised works (Alonso-Mora et al., 2017; Hyland and Mahmassani, 2018) design novel operational strategies but simulate with simple traffic assumptions, such as using static or historical travel times. This could lead to over-optimistic results, as the congestion effect has been ignored Levin et al. (2017). On the other hand, simulation-emphasised studies (Gurumurthy et al., 2019; Räth et al., 2023) employ simple heuristic operation methods to evaluate the impacts of SAVs. As the potential of ridesharing has not been fully exploited, its impact might be underestimated. To address this research gap, it is necessary to combine optimisation- and simulation-based methods to assess the impacts of SAV-enabled DRS services more accurately.
3. Research questions and objectives

DRS service operation is a challenging problem that not only affect passengers’ travel experience but also the platform profits and network traffic. This dissertation aims to propose effective and efficient DRS operation strategies and analyse their impacts on travellers, system performance, and traffic congestion. To fulfil this goal, three primary research questions (RQ) have been formulated based on the research gaps identified in the previous chapter. For each research question, the associated research objectives are provided.

**RQ1: How to mitigate endogenous congestion caused by large-scale DRS fleet when operating such a service on a daily basis.**

As discussed in Chapter 1 and Chapter 2, the growth of MoD services and the advent of SAVs are envisioned to boost the presence of ridesharing vehicles. Therefore, ridesharing will soon become a source of traffic congestion itself and thereby significantly affect urban traffic patterns. Corresponding to RG1, the research objective is to design a real-time MoD operation framework that enables the optimisation of ridesharing vehicle assignment and routing considering endogenous congestion.

**RQ2: How to fairly charge DRS travellers and optimise vehicle-traveller match considering both ride-hailing and ridesharing and traveller’s mode choice?**

As outlined in Chapter 2, existing studies assume that travellers are fully compliant with the MoD platform’s decisions regarding pricing and vehicle assignments. However, in reality, travellers are free to choose different modes based on monetary costs and travel experience, which may conflict with the results derived from the system perspective. Corresponding to RG2, the research objective is to design a DRS framework that enables the optimisation of vehicle-traveller matching while considering pricing fairness and the travellers’ mode choice. On top of it, an effective fairness-
Research questions and objectives

aware pricing method needs to be designed for real-time DRS.

**RQ3: How to assess the impacts of a shared autonomous vehicle fleet with dynamic ridesharing at a disaggregated level, considering optimal matching and fairness pricing?**

As summarised in Chapter 2, the optimisation-focused studies may overestimate the effect of DRS due to unrealistic travel times, while the simulation-focused studies might underestimate the effect when only heuristic methods are used. Corresponding to **RG3**, the research objective is to propose an SAV simulation framework that incorporates optimisation-based DRS pricing and matching, while considering travellers’ mode choice and pricing fairness. Compared to the existing methods, the proposed simulation methodology is envisioned to evaluate optimisation-based DRS matching and pricing methods, while simulating both conventional vehicles and SAVs at a mesoscopic level.

Figure 3.1 illustrates the relationships between **RG**, **RQ**, and the published papers. The building blocks of this thesis include real-time DRS operation, travellers, and urban traffic. Specifically, there are mainly four pillars in DRS operation, which are vehicle-traveller matching, vehicle routing, pricing, and relocation. In particular, vehicle relocation, or rebalancing, means to pro-actively relocate vehicles to where they are potentially needed based on predictions of future demand. Although relocation has been extensively studied in one-way carsharing system (Jorge et al., 2014), this thesis leaves it for future research as we do not discuss demand forecasting in this work. For completeness, only a simple relocation method is employed in **RG3**. Instead of prediction, the unmatched requests are employed as a representation of future demand, and empty vehicles are dispatched to these requests as a form of rebalancing. As for the travellers, we mainly consider their travel preferences and mode choices. Lastly, the urban traffic is divided into MoD fleet and other modes, which include private cars, taxis, and public transport. These building blocks are labelled with numbers from one to seven. As shown in the figure, we identified the **RG1** from **RQ1**, which mainly involves DRS matching and routing, and MoD fleet. Besides, the second publication stems from the **RQ2** and **RG2**, involving DRS matching and pricing, as well as the traveller’s mode choice. Lastly, the **RQ3** and associated **RG3** covers all topics. Hence the third publication manages to provide a unified simulation-based framework to assess the DRS service performance and urban traffic dynamics comprehensively.
Research questions and objectives

Figure 3.1. Relationships between RGs, RQs, and publications
4. Research methodology

In this Chapter, we first provide a general overview of the methodology-related concepts, which are employed throughout three publications. Next, to address each of the proposed research questions, a detailed research methodology associated with each publication is presented.

4.1 Methodology overview

To address the research questions proposed in Chapter 3, an overview of the concepts used in the included publications is summarised.

As illustrated in Figure 4.1, mainly two modules, optimisation and simulation, form the pillars of the methodology. To start with, the input consists of travel demand, MoD fleet, and an urban network. Next, in the real-time operation of a DRS system, travel requests emerge in chronological order. Subsequently, the DRS service operator is responsible for assigning vehicles to these waiting requests. An optimisation problem is then formulated, where the constraints ensure a one-to-one vehicle-traveller match, which can significantly improve computational efficiency.

Next, the optimisation results, in the form of updated vehicle schedules, are forwarded to the simulator. Since the focus of Publication I and Publication III includes a detailed analysis of traffic congestion, an open-source dynamic network loading (Han et al., 2019) and a commercial Aimsun Next software (Aimsun, 2023) are utilised in Publication I and III, respectively. Nevertheless, the dynamic network loading algorithm is integrated as part of the solution to the problem, while Aimsun Next is employed as a pure simulator. Moreover, the travellers’ choice model is only adopted in Publication II and III to enable travellers to choose from different modes. Similarly, other traffic, such as private cars, and automated vehicles, is simulated in Publication II and III. The simulator implements the operational decisions and simulates the movement of ridesharing vehicles. The changed vehicle statuses and traffic conditions are available to the service operator in real-time.
4.2 How to mitigate endogenous congestion caused by a large-scale DRS fleet when operating such a service on a daily basis? (RQ1)

As summarised in the RG1, existing DRS studies overlook the endogenous congestion incurred by the MoD fleet. To address this problem, a vehicle assignment and routing method considering endogenous congestion has been developed in Publication I. The main assumptions of this research include: 1) link travel time changes over time and space; and 2) a redundant network with route alternatives for any OD pair.

Firstly, to reduce the computational challenge, we decompose the congestion-avoid DRS operation problem into two subproblems: given the current schedules of the entire fleet and the current traffic conditions, I) how to predict the time-dependent link travel time in the following time steps? II) how to route and assign vehicles to avoid predicted congestion and mitigate possible aggravation? For subproblem I, a variety of traffic prediction models can be used, from BPR function to cell transmission model, or even advanced traffic simulators. We employ the classic LWR hydrodynamic model (Lighthill and Whitham, 1955; Richards, 1956) to depict the within-link traffic flow while using the signalised junction model proposed by (Han et al., 2014; Han and Gayah, 2015) to specify how traffic propagates at intersections. For subproblem II, we first introduce two types of congestion, and propose corresponding methods to avoid them. As shown in Figure 4.2, the first subfigure (a) depicts the current traffic status and vehicles’ schedules. Based on this information, we can predict future congestion using
the hydrodynamic model. Therefore, we term this type of congestion **prior-predicted congestion**, depicted as red bars. An efficient time-dependent shortest path finding algorithm is envisioned to circumvent this type of congestion. However, considering the computational burden for real-time system implementation, we could distribute the calculation or reduce the frequency of using such algorithms. This is an appropriate approach, as traffic in the short term typically remains unchanged. Additionally, if the routes of two newly assigned vehicles (representative, possibly hundreds in reality) overlap both in time and space, new congestion may arise. We refer to this type of congestion as **batch-predicted congestion**, coloured in yellow. Note that the assignment and routing decisions should be made simultaneously, not sequentially. Therefore, two types of congestion should be considered at the same time. To address these two types of congestion, we formulate an integer linear programming model to integrate vehicle-traveler matching with the time-dependent multi-path choice problem.

After decomposing the congestion-avoid DRS operation problem, we propose a decentralised operation framework, as illustrated in Figure 4.3. Following the path of the incoming travel requests, we explain the purpose of every module and their interactions. To start with, *Travellers* submit their requests by specifying their origin-destination (OD), waiting and detour time. The *Ridesharing Platform* then batches the requests within a short time period. Batched requests are forwarded to the *Vehicle* module, where vehicles are distributed, each capable of performing computational tasks independently. Firstly, each vehicle is responsible for identifying potential requests using a distance-based searching method. Subsequently, for each potential vehicle-request pair, a Single Vehicle Dial-A-Ride Problem (DARP) (Marković et al., 2015; Ho et al., 2018) needs to be solved to determine the optimal route plan, which consists of a series of sequential pick-up and drop-off nodes. To account for the fact that link travel time
is endogenously affected by the assigned trips and routes, we include a Traffic Prediction module. This module is capable of predicting the time-space varying traffic based on the current traffic condition and current vehicles’ schedules. Based on the real-time and predicted traffic conditions, multiple time-dependent paths are calculated for each optimal route plan via the Dynamic Routing model. Lastly, the filtered k-shortest paths and travel time for each potential vehicle-request pair are forwarded to the optimisation module. By solving an ILP, this module determines which vehicle to serve which request alone which route such that the sum of travel cost and predicted congestion are minimised. After optimisation, vehicles’ schedules are updated. The above steps are iteratively performed at each batch interval to satisfy real-time requests.

4.3 How to fairly charge dynamic ridesharing travellers and optimise vehicle-traveller match considering both ride-hailing and ridesharing and traveller’s mode choice? (RQ2)

To fill the RG2, we design a DRS operational framework considering travellers’ mode choice and fairness pricing. As depicted in Figure. 4.4, there are primarily three main components, namely travellers, MoD platform, and its fleet. In Publication II, we assume that the MoD system manages a fleet of vehicles and provides both ridehailing (solo trip) and ridesharing services. A request waiting pool is created to store these unmatched requests. These requests, together with the incoming requests, are forwarded to the platform for matching at every time step. Travellers are assumed to leave the system if the waiting time exceeds their limits. In order to match travellers with vehicles, a detailed operation solution is given in
Figure 4.4. DRS framework accounts for traveller mode choice and fairness pricing

Figure 4.5. As usual, requests are batched every $\Delta t$ seconds, and candidate vehicles are found for each of them. Meanwhile, the new request’s OD is inserted into the schedule of candidate vehicles and the trip price is calculated accordingly. To calculate the ridesharing price, a discount function is designed to quantify the degree of inconvenience caused by ridesharing. We first define a detour index to reflect the detour rate. Then, a ridesharing index is introduced to reflect the distance and the number of co-riders of shared rides experienced by a traveller. Based on these two variables, a multiplicative discount function is formulated. Note that the travel fare for previously assigned requests changes if the trip is shared with the new traveller. Given the available trip price plans, several ILPs are formulated to determine the optimal vehicle-traveller match. A more detailed description of ridesharing pricing and optimisation formulation can be found in Publication II.

The optimisation results, translated into the service menu, are forwarded to each potential traveller. Upon receiving the service menu, travellers choose the service or exit based on their individual utilities. To model the traveller’s choice behaviour, the well-known discrete choice model, more specifically, a multinomial logit model (Ben-Akiva and Lerman, 1985), is utilised. Travellers can select between ridehailing and ridesharing services, as well as leave the platform by turning to other modes, such as public transport. If a traveller chooses the ridesharing service, we assume the operator would conduct a fairness check before confirming the offer. By doing so, travellers who receive unfair prices have the option to refuse before starting the trip. Consequently, we can quantify the loss caused by unfair pricing. Finally, vehicles’ schedules and routes are updated to deliver all confirmed travellers.
4.4 How to assess the impacts of a shared autonomous vehicle fleet with dynamic ridesharing at a disaggregated level, considering optimal matching and fairness pricing? (RQ3)

To fill the RG3, an optimisation-simulation combined framework is proposed. First, a general framework is illustrated and explained. Next, a detailed description of the interactions between the fleet operator and the traffic simulator is given.

As illustrated in Figure 4.6, there are mainly three components of the framework, including the traveller, fleet operator, and mobility service fleet and traffic simulator. The overall procedures are similar to Figure 4.4. However, they are different in three aspects. First, for the fleet operator, a new relocation module is added to improve the service performance. Second, for the traveller, only ridesharing service is available. Travellers can only select between ridesharing or private cars. Lastly, in terms of simulation, we simulated both SAVs and private vehicles using commercial software to accurately simulate traffic conditions.

Furthermore, we introduce the traffic simulator Aimsun Next and the time-based communication between the operator and the simulator. Aimsun Ride is a simulation platform for planning towards new and primarily demand-responsive mobility in urban environments. It is an agent-based demand-supply interaction framework for multimodal and multi-operator fleet-based service systems, coupled with the state-of-the-art Aimsun Next’s multi-class mesoscopic traffic simulator (Aimsun, 2023).

An important design consideration in Aimsun Ride’s architecture lies in its ability to communicate interoperably and flexibly with any type of service operator as part of a simulation-based system analysis process. Due to such communication requirements, Aimsun Ride offers a TCP/IP interface, i.e., a gRPC-based (google Remote Procedure Call framework) API, which enables flexible server-client implementations with external Python modules that define and establish the communication types and
patterns between service operators and Aimsun Ride. Figure 4.7 illustrates the time-based communication between Aimsun Ride and Operator. On time-based communication, all requests are passed to the service operator. Aimsun Ride is called by the service operator at a fixed time interval $\Delta t$. A callback is sent from Aimsun Ride to the Service Operator asking for an action plan every $\Delta t$. Following the aforementioned operation procedures, the Service Operator plans the vehicle assignment and communicates the final schedule for each vehicle-request pair to Aimsun Ride. The simulator implements the operational decisions and simulates the traffic, including both SAVs and conventional private vehicles.
Figure 4.7. Time-based communication between DRS operator and a traffic simulator: Aimsun Ride
5. Scientific contribution

This chapter provides a summary of the contributions and key findings related to each research question, as presented in three peer-reviewed publications. The details of each publication have been elaborated on in the following.

5.1 Publication I

This paper addresses the RQ1. In this publication, we design a management framework and propose an optimisation-based methodology for DRS while considering its impacts on traffic dynamics. The framework is based on the federated structure proposed by (Simonetto et al., 2019), which is extended to incorporate a traffic dynamics module. The main contributions of Publication I are summarised as follows:

• To enable efficient DRS routing while considering the fleet endogenous congestion effects, a dynamic network loading algorithm, based on the classic LWR traffic flow model, is integrated with a DRS operation framework.

• With the knowledge of simulated and predicted real-time traffic dynamics, a novel time-dependent k-shortest path-based model is proposed to jointly optimise DRS assignment and routing.

• The decentralised real-time DRS management framework is capable of coping with high travel demand at a lower computational complexity.

We design a series of numerical experiments to test the proposed framework and model. First, the proposed method is tested on a small grid network. Due to lower computational costs, a series of sensitivities analysis on different parameters is discussed. Second, we employ the classic Sixoux Falls network with peak-hour demand to compare the proposed
method with other strategies. The simulation results reveal that the proposed congestion-avoiding and -mitigating method can dramatically reduce endogenous congestion. Compared to the baseline scenario, the proposed method reduces the average link travel delay by 74.2% and decreases the standard deviation of link travel time by 50.1%. Fundamentally, the proposed vehicle assignment and routing method prevents the occurrence of highly congested links by directing vehicles to less saturated links while maintaining the number of vehicles below the road capacity. These findings show that the proposed method can optimise the utilisation of road capacity when dealing with the same travel demand. Furthermore, due to a less congested network, ridesharing performance is enhanced as the travellers experience less waiting and travel time.

5.2 Publication II

Publication II aims to address the RQ2. In this paper, a MoD framework incorporating traveller’s choices is introduced to optimise vehicle-traveller matching and pricing in the presence of co-existing ridehailing and ridesharing services. The main contributions are summarised as follows:

- We design an MoD framework that enables the optimisation of vehicle-traveller matching while considering pricing fairness in the presence of both ride-hailing and ridesharing services.

- Define six fairness principles for ridesharing pricing.

- Design a discount function for dynamic ridesharing pricing that ensures pricing fairness.

- Accounting for the traveller’s mode choice, a fair-price-based vehicle-traveller matching problem is formulated into a computationally efficient linear integer problem.

In this study, we assume travellers to be cost-sensitive and consider three service alternatives as options, which are ridehailing, ridesharing, or other modes, respectively. To account for ridesharing trip inconvenience and co-rider’s fairness, we define six principles and design a discount function that satisfies these principles. On the basis of the proposed pricing method, several ILPs are formulated to determine the optimal vehicle assignment. In particular, an integrated method is proposed to account for the interplay between two MoD services and traveller’s mode choices. A set of simulations is implemented to test the proposed models. We utilised the NYC...
taxi dataset to compare the proposed pricing method with other advanced ones while implementing them with different optimisation models. The integrated model that combines both ridehailing and ridesharing services outperforms other methods. Specifically, the integrated method achieves 20% more profit by serving 18% more travellers with only 2% more VKT, using the same fleet. The fundamental reason is that the proposed fairness-aware method can prevent the occurrence of unfair pricing. Hence more travellers stay in the system and are eventually served by the platform. It is noteworthy that the number of served travellers almost doubled, but the average waiting and detour time only increased slightly. On top of that, a series of numerical experiments are conducted in a toy grid network for sensitivity analysis. The results reveal that the proposed integrated optimisation method consistently outperforms its counterpart regardless of different choices of parameters. Nevertheless, we found that a moderate discount coefficient and a larger fleet size with more ridesharing vehicles contribute to the improvement of the integrated method.

5.3 Publication III

To address RG3 and RQ3, this paper presents a large-scale optimisation-simulation combined framework to evaluate the performance of DRS-SAV operation and its impact on traffic congestion. The main contributions are summarised as follows:

- an integrated optimisation-based real-time DRS framework incorporating fairness pricing, vehicle-traveller matching and relocation;

- traveller’s mode choice resulting from the arising congestion pattern and service performance;

- simulating both private human-driven vehicles (PVs) and SAVs using a mesoscopic traffic simulator.

The simulation results reveal that advanced operation strategies are critical for successful DRS implementation. Intuitive rule-based methods are unable to exploit the potential of DRS and thus limit the utilisation of DRS. Compared to heuristic methods, the optimisation-based matching can serve 31.2% more travellers with 6.1% less VKT and 1.67 minutes longer waiting time on average. Furthermore, accounting for travellers’ mode choices and pricing fairness enhance the performance of such a DRS system. Compared to the conventional pricing method, fairness pricing serves 26.3% more travellers with 3.9% less VKT and 1.4 minutes less waiting time. Note that all these findings are derived from simulations.
conducted with a realistic travel time and traffic flow model, enhancing the reliability of the results.

Moreover, optimisation-based DRS operation can greatly improve the urban traffic situation. With optimisation and fair pricing enabled operation method, the same SAV fleet can serve more travellers with averagely higher travel speed and lower road density. This is probably the result of the highest number of shared trips across scenarios. This, coupled with the highest number of served requests (and consequently the lowest number of private vehicles), results in an overall reduction in vehicles deployed and travelling to serve the same demand. The result suggests that combining the proposed optimisation algorithm with fair pricing yields the biggest improvements, not only for the SAV fleet but also for the background traffic. Therefore, a joint optimised method is critical for the DRS operator to enhance both fleet performance and traffic efficiency. In contrast, inappropriate DRS strategies might exacerbate the congestion. We also find that separating vehicle assignment from pricing leads to inferior performance.
6. Discussion and future directions

6.1 Summary of the outcomes

This dissertation aims to address the on-demand ridesharing operation problems, including routing, matching, and pricing. While the first research question focuses on routing, the second one emphasises pricing. Moreover, the matching between vehicles and travellers is throughout all the publications as it is the essence of the DRS service. Lastly, we investigate the impacts of advanced operation strategies on system performance and traffic efficiency, considering mixed traffic.

The first research question has been addressed by proposing a method combining routing with matching to actively prevent from creating congestion. Specifically, we introduced an extended linear assignment problem that considers multiple path alternatives. Due to the linearity and candidate vehicle searching method, the proposed model shows great scalability when coping with peak-hour demand. A first set of simulations is implemented on a toy network to analyse the sensitivities of different parameters. Recommendations are provided for setting these parameters. On the other hand, we conduct numerical experiments on a more realistic urban network with peak-hour demand patterns. The results show that the proposed multi-path-based optimisation method can significantly improve both service and network efficiency.

The second research question has been addressed by proposing a fairness-aware pricing method. Besides, we first introduce an MoD framework accounting for traveller's modal choices when both ridehailing and ridesharing services are provided. Computationally efficient optimisation problems are formulated to maximise platform profit. We first compared the proposed method with advanced pricing methods. The simulation results reveal that our method can achieve more profit by serving more travellers with the same fleet, while only slightly increasing VMT, traveller's waiting and detour time. Furthermore, a set of simulations is implemented in a
small network for sensitivity analysis. The proposed method shows great robustness regardless of different choices of parameters.

The third research question has been addressed by the proposed large-scale DRS assessing framework. The complete framework integrates an advanced disaggregated mobility and traffic simulator with optimisation-based operation strategies. SimMobility is utilised to synthesise the future demand for SAV. We compare the optimal assignment and fairness pricing with other heuristic methods and test various scenarios in a real urban network. The simulation results indicate that advanced operation strategies are critical for successful DRS implementation. The fair pricing and optimal matching combined method not only greatly improve the fleet performance, but also alleviate traffic congestion. In contrast, intuitive rule-based methods or separating pricing from matching are unable to exploit the potential of DRS and limit the utilisation of DRS.

6.2 Recommendations for future research

Over the past few years, there has been a growing number of studies about on-demand mobility and its impact on society, transportation, and the environment. Numerous innovative strategies have been proposed for the sake of improving the efficiency of such a system. Nonetheless, compared to ride-hailing, ridesharing has not been as well embraced by the public. Aside from the complexity of ridesharing algorithms, people’s psychological attitudes, such as safety and privacy concerns, as well as discomfort due to sharing, hinder the widespread adoption of such a service. However, with the advent of automated driving technology, shared minibuses or shuttles might prove to be promising carriers for ridesharing implementation. Based on the findings and methodologies of this dissertation, here are the recommendations for future research.

Throughout the thesis, we deliberately ignore the driver’s behaviour as we aim to contribute to both human-driven and SAV research. Nonetheless, we are fully aware of the importance of drivers, who play a critical role in the two-sided market of MoD services (Ashkrof et al., 2022). Therefore, it would be interesting to model the driver’s behaviour in terms of pricing and routing.

Additionally, vehicle empty driving, whether for relocation purposes or while en route to pick up passengers, is believed to contribute to congestion. We ignored the vehicle relocation in the first and second publications. However, we found in the third paper that vehicle relocation can greatly improve the system performance and serve more passengers when the supply-demand is imbalanced, as is often the case in practical scenarios. Therefore, how to efficiently relocate vehicles, such as using machine learning methods to predict future demand, is a promising direction for
future research. Besides, accounting for the inconvenience of relocation trips, location-specific pricing methods could counteract the operational cost of relocation.

Meanwhile, fleet sizing is a critical element in MoD operation, closely related to and interacting with various aspects of system performance such as operational cost, the number of satisfied trips, vehicle idle time, empty driving distance, and traffic congestion. In this thesis, we assume a fixed fleet size. However, it would be interesting to integrate the fleet size design problem with conventional matching and pricing ridesharing problems, or to integrate fleet sizing with endogenous demand and congestion effects (Fan et al., 2023).

On top of that, it would be interesting to investigate the cooperation and competition between different on-demand service providers. Most of the preceding ridesharing research assumes a single centralised service operator. In reality, there are multiple service providers, such as Uber and Lyft, which are operating similar mobility services and competing for customers. Recently more studies (Wang et al., 2022; Kondor et al., 2022) have started to investigate the interplay between multiple MoD operators. However, exploring the effect of such competition on society and the transportation system, as well as how to regulate such competition or advocate cooperation from the government’s perspective, remains a challenging problem.

Finally, integrating simMobility with traffic simulators to explore the interactions between traveller’s behaviours and the ridesharing service quality would be a promising avenue. Current operation-focused studies employ existing datasets to test the performance of proposed strategies. However, when it comes to the SAVs, the lack of actual datasets requires using simMobility method to predict and generate future demand. Instead of using fixed travel demand, it would be interesting to investigate the impact of DRS-SAV on traveller behaviours and the transportation system, including both public transit and private cars.


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References


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Excessive private vehicles in densely populated cities, together with the increasing need for mobility, have been constantly challenging the existing transportation systems. Fortunately, mobility on-demand services, such as ride-hailing and ridesharing, are becoming a growing trend in megacities due to their convenience and cost-effectiveness. These services are envisioned as enablers of a shift from car ownership to vehicle usage. Nonetheless, the impact of mobility on-demand service on transport systems is complicated and largely depends on governance and operation strategies. Accordingly, this dissertation aims at developing novel management strategies, involving matching, pricing, and routing, to improve ridesharing system efficiency. Meanwhile, the impact of such methods on urban transportation systems is evaluated.