A survey of models and algorithms for optimizing shared mobility

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Abstract

The rise of research into shared mobility systems reflects emerging challenges, such as rising traffic congestion, rising oil prices and rising environmental concern. The operations research community has turned towards more sharable and sustainable systems of transportation. Shared mobility systems can be collapsed into two main streams: those where people share rides and those where parcel transportation and people transportation are combined. This survey sets out to review recent research in this area, including different optimization approaches, and to provide guidelines and promising directions for future research. It makes a distinction between prearranged and real-time problem settings and their methods of solution, and also gives an overview of real-case applications relevant to the research area.

Keywords: Optimization, passenger and freight transportation, prearranged and real-time ridesharing, exact and heuristic methods.

1. Introduction

The concept of shared mobility has gained popularity in recent years, attracting attention from the operations research community, especially after the world of transportation witnessed a mini-revolution with the launch of shared mobility services like Vélib, Autolib, Zipcar, Car2Go and others. Emerging challenges, such as growing levels of traffic congestion and limited oil supplies with their increasing prices, together with the rising environmental concerns have pushed research towards more sharable and sustainable systems of transportation. Applying this *sharing* concept in real-life transportation systems is expected to afford a set of potential benefits, whether for people sharing their daily trips or for combined passenger and freight transportation.

Shared mobility comes with many benefits, such as decreasing congestion and pollution levels and reducing transportation costs for both people and goods, but it also has challenges that are holding back widespread adoption. Furuhata et al. (2013) identified three major challenges for agencies providing shared rides to passengers. These are: designing attractive mechanisms, proper ride arrangement, and building trust among unknown passengers in online systems. Thus, in order to be adopted more widely, a shared mobility service should be easy to establish and provide a safe, efficient and economical trip. As such, it should be able to compete with the immediate access to door-to-door transportation that private cars provide (Agatz et al. (2012)).

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Another important aspect is the emergence of autonomous mobility services and their potential application to existing shared mobility systems. Fully autonomous vehicles are expected to reduce traveling costs and provide a safer and more comfortable and sustainable mode of transportation (Meyer et al. (2017)). If those assumptions translate to reality, autonomous vehicles will dramatically change the urban landscape, and if they can be used as a shared transportation service, they could reshape the future of shared mobility systems (Chen et al. (2016b)).

From a logistics system perspective, swiftly-growing urbanization rates, and consequently the potential change in people's demands for goods in urban areas, justify the need to develop new urban logistics systems. These new systems should ensure efficient urban mobility, not just for people, but for goods as well (Fatnassi et al. (2015)). Thus, much of the recent research has focused on increasing the sustainability of mobility systems. Projects have focused on improving existing transportation systems and service quality and designing new systems that can offer a more sustainable and ecological approach and thus contend with rising urban challenges. One innovative idea is to combine individual freight and passenger transportation streams in an urban area, prompting efforts to study the efficiency gains made when people and goods share rides and identify the potential challenges facing this combination.

The increasing need for new technologies and services that support the development of sustainable and innovative shared mobility systems is coupled with the need to develop new operations research models and optimization approaches. An increasing amount of research is thus directed towards building new models and methods that can efficiently operate these systems. Reviewing the literature on shared mobility systems for passenger transportation, Furuhata et al. (2013) surveyed the existing ridesharing systems and identified their key challenges. The paper also classified these systems according to their different features, matching search strategies, pricing methods and target demand segments. Agatz et al. (2012) surveyed the different operations research models that allow travelers (drivers and riders) to be matched in real-time, and reviewed the optimization challenges that arise in such real-time systems and the methods used to operate them. A more recent survey by Molenbruch et al. (2017) reviewed the literature on demand-responsive ridesharing systems, called dial-a-ride problems (DARPs). The authors introduce a taxonomy classifying the reviewed papers according to their real-time characteristics, service design, and solution methods. Similarly, Ho et al. (2018) presented an up-to-date review of recent studies on dial-a-ride problems (DARPs) with their different variants and solution methodologies. Moreover, the paper introduced references to benchmark instances, investigates their application areas, and suggests directions for future research. City logistics is a major field of innovation in freight transportation, so the rising importance of sharing aspects in last mile distribution makes it equally important to investigate the latest developments in city logistics. Savelsbergh and Van Woensel (2016) reviewed the most recent trends and challenges in city logistics and identified opportunities for research. Sampaio Oliveira et al. (2017) studied the crowd-sourcing logistics model, which aims to use available capacity on trips already taking place, called the *crowd*, to deliver goods in urban areas. The paper reviewed the latest developments in crowd logistics along with their different features, applications, deployment issues and impacts on city logistics.

Whereas these reviews on shared mobility have focused on either people or freight transportation considering one variant of the problem (dynamic ridesharing systems and carpooling services (Agatz et al. (2012); Furuhata et al. (2013)), DARPs (Molenbruch et al. (2017); Ho et al. (2018)), city logistics (Savelsbergh and Van Woensel (2016)), crowd-logistics (Sampaio Oliveira et al. (2017)) and other variants), here we review different variants of the shared mobility problem for both people and goods. We thus focus on shared mobility systems where *(i)* travelers share their rides to reduce travel costs, usually called *ridesharing* systems, or where *(ii)* passenger and freight transportation are combined. We find that although the different variants can share similar modeling features, formulations and solution approaches, their context of application varies. For example, A DARP-based formulation can be used to model both types of shared mobility systems, but some of its features can vary depending on the context in which it is applied. We thus study these variants according to their modeling choices, defining features and solution methods, and we identify their common and varying characteristics. This survey brings several key contributions: ***(1)*** a comprehensive overview of recent papers on shared mobility for transportation of people and goods, ***(2)*** an extensive study of the different variants of the problem based on their application contexts, models, features and solution approaches, ***(3)*** an overview of the latest trends in research on real-time shared mobility systems, shared autonomous mobility and crowd-based logistics, ***(4)*** a tabulated overview for each section summarizing the reviewed papers and their problem characteristics and solution methods, and ***(5)*** a review of recent shared mobility case studies analyzed and classified according to their scope and the approaches used.

This paper is organized as follows. In section 2, we present the different variants of the shared mobility problem, study their different features and modeling approaches, and explain how we build on them. In section 3, we focus on mobility systems that allow people to share their rides, including those with real-time settings and those that consider shared autonomous vehicles. In section 4, we investigate the latest developments in city logistics and go on to review the integrated passenger and freight transportation problem with its solution methods and applications. This review of the literature on ridesharing and combined systems is split into two separate sections to facilitate the organization of the survey and help readers easily identify the parts of the literature that interest them most. In addition, each section comes with a set of case studies on the relevant shared mobility topics. Finally, in section 5, we summarize the key findings and suggest directions for future research.

2. Shared mobility problems

2.1. Background

As introduced earlier, the concept of shared mobility applies not just to people transportation but also to combined people and freight transportation to make better use of available transportation resources. The literature has introduced a number of variants of the shared mobility problem for people and freight transportation (Figure 1). Shared mobility systems for people transportation aim to minimize the number of vacant seats in vehicles in order to reduce the number of used vehicles, and thus traffic congestion and pollution. This can be achieved using a number of concepts, such as; **ridesharing**, **carpooling**, **vanpooling**, **car-sharing**, **dial-a-ride** and others. **Ridesharing** allows people with similar itineraries and time schedules to share a vehicle for a trip so that each person's travel costs (i.e. fuel, toll, parking expenses, etc.) are reduced (Furuhata et al. (2013)). Based on this definition, we use the term "*ridesharing*" throughout the paper to represent this category of systems in which people share their rides. The idea of ride-sharing has many benefits including reducing travel cost and time, decreasing fuel and energy consumption, alleviating traffic congestion and thus reducing air pollution. There are several variants of the ridesharing problem , most of which develop efficient mobility systems that allow travelers to share their trips and thus enhance their travel experience (Agatz et al. (2012)). Planning for rideshared trips can be categorized into 'prearranged', or 'static' ridesharing, and 'dynamic' ridesharing. In **prearranged ridesharing**, travelers' demand (drivers and riders) is known beforehand (i.e. travelers' origins, destinations, and departure and arrival times are given in advance) and can thus be used to plan their shared trips. Such prearranged services are mainly used for planning regular commuter trips as well as shared long-distance trips (e.g. inter-city trips). However, long-distance trips generally have more flexible time schedules than commuting trips. **Dynamic ridesharing** focuses on matching drivers and riders on-the-fly. In other words, new drivers, offering rides, and riders, requesting rides, can enter and leave the system at any time, and the system then tries to match their trips at

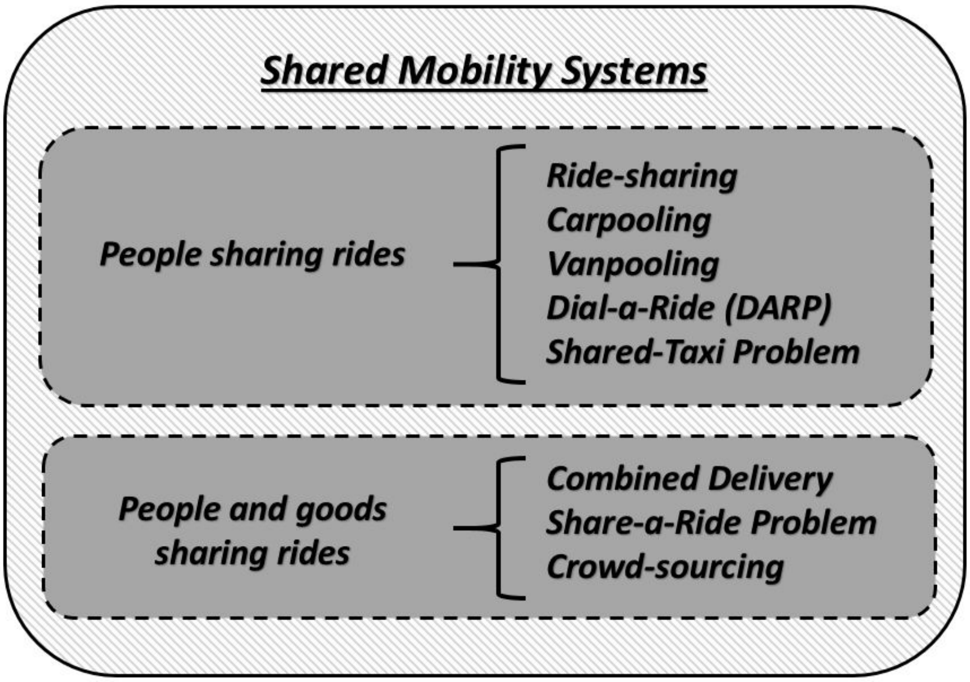

Figure 1: Shared mobility - Problem variants

short notice (or even en-route). In their review of dynamic ridesharing systems, Agatz et al. (2012) focused on the optimization problem of efficiently matching drivers and passengers. This ride-matching problem has two steps. First, it determines efficient vehicle routes, and then it assigns passengers to those vehicles taking into consideration the conflicting objectives of maximizing the number of matched travelers and minimizing the operation cost and passenger inconvenience (these real-time systems are further explored in section 3.2).

One variant of the ridesharing problem is called the carpooling problem. **Carpooling** was first introduced by large companies in an effort to encourage their employees to pick up colleagues while driving to/from work. The idea was to minimize the number of cars traveling to their sites every day (Baldacci et al. (2004)). Carpooling is generally used for commuting but has become increasingly popular for longer one-off journeys. The carpooling problem aims to determine the subsets of travelers that will share the same trip and the paths these shared trips should follow in order to maximize sharing and minimize travel costs. In order to increase the flexibility of carpooling services, which are usually prearranged, the concept of flexible carpooling has been introduced (Shaheen et al. (2016)). **Flexible carpooling**, also called casual carpooling or slugging, is a semi-organized service in which destination, meeting point and departure times are all known in advance among potential participants. The main difference is that rideshares are formed spontaneously at the meeting point on a first-come first-served basis (Chan and Shaheen (2012)). This enhanced flexibility opened the door to deploying new carpooling services, not only for daily commutes but for long-distance trips as well (see SlugLines, SmartSlug and KangaRide for example). Along similar lines, Kaan and Olinick (2013) consider the **vanpooling** problem with its optimization models and solution algorithms. In this problem, commuters in the vanpool drive to an intermediate location, called a park-and-ride location, and then take a van and ride together to the target destination. Car/vanpooling, which can be operated on daily or long-term bases (Wolfler Calvo et al. (2004)), provide regular and cost efficient means of transportation, they do not accommodate unexpected changes of schedule. By contrast, the **dial-a-ride (DARP)** provides shared trips between any origin and destination in response to advanced passenger requests within a specific area (see Molenbruch et al. (2017); Ho et al. (2018) for recent review). The DARP models a demand-responsive transportation mode in which the aim is to define a set of routes in order to satisfy passenger requests at minimized costs (Masson et al. (2014); Ritzinger et al. (2016)). Each request consists of transporting a passenger from his/her origin location to his/her destination location where passengers with similar route and time preferences can share the same vehicle as long as there is capacity. As such, solving the DARP is about minimizing the total travel distance, and thereby travel time, while respecting rider-specified time restrictions and any vehicle restriction constraints (more problem features and objectives are discussed in sections 2.2 and 2.3 respectively). These demand-responsive systems often focus on providing service to people with reduced mobility (e.g. elderly, handicapped etc.). The main difference between a DARP and a dynamic ridesharing problem is that a driver in the DARP can provide service to a wide set of passengers, as the drivers in this case are part of the service, and thus have less restrictions regarding route and time. In contrast, a driver in a dynamic ridesharing context can only provide service to passengers with similar route and time schedules to the driver (Gu et al. (2016)). In other words, in DARP, all drivers are professional and typically operate out of one or more depots, whereas in dynamic ridesharing each driver is often an individual who has a specific origin and destination and may have preferences to be considered (like a maximum detour time, maximum number of stops, etc.).

Another variant of the ridesharing problem is the **shared-taxi** problem introduced by Hosni et al. (2014) as a multi-vehicle dynamic DARP. In the shared-taxi problem, passengers indicate their desired pickup and drop-off locations, their earliest/latest acceptable pickup/drop-off time, and a maximum trip time. Solving the shared-taxi problem aims to optimally assign passengers to taxis and determine the optimal route for each taxi, which means this problem shares the same characteristics, such as demand-responsiveness, as the DARP. However, the main difference is that most shared-taxi services aim to minimize the response time to passenger requests whereas dial-a-ride systems aim to minimize vehicle operating cost by reducing the number of vehicles used to serve given passenger demands (Jung et al. (2016)). When considering ridesharing variants, it is important to differentiate ridesharing from carsharing, which is a different concept. **Carsharing** is a car rental service in which people who are interested in making only occasional use of a vehicle can rent cars for short periods of time (Agatz et al. (2012)). Although carsharing shares the aim of reducing car usage and increasing mobility with ridesharing, the optimization challenges that arise in both systems are different. Those challenges include, determining depot locations and assigning and redistributing vehicles among these depots. Although the carsharing concept allows people to occasionally use a network of vehicles for short periods of time, they do not necessarily share their trips with other travelers, which rules carsharing systems outside the scope of this review. Here we use the different variants of ridesharing introduced so far to classify recent studies on shared mobility systems for people transportation (see section 3).

On the other hand, **combining** passenger and freight flows has the potential to improve the performance of existing transportation services as their needs can be satisfied with fewer resources (Trentini et al. (2015)). In this kind of **combined delivery** system, spare capacity in public transport systems can be used for retail store replenishment, or taxis can move or deliver freight when carrying a passenger or during idle time. In an integrated system, when transporting freight, we need to decide whether to use a pure freight or people transportation network or a combination of the two (Savelsbergh and Van Woensel (2016)). This choice depends on the origin location, destination, and due time of freight. In our paper, the focus is on systems in which people and freight transportation are combined. Li et al. (2014) introduced the **share-a-ride**

problem (SARP) in which people and parcels are handled in an integrated way by the same taxi network. In this problem, a number of taxis drive around in an urban area to serve passenger requests but can also deliver some freight (parcels), from their origins to their final destinations, as long as these deliveries do not add significant extra time to their passengers' trips. Further, Ghilas et al. (2016a) explored an integrated solution for simultaneous passenger and freight transportation so that fewer vehicles are required. In their problem, a set of pickup and delivery vehicles is used to serve a set of parcel delivery requests where a part of the delivery process is carried out on a scheduled passenger transportation service. Trentini et al. (2015) introduced another integrated system in which goods are transported in city buses, which have some spare capacity, from a distribution center to a set of bus stops before they can be delivered to final customers by a fleet of near-zero emissions city freighters.

Increasing interest in such combined systems has led to the concept of crowd-sourced delivery. **Crowd-sourcing** allows activities that were traditionally performed by a certain agent or company to be outsourced to a large pool of individuals (Goetting and Handover (2016)), which aligns it to the concept of *sharing economy*. Crowd-sourced delivery, or **crowd-shipping**, is based on sharing excess and underused assets, which here translates as using excess capacity on journeys already taking place in order to make deliveries. As such, crowd-sourced delivery could revolutionize delivery by increasing operational efficiency and reducing transportation costs. The problem of combining passenger and freight transportation shares many features with the ridesharing problem where only passengers are considered. However, it has some complicating features as well, such as transfers, synchronization, capacity constraints, multiple echelons, etc. (Savelsbergh and Van Woensel (2016)). The key to successfully combining passenger and freight transportation is to ensure there is no significant negative effect on people when goods are transported or delivered during their journey. We explore and discuss these combined systems in section 4.

Variant	Goods transport	On-demand	Daily commute	Long-distance	Pre-arranged	Real-time
Carpooling			✓		✓	
Flexible Carpooling			✓	✓	✓	✓
Vanpooling			✓		✓	
Prearranged Ride-sharing			✓	✓	✓	
Long-distance Ride-sharing				✓	✓	
Dynamic Ride-sharing		✓				✓
DARP	✓	✓			✓	✓
Shared-Taxi		✓				✓
Combined Delivery	✓				✓	✓
Share-a-Ride Problem	✓				✓	✓
Crowd-sourcing	✓			✓	✓	✓

Table 1: Shared mobility variants for people transportation - Different characteristics

Table 1 gives a roll-up summary of the different variants of recent shared mobility problems. Below we give a more detailed analysis of these variants and the modeling approaches and optimization methods commonly used.

2.2. *Modeling and features*

In the shared mobility problem, a set of transportation requests, representing passengers or passengers-plus-goods, need to go from their origins to their destinations while satisfying certain criteria and respecting certain service specifications. The service provider receives these different requests and then arranges with its available transportation resources (vehicles, car parks, drivers etc.) for the delivery process. This planning of shared trips is one of the main tasks in shared mobility. In this problem, the service is shared in the sense that multiple requests might be serviced using the same resource (e.g. vehicle) at the same time. In order to establish this shared service, a set of features and constraints should be considered. Shared mobility problems are usually modeled using different vehicle routing problem (VRP) formulations that represent these features as a set of additional constraints characterizing each variant of the problem. Many of these features can be found in both ridesharing systems and systems combining passenger and freight transportation, but other features can relate to either ridesharing systems or combined systems, but not both. In the following, we summarize the different types of features and constraints reported in the literature for the shared mobility problem. Furthermore, we identify problem variants that consider each type of constraint discussed in order to get a clear picture of these variants and their common and different characteristics.

Routing constraints (RC):

In shared mobility systems, every request needs to be transported from its origin to its destination, and the origin location has to be visited first. This feature applies to both passengers and goods but can have some variations. For example, in some ridesharing applications, a passenger can be picked up or dropped off at an intermediate location, usually called *meeting point*, which can lead to shorter detours (Stiglic et al. (2016a)). Another example is found in multi-echelon transportation systems where goods are transported through a scheduled line to a public transport station and then delivered by vehicle to their final destination (Ghilas et al. (2016b)). While most models insist that each transportation request is served by one vehicle at most (as in Hosni et al. (2014) for a shared-taxi problem and Li et al. (2014) for a multi-echelon combined system), some models allow these requests to be transferred using multiple vehicles (as in Herbawi and Weber (2011) for a dynamic multi-hop ride-sharing problem and Masson et al. (2014) for a DARP with transfers).

Furthermore, in demand-responsive transportation systems (including DARP and shared-taxi systems) and many logistics systems in which a fleet of vehicles is located at specific locations (depots) and ready for service, there is an additional constraint imposed on the route each vehicle will follow: each vehicle should return to one of the depots when its trip is finished. In some simplified problem settings, a vehicle might have to return to the same depot from which it started its trip. Moreover, any shared mobility model must ensure each vehicle reaches and leaves a corresponding location (request origin or destination, depot, intermediate meeting point or a public transport station). This constraint ensures conservation of flow, and is very common in shared mobility problems. In some combined systems, passenger requests are given higher priority when building routes to serve both passengers and goods (Li et al. (2014)). The routes are first constructed based on passenger requests, then freight requests are only inserted when passenger trips are not significantly affected. Routing constraints are usually considered hard constraints, because violating them might lead to detached vehicle routes or a request being picked up but not delivered to destination. Thus, these constraints need to be strictly respected when modeling and solving a shared mobility problem.

Time constraints (TC):

Besides indicating where a transportation request needs to be picked up and where it should be transported to, a shared trip must also indicate when this process can take place. This is usually done by associating a *time window* with each transportation request, whether for a passenger or freight. In ridesharing systems, this time window is usually given by each passenger indicating the earliest departure time from his/her origin and the latest arrival time at his/her destination. Thus, in order for a passenger to participate in a shared trip, he/she should be picked up at origin and dropped off at destination within the time window he/she has specified (Stiglic et al. (2016a)). Like passenger requests, freight delivery requests may also be associated with a time window. In some cases, two time windows are used to represent these time restrictions: a pickup time window, indicating when a request should be picked up, and a drop-off time window, indicating when it should be delivered (Ghilas et al. (2016a)).

In addition, there could be added restrictions on the duration of the shared trips. In most ridesharing systems, a set of drivers, offering rides, and riders, looking for rides, are matched to share their trips. In order to accommodate the riders, the driver might have to make a detour from his original itinerary and make some extra stops (Furuhata et al. (2013)). The length of this potential detour depends on how far the driver is willing to extend his/her trip time. Moreover, if drivers have sufficient time flexibility, they might provide rides to multiple riders simultaneously. Of course, pick-up and drop-off of several riders in a single trip adds layers of complexity to the planning decisions (Agatz et al. (2011)). Thus, a successful ridesharing respects the departure and arrival times for all participants, as well as the maximum detour time for the driver. In DARP-like systems, drivers are employed by the service provider (like in shared-taxi services), and thus have no preferences in terms of departure, arrival and detour times. In such systems, other time restrictions might be considered, such as: maximum working hours for drivers, a maximum response time for processing a passenger request, and the maximum service time for vehicles, which is usually related to recharging and maintenance operations (Li et al. (2014)). Most of the previous scheduling constraints also apply to combined systems transporting passengers and goods through the same network. One difference is that in combined systems, every participant specifies a trip excess time which indicates his/her readiness to extend the trip in order to pick up and deliver some goods (Li et al. (2016a)). Thus, successful integration of passengers and goods in a shared trip should respect the maximum extra time that participating passengers are ready to accept.

Unlike routing constraints, time constraints, also called scheduling constraints, are considered soft constraints, because violating them might not detach vehicle routes or intercept the flow, but may result in passengers or freight arriving late to their destinations, especially in real-world conditions. Violating these constraints may thus be allowed if it increases the likelihood of finding a solution, but discouraged through a penalty cost.

Capacity constraints (CC):

A capacity constraint is a factor that prevents a shared transportation resource from being overused. In ridesharing systems, a capacity constraint limits the number of passengers sharing the same vehicle at the same time to the number of vacant seats in that vehicle (Santos and Xavier (2015)). Besides limiting the maximum number of passengers, many vanpooling systems also require a minimum number of passengers to form a vanpool for a shared trip (Kaan and Olinick (2013)). Number of participants in a shared vanpooling trip must therefore be within these two limits. In logistics systems, a capacity constraint ensures that the volume of goods to be transported does not exceed the available space provided by the transportation service (Savelsbergh and Van Woensel (2016)). This constraint holds valid whether goods are transported using a fleet of vehicles (Li et al. (2014)), public transport (Behiri et al. (2018)) or any other transportation service. In addition, in integrated models where passengers and goods are transported together, constraints on both capacities may need to be considered. This is because most of the reviewed literature assumes that passengers and goods are transported in separate compartments (Ghilas et al. (2016c)). In an uncertain environment, where passenger or freight demand is stochastic, these capacity constraints might be violated, and should thus be treated using stochastic approaches.

Cost constraints (OC):

In some problem settings, a ridesharing participant may specify a maximum travel cost that he/she is willing to pay for the shared trip, and should thus be matched to shared trips that stay under the maximum amount specified. Furthermore, in order to attract more participants, travel costs in ridesharing systems should be competitive with other modes of transportation. A good example can be found in vanpooling systems where passengers are only assigned to vanpools that are cheaper than their current commuting costs (Kaan and Olinick (2013)). However, integrating goods delivery with passenger trips that already take place could decrease travel costs for participants and transportation costs for goods (Crainic and Montreuil (2016)). Even if passengers would have longer detours when freight delivery is added to their trip, they would still get lower travel cost than if no deliveries are added. However, the bulk of research on these combined systems does not consider travel and transportation cost as a feature or constraint in the system but more as an objective to be minimized given its importance for service operators (as we will see in Section 2.3).

Synchronization constraints (SC):

Many recent research papers have focused on studying different synchronization constraints in shared mobility problems. An extensive review by Drexl (2012) identified five different types of synchronization constraints for VRPs. The first type of synchronization constraint, called **task synchronization**, is required when multiple transportation units are capable of serving a task (i.e. a transportation request). In other words, a task synchronization constraint ensures that each request (passenger or freight) is served exactly once by one or more vehicles (Fink et al. (2018)). Furthermore, when the operations performed by different transportation units need to be coordinated in terms of space and time, **operation synchronization** is required. In other words, a schedule for a vehicle in a shared mobility system should be built to take into account the schedules of other vehicles, so their schedules need to be synchronized. Logistics systems offer good examples of when operation synchronization is needed: for example, a system where two different vehicles arrive at different customer locations, one delivering the product and the other carrying the crew to install it (Hojabri et al. (2018)), or a system in which multiple vehicles cooperate in order to transport one big-size cargo (Hu and Wei (2018)). Another type of synchronization constraints is called **movement synchronization**. In some ridesharing systems where passengers are allowed to transfer from one vehicle to another on the way to their destination, the arrival and departure of vehicles to and from transfer points need to be synchronized (see Masson et al. (2014) for an example). Another example is found in multi-echelon systems where goods are transported with passengers through a scheduled transport line after being collected by a fleet of vehicles. Such systems also need to ensure synchronization between requests and the collecting vehicles, and between requests and the scheduled line departures (Ghilas et al. (2016b)). **Load synchronization** ensures that the right amount of load is collected and delivered to a customer, or in other words, no load is lost when transferred between different transportation units. This is the case when deliveries are done using two distinct fleets of vehicles where a request is transferred from one vehicle to another at satellite locations before it can be delivered to a customer (Grangier et al. (2016)). The same load synchronization constraint is needed when deliveries are transferred between pickup and delivery vehicles and a public transport line in a multi-echelon transportation system. Finally, **resource synchronization** ensures that the use of resources common to different transportation units is limited to availability (Drexl (2012)). Number of drivers, vehicle fleet size, available parking slots, vacant seats for riders to share, and the available space and capacity in transportation units in both ridesharing and combined systems are all examples of limited resources whose use needs to be synchronized. Xiang et al. (2006) considered a DARP with passenger-driver and passenger-vehicle compatibility constraints. They classified passengers into different levels, and ruled that vehicles could only accommodate passengers of corresponding levels, i.e. a passenger can only use a vehicle of the same or higher level. As a rule, modeling synchronization constraints yields more complex and non-linear mathematical formulations (e.g. implications) which need to be handled using linearization techniques. However, these constraints are important for modeling realistic settings and, from an algorithmic perspective, can be used to decompose hard problems (e.g. they can be used as coupling constraints in a column generation based approach; see Fink et al. (2018)).

2.3. *Objective functions*

Most objectives that shared mobility problems aim to optimize can be classified into two main categories; **operational** objectives and **quality-related** objectives. Operational objectives are usually about optimizing system-wide operating costs, such as minimizing vehicle miles and transportation time, maximizing the number of serviced requests, minimizing the number of required vehicles, and others. Quality-related objectives are about enhancing the quality of service provided. For example, minimizing total passenger ride or waiting time might yield a better performance from the passenger perspective but not from a system-wide perspective. Furthermore, minimizing system-wide travel time does not necessarily mean shorter travel times for every passenger. This difference between **collective** and **individual** perspectives in shared mobility systems justifies the need for methods that consider both operational and quality-related objectives. A good example can be found in Kalczynski and Miklas-Kalczynska (2018) where a decentralized approach takes carpool participant preferences into account while maintaining the same system-wide savings that can be obtained in centralized approaches.

Much of the research on shared mobility is focused on optimizing a single operational objective, but there are papers that consider multiple-objective systems combining operational with quality-related objectives. In **single objective** systems, service quality considerations are represented as constraints in the model to ensure a minimum service level (Molenbruch et al. (2017)). In other words, a set of constraints limiting passenger extra ride times, caused by deviations from their original routes, are added when optimizing the system. Likewise, most of ridesharing research has focused minimizing the system-wide travel distance (vehicle miles) or total travel time. For example, in Wolfler Calvo et al. (2004), the system-wide travel time in a carpooling system is minimized with an added penalty cost for unserved requests. In a dynamic environment, where transportation demand is revealed in real-time, satisfying full demand may not be attainable, in which case it becomes pertinent to maximize the number of served requests as it extends the reach of the transportation service (Berbeglia et al. (2012)). Some studies have considered maximizing the total profit obtained from the ridesharing system (see Hosni et al. (2014) for a shared-taxi problem and Parragh et al. (2015) for a DARP) or minimizing the total cost of operating it (see Kaan and Olinick (2013) for a vanpooling problem and Braekers et al. (2016) for a DARP). Moreover, some more problem-specific objectives have been considered in the literature, such as; minimizing the number of required vehicles (Guerriero et al. (2013)), minimizing vehicle emissions (Atahran et al. (2014)), maximizing passenger occupancy rate (Garaix et al. (2011)), minimizing staff workload (Lim et al. (2017)), and maximizing system reliability (Pimenta et al. (2017)). Most studies on combined crowd-sourced systems have focused on either maximizing the profit obtained by integrating passenger and freight flows (Li et al. (2014)) or minimizing the operational cost of these systems (Ghilas et al. (2016a)), but there have been efforts to consider additional objectives, such as minimizing the number of vehicles required to operate the system (Trentini et al. (2015)) and minimizing the total wait time of demands before being serviced (Behiri et al. (2018)). The recent shared mobility studies listed in Table 2 and 5 have been classified using these different objectives.

As mentioned above, **multi-objective** systems consider a combination of two or more of the above-listed single objectives. Solving multi-objective problems requires different methods to those employed for solving single-objective problems. The literature identifies three main techniques for dealing with multi-objective problems. The first, and most popular approach is to aggregate the different objectives into a **weighted-sum** objective with different measures. In this approach, a weight has to be defined for each of the combined objectives. As such, the relative importance of each objective needs to be quantifiable and well-defined. A good example can be found in Kirchler and Wolfler Calvo (2013) who used an aggregated objective function combining six different objectives: minimizing routing cost, excess ride time, passenger waiting time, route durations, early arrival times at pickup and delivery nodes, and number of unserved requests. Another example of a weighted-sum objective can be found in Lehuédé et al. (2014). One drawback of the weighted-sum approach is that it might not be able to find the full set of non-dominated solutions for optimization problems in which some variables are constrained to be integers (i.e. non-convex optimization problems). In addition to weighted-sum approach, some papers consider a **hierarchical**, also called **lexicographical**, objective function. In this approach, the different objectives are ordered according to their importance, and first the main objective is optimized to generate a set of solutions, then a secondary objective is optimized whenever two solutions with the same quality, in terms of the main objective, are obtained. Stiglic et al. (2016a) considered a ridesharing system with a lexicographic objective function. First, the system generates solutions that maximize the number of matched participants and then the secondary objective is used to select solutions that maximize the distance savings (see also Schilde et al. (2014)). This approach is therefore efficient in problems where the different objectives can be classified into main and secondary objectives. Finally, the third approach for dealing with multi-objective problems is to obtain the set of non-dominated solutions in terms of the different criteria, called **Pareto frontier** (Paquette et al. (2013)). The main advantage of this approach is that it helps decision makers analyze the relations between the different objectives, as it provides all the possible optimal solutions. However, this approach might not be applicable for dynamic shared mobility systems where decisions need to be taken in relatively short time frames, as it requires obtaining the full set of optimal solutions and a human being to select the best solution among them (Molenbruch et al. (2017)).

2.4. Computational complexity and solution approaches

As mentioned above, the shared mobility problem is a generalization of the vehicle routing problem (VRP) and is NP-hard in general. In addition, simplified variants of the problem (e.g. with a single-driver single-rider setting, single pickup and dropoff or a single-objective function) are still NP-hard (Gu et al. (2016)). Furthermore, solving these problems becomes more complex when they have dynamic settings and stochastic input data. Thus, both **exact** and **heuristic** solution approaches have been introduced in the literature. Due to the complexity of shared mobility problems, most studies have focused on developing approximation and heuristic approaches for solving them. That said, a number of studies have developed exact methods for solving simplified variants of the problem. These exact methods are usually used to solve static problem variants with deterministic data, e.g. a column generation-based method for the carpooling problem (Baldacci et al. (2004)), a branch-and-cut algorithm for a multi-vehicle static DARP (Cordeau and Laporte (2007)), a two phase method for generating optimal matches in a static ride-sharing problem (Stiglic et al. (2016a)), and a branch-and-price algorithm for a crowd-sourced system with a scheduled line for transporting passengers and goods (Ghilas et al. (2016a)). However, solving these static variants becomes more complex when complicating features are added to the system, such as allowing passenger transfers, integrating public transport, and considering vehicle/driver compatibility. To deal with these complex features, a number of heuristic approaches have been introduced, such as a local search strategy for a static DARP with complex constraints (Xiang et al. (2006)), an Adaptive Large Neighborhood Search (ALNS) heuristic for the DARP with transfers (Masson et al. (2014)), a constraint-based Large Neighborhood Search (Jain and V. Hentenryck (2011)), an integrated column generation in a Large Neighborhood Search (Parragh and

Schmid (2013)) for a static DARP, a Lagrangian decomposition heuristic for the static shared-taxi problem (Hosni et al. (2014)), and another ALNS approach for the crowd-sourced delivery system with scheduled line (Ghilas et al. (2016b)).

Nevertheless, even these heuristic algorithms often have large computation times limiting the size of instances on which they can be tested, which consequently also limits their usability for large-scale and dynamic systems which need to be re-optimized at regular intervals as new transportation requests enter the system. As a result, heuristic approaches need to be improved so that good-quality solutions can be obtained in short computational times. In order to clarify how a heuristic approach can be improved to handle dynamic problem settings, we take the ALNS heuristic as an example. In a classical ALNS-based method, a set of insertion and removal operators are used to enhance a current solution. Thus, at each iteration, one insertion operator and one removal operator are selected and applied to the current solution seeking an improvement. This process continues until an acceptable solution is found or a maximum number of iterations is reached. In order to minimize the number of required iterations, and thus the computation time, the classical ALNS can be improved by adding a score to each operator (Masmoudi et al. (2016)). If using one operator, whether it is an insertion or removal operator, brings an improvement to the current solution, then the score of the operator used will be increased. The probability of using this operator in the next iterations will thus be higher, and so an acceptable solution would be reached in a shorter time.

For the **uncertainty** factor, more advanced techniques are needed for solving shared mobility problems with one or more source of uncertainty. This is because a solution obtained by solving the deterministic version of the problem might not be valid when uncertainty is revealed. The most common source of uncertainty lies in transportation **demands**, where some of the data on transportation requests is unknown at the moment the shared trips are planned. This uncertainty might be in request occurrence times or locations (Ghilas et al. (2016c)). AAnother important aspect is the stochasticity of travel times, as traffic, accidents, and other factors make it impossible to know travel times between different locations in advance (Heilporn et al. (2011)). Due to the complexity of this uncertainty, most studies have not considered any more than one source. However, there has been some research on integrating multiple sources of uncertainty (e.g. considering stochastic travel times and delivery locations; Li et al. (2016b)). For solving shared mobility problems that involve uncertainty, the literature has identified two categories of methods. The most common approach is to make a decision and then minimize the expected (recourse) costs induced by the consequences of this decision. This approach is called **stochastic programming with recourse**. In the second approach, called **multi-scenario approach**, the expected costs are estimated by evaluating a solution on a set of different scenarios. In this approach, heuristic algorithms can be efficiently used to obtain a solution each time a new scenario is tested (for more details on stochastic models and their solution approaches, interested readers are referred to Ritzinger et al. (2016)).

3. People sharing rides

This section focuses on introducing shared mobility problems for people transportation. The idea is to, *(i)* investigate the potential benefits and planning aspects (Section 3.1), *(ii)* review the modeling choices and optimization approaches in real-time settings (Section 3.2), and *(iii)* discuss the potential integration of new automated services in such shared systems (Section 3.3). We also provide an overview table summarizing the papers reviewed and their problem characteristics and solution approaches (Table 2).

3.1. Planning and potential benefits

As mentioned above, the increasing demand for passenger transportation has attracted more research into enhancing the efficiency and quality of existing public transport systems and developing new systems that can provide more sustainable solutions (Wolfler Calvo et al. (2004)). Ridesharing is one opportunity to provide a reduced-cost mobility service that is as flexible as private cars but can also increase occupancy rates and decrease traffic and pollution levels (Furuhata et al. (2013)).

In a ridesharing system, drivers and riders share the travel costs so that each benefits from the shared ride. Benefit can be obtained when the travel cost of a shared ride is lower than the cost of the alternative means of transport (individual car trips, taxis or public transport). While some users choose to participate in a shared ride to reduce their travel expenses, others may be motivated by the potential social and environmental benefits (Furuhata et al. (2013)). Besides the potential cost savings, ridesharing can also allow drivers to reduce their travel time because they will be able to take high-occupancy lanes reserved for vehicles with two or more occupants (Stiglic et al. (2015)). Riders, on the other hand, may appreciate dispensing with the need to drive or own a vehicle. Despite its potential advantages, there are also major obstacles that prevent wider uptake of ridesharing. According to Furuhata et al. (2013), the two main barriers to wider adoption of ridesharing are coordinating passenger trips that have similar itineraries and time schedules, and developing effective methods to encourage participation. Limited flexibility in participants' itineraries and time schedules may result in many of them not finding a match. Other issues like privacy, safety, social discomfort and pricing are also challenges for ridesharing systems. For example, a potential participant may be willing to share rides with colleagues and friends, but not with complete strangers (Agatz et al. (2012)). As such, new methods for arranging the shared rides need to be developed, and reputation and profiling systems for addressing these social and privacy concerns need to be built.

In order to attract more riders and facilitate matching them in shared rides, we identify some the concepts in the literature that can help maximize the potential benefits of a ridesharing system. One of those concepts is to consider a set of meeting points where a shared ride can take place. Thus, a rider might be picked up at his/her origin location or at a pickup meeting point and dropped off at his/her destination location or at a drop-off meeting point. Meeting points would thus allow drivers to have smaller detours while maintaining a good-enough quality of service for the riders. Stiglic et al. (2015) investigated benefits of using meeting points in a ridesharing system and found that as they can lead to shorter detours, meeting points have the potential to increase the system-wide distance savings as well as the number of participants that can be matched in the system. With the aim of attracting more riders, especially from suburban areas, Stiglic et al. (2018) examined the potential benefits of integrating ridesharing and public transport, and found that the two can prove complementary. While ridesharing can bring passengers from less-densely-populated areas to public transport, the public transport system allows ridesharing to provide service to more passengers and reduce drivers' detours. Another concept is to allow riders requesting a shared ride to transfer between drivers, and thus use more than one driver to reach his/her final destination. Herbawi and Weber (2011) considered a version of this multi-hop ridesharing problem in which the transportation network is formed by driver ridesharing offers. Thus, drivers do not deviate from their original itineraries while riders have to find routes that minimize their travel time, costs, and the number of transfers required to reach their final destination. Masson et al. (2014) considered ridesharing settings in which riders are allowed to transfer between vehicles at intermediate transfer points, and suggested that these transfers can lead to considerable savings, especially when multiple transfers are allowed. To guarantee a certain level of service, Lee and Savelsbergh (2015) investigated the benefits of deploying a number of dedicated drivers to provide service to unmatched riders, and identified the environments in which dedicated drivers are most beneficial. When the number of riders increases to a certain point, the need to deploy a set of dedicated drivers became essential to maintain an acceptable service level.

3.2. *Real-time ridesharing*

As introduced earlier in section 2, a real-time ridesharing system aims to bring travelers together at short notice. Furthermore, a real-time ridesharing system might need to be re-optimized at regular intervals as more travelers enter or leave the system. In addition, travelers already en route need to be notified of any change of plan at each time the system is re-optimized, as their original routes might be updated. This automated process requires efficient models and algorithms for matching drivers and riders in very short computation times. As a result, many recent studies on real-time ridesharing systems have focused on developing heuristic approaches, as they can provide good-quality solutions in relatively short computation times. Nevertheless, such systems can also be addressed by enumeration (exact) algorithms (like branch-and-bound). Due to their brute-force nature, using enumeration algorithms for such real-time systems may require an additional preprocessing effort in order to fit the short computation times needed. Some preprocessing techniques can tighten travelers' time windows, eliminating unnecessary variables and constraints and identifying inequalities for narrowing the solution space (Liu et al. (2014)). For example, Agatz et al. (2011) introduced an efficient rolling horizon approach that can provide high-quality solutions for dynamic ridesharing systems where drivers and riders continuously enter and leave the system. In a later survey, Agatz et al. (2012) provided a review of the related operations research-based models in the academic literature. Here we review the more recent studies and their solution approaches.

Huang et al. (2013) proposed a branch-and-bound algorithm and an integer programming algorithm for solving the problem of large-scale real-time ridesharing, and introduced a kinetic tree algorithm capable of better scheduling dynamic requests and adjusting routes on-the-fly. Liu et al. (2014) proposed a branch-and-cut algorithm to solve a realistic DARP with multiple trips and request types and a heterogeneous fleet of vehicles with configurable capacity and manpower planning. To solve the dynamic ridesharing problem over a full-day time horizon, Santos and Xavier (2015) suggested dividing the day into time periods, after which a deterministic instance of the problem can be generated and solved by a greedy randomized adaptive search procedure (GRASP). Ma et al. (2015) introduced a dynamic taxi-sharing system based on a mobile-cloud architecture. In their proposition, the system first uses a search method, based on a spatio-temporal index, to find candidate taxis for every ride request, and then a taxi that satisfies the request with the shortest detour is selected through a scheduling process. Jung et al. (2016) later suggested applying hybrid-simulated annealing (HSA) to dynamically assign passenger requests to shared taxis. In addition, it investigates what type of objective functions and constraints could be employed to improve the system and prevent excessive passenger detours. Braekers and Kovacs (2016) proposed different formulations for the DARP with driver consistency (DC-DARP). For solving this problem, the authors developed a large neighborhood search algorithm that finds near-optimal solutions in short computation times. Masmoudi et al. (2017) propose three metaheuristics for solving the Heterogeneous Dial-a-Ride problem (HDARP). These are: an improved ALNS-based method, Hybrid Bees Algorithm with Simulated Annealing (BA-SA), and with Deterministic Annealing (BA-DA). More recently, Masoud et al. (2017) proposed an exact and real-time ride-matching algorithm, and the approach maximizes the number of served riders while accounting for their travel preferences. The system also aims to minimize the number of transfers and waiting times for riders, and make their shared trips more comfortable. As ridesharing participants might not accept the matches proposed by the service provider on-the-fly, it becomes important to analyze how stable the generated matches are. For this purpose, Wang et al. (2018) studies the stability of rideshare matches by providing several mathematical programming methods to generate near-stable matches in real-time. Their results suggested that taking stability considerations into account comes with only a small additional cost to the system-wide performance in terms of traveled-distance savings.

To conclude, the development of new methods and algorithms for providing good-quality solutions in short times is at the heart of the real-time ridesharing concept, which is why we found rising interest from the OR research community to address the optimization issues in real-time ridesharing systems. In many ridesharing systems, like in major metropolitan areas, thousands of drivers and riders might be traveling between thousands of different locations at the same time, thus creating a need for fast optimization approaches that can match their different trips quickly. Most recent studies have focused on developing heuristic approaches that can solve large-scale ridesharing problems in real-time (see Table 2) and the door is open for introducing new heuristic techniques. In what follows, we identify possible directions for future research. First, *(i)*, as few papers have considered synchronization aspects in such real-time systems (see Table 2), more research should study these aspects and introduce them in future ridesharing systems. An example would be to allow flexible driver-to-vehicle assignments and multi-depot settings which require drivers and vehicles to be synchronized. Second, *(ii)*, very few papers have considered cost restrictions when matching travelers in share rides (cost constraints). An interesting avenue for research would be to focus more on individual traveler benefits from ridesharing beside the system-wide cost considerations. Third, *(iii)*, decomposition techniques could be integrated into algorithms for solving multi-objective problems to consider more quality-related objective functions. This is because most of the reviewed papers have considered a single operational objective with a minimum service quality level due to complexity aspects (see Table 2). Finally, *(iv)* for exact approaches, we see three possible techniques to enhance their performance on responding to real-time system needs. These are: developing preprocessing techniques that can decrease the enumeration effort, decomposing the problem based on geographic partitioning or time intervals to make the size of the problem to be solved at each time smaller, and developing faster algorithms for solving the subproblem in a decomposition-based approach (e.g. branch-and-price, branch-and-cut, and so on) where most of the computational effort is spent on solving the subproblems. That said, ridesharing systems that can handle requests dynamically are clearly gaining the upper hand. As new innovations and transport technologies are introduced, we need more research into responding to traveler needs in future real-time ridesharing systems.

3.3. *Ridesharing with autonomous vehicles*

Autonomous vehicles (AVs), also dubbed driverless, automated or self-driving, are an emerging technology expected to bring fundamental shifts in people transportation. AVs are expected to provide a sustainable solution that can enhance road safety levels and traffic flows, reduce fuel consumption, and thus improve passenger mobility in general (Katrakazas et al. (2015)). The potential deployment of autonomous vehicles in tandem with the increasing need for shared mobility services has attracted the attention of the operations research community, especially now that many large mobility providers (Tesla, Ford, Lyft and others) have announced plans to deploy new autonomous mobility services (Sparrow and Howard (2017)). Furthermore, recent studies on different cities have concluded that if AVs are shared, then the number of vehicles needed to provide service to all travelers will significantly decrease (Levin et al. (2016)). Despite their potential benefits, shared autonomous vehicles also come with security concerns. In other words, if autonomous vehicles do not prove safer than human-driven vehicles, they might not be legally viable for widespread use (Hevelke and Nida-Rümelin (2015)). In a study assessing public interest in such new technology, Daziano et al. (2016) derived estimates of how much consumers are willing to pay to let vehicles drive for them. Their results show that modeling flexible user preferences is an important determinant of the amount they are willing to pay for automation. Krueger et al. (2016) showed that other service attributes, such as travel cost, travel time and rider waiting time, might be critical factors for uptake of shared autonomous vehicles (for related studies, see Bansal and Kockelman (2016),Yap et al. (2016), Bansal et al. (2016), Zmud and Sener (2017)). Another concern is the potential increase in vehicle miles traveled due to repositioning trips performed by shared autonomous vehicles in order to reach new travelers.

Reference	Problem variant	Method	Objective	Constraints					Characteristic
				RC	TC	CC	OC	SC	
Baldacci et al. (2004)	Car-pooling	E	D, P	✓	✓	✓		✓	M
Wolfler Calvo et al. (2004)	Car-pooling	H	T	✓	✓	✓			M
Xiang et al. (2006)	DARP	H	C	✓	✓	✓			M
Cordeau and Laporte (2007)	DARP	E, H	D	✓	✓	✓			M
Jain and V. Hentenryck (2011)	DARP	H	D	✓	✓	✓			M
Heilporn et al. (2011)	DARP	E	C	✓	✓	✓			M
Garaix et al. (2011)	DARP	E	O	✓	✓	✓		✓	M
Herbawi and Weber (2012)	D. Ride-sharing	H	D, T, P	✓	✓	✓		✓	M
Berbeglia et al. (2012)	DARP	H	P	✓	✓	✓			M
Kaan and Olinick (2013)	Van-pooling	H	C	✓	✓	✓	✓		M
Parragh and Schmid (2013)	DARP	E, H	C	✓	✓	✓			M
Huang et al. (2013)	D. Ride-sharing	E, H	C	✓	✓				S
Kirchler and Wolfler Calvo (2013)	DARP	H	C, T, N	✓	✓	✓		✓	M
Masson et al. (2014)	DARP	H	D	✓	✓	✓		✓	M
Lehuédé et al. (2014)	DARP	H	T, N	✓	✓	✓		✓	M
Hosni et al. (2014)	Shared-taxi	H	C	✓	✓	✓		✓	M
Atahran et al. (2014)	DARP	H	V	✓	✓	✓			M
Liu et al. (2014)	DARP	E	T	✓	✓	✓			M
Stiglic et al. (2015)	P. Ride-sharing	E	P, D	✓	✓	✓			M
Lee and Savelsbergh (2015)	D. Ride-sharing	H	C	✓	✓			✓	S
Santos and Xavier (2015)	D. Ride-sharing	H	P	✓	✓	✓			M
Parragh et al. (2015)	DARP	E, H	C	✓	✓	✓			M
Ma et al. (2015)	Shared-taxi	H	D	✓	✓	✓	✓		M
Ritzinger et al. (2016)	DARP	H	T	✓	✓	✓			M
Jung et al. (2016)	Shared-taxi	H	T, C	✓	✓	✓			M
Masmoudi et al. (2016)	DARP	H	C	✓	✓	✓			M
Braekers and Kovacs (2016)	DARP	E, H	C	✓	✓	✓			M
Masmoudi et al. (2017)	DARP	H	C	✓	✓	✓			M
Masoud et al. (2017)	D. Ride-sharing	E	P	✓	✓	✓	✓		M
Pimenta et al. (2017)	DARP	H	R	✓	✓	✓			M
Alonso-Mora et al. (2017)	D. Ride-sharing	E	C	✓	✓	✓			M
Stiglic et al. (2018)	P. Ride-sharing	E	P, D	✓	✓	✓		✓	M
Kalczynski and Miklas-Kalczynska (2018)	Car-pooling	H	D	✓	✓	✓			M
Wang et al. (2018)	D. Ride-sharing	H	D	✓	✓	✓			S

Method: **E**: Exact approach, **H**: Heuristic approach.

Objectives: **D**: Min. Travel Distance, **T**: Min. Travel Time, **P**: Max. Number of Participants, **C**: Min. Operational Cost, **V**: Min Vehicle Emissions, **R**: Max. System Reliability, **O**: Max. Occupancy Rate, **N**: Min. Number of Used Vehicles.

Characteristic: **S**: Single rider per trip, **M**: Multiple rider per trip.

Table 2: Shared mobility - Ride-sharing systems

Two main AV ownership models are being considered for future transportation systems: AVs as a public service, or privately-owned AVs. In the case of AVs as a public service, we consider a fleet of such vehicles at specific locations (depots). AVs are invoked from their stations to satisfy mobility demands in an urban area such that a single AV can serve multiple demands before going back to a depot. Privately owned AVs cannot just bring their owners from their homes to their work locations in the morning and bring them back in the evening while providing ridesharing opportunities to other users, but they can also serve other users when their owners do not need them (e.g. while they are at work). Although some companies (Tesla and Ford) have stated plans to sell AVs to consumers, many transportation companies have either explicitly stated or implicitly implies that they initially plan to use AVs to provide public transportation services rather than selling individual AVs to private consumers for personal use (Hyland and Mahmassani (2017)). Given this potential shift from a society that is heavily reliant on privately-owned vehicles to one in which transportation services are provided through fleets of vehicles operated by private companies, significant research is needed to plan such new systems and maximize their efficiency.

That said, there is a surge of interest in developing new methods for operating autonomous vehicles. Such methods consist of finding a path between different locations and determining the safest and most feasible itinerary. Hyland and Mahmassani (2017) introduced a taxonomy for classifying vehicle fleet management problems to inform future research on autonomous vehicle fleets. Their paper reviewed the existing categories to classify scheduling and routing problems, then refine some of them as they relate to the AV fleet problem, and proposed novel taxonomic categories for classifying AV fleet management problems. Kümmel et al. (2017) proposed a framework for AVs based on the model of a family (where the father is provider of physical services, the mother is strategic manager, and the children are individual AVs). In this decentralized model, vehicles are allowed to inter-negotiate while the fleet manager can set fleet strategies and pre-allocate vehicles to locations where increasing demand is expected. In another framework for modeling shared AVs, Levin et al. (2016) proposed a heuristic for dynamically constructing shared rides using AVs. The proposed approach consists of a dispatcher that checks whether there is any AV that is already located or en route to where a travel demand has appeared and then assigns the AV to carry the longest-waiting traveler. Furthermore, other travelers are allowed to join the shared trip if they are traveling to the same or close-enough destination, although priority remains with the travelers already in the vehicle. Alonso-Mora et al. (2017) proposed a mathematical model for a large-scale real-time ridesharing system that dynamically finds optimal routes for vehicles serving online requests while taking into account their actual locations. Their algorithm, which applies to fleets of AVs, uses constrained optimization to improve an initial greedy assignment and return good quality-solutions that converge to the optimal assignment over time. In addition, Pimenta et al. (2017) considered a dial-a-ride system in which a set of small AVs operates between different sections in a closed industrial site. For routing decisions, the paper proposes a heuristic approach based on GRASP and an insertion mechanism. Another study, by Ma et al. (2017), introduced a linear programming model for an AV sharing and reservation (AVSR) system in which travelers book AVs in advance and the system arranges their routes and schedules. Chen et al. (2017) studied potential use of AVs and presented a mathematical framework for designing AV zones in a general network. The paper also provides a numerical study to demonstrate the performance of the proposed model.

To conclude, there has been a surge in research on AVs in domains from computer science to robotics and engineering, but far less research into how to plan and operate AV services. We believe there are two main reasons for this gap. First, most of scientific and technological advances have been made by AV manufacturers and service providers who tend to keep their methods and techniques a commercial secret. Second, many studies have suggested that the same methods and algorithms that operate conventional vehicles will continue to apply to AVs, and so a switch from conventional vehicles to AVs does not necessarily entail any real change in the way they operate in a transportation system. From a modeling perspective, this statement holds for many cases. However, there are some variations in which AV-based systems need to be considered differently. For example, privately-owned AVs might be allowed to operate while their owners do not need them, and they might be able to use dedicated roads which could reduce their traffic-related issues compared to conventional vehicles. In addition, AVs are expected to be electric, and so planning their charging and maintenance operations might require different approaches, especially as they have a different service range and they need time to recharge, which could be time-consuming at some intermediate locations (Hiermann et al. (2019)). Further research should target *(i)* better understanding how AVs can be operated, owned and shared in future transportation systems, *(ii)* identifying their impacts on people transportation and how AVs respond to passenger mobility needs, *(iii)* analyzing how shared AVs perform in different scenarios and real-life situations, including varying transportation demand and network topologies, *(iv)* identifying the new features introduced by AVs and studying how these features could affect existing ridesharing models, and *(v)* introducing efficient solution approaches that can operate large-scale AV systems and factor in the critical issue of their recharging and maintenance operations.

3.4. Case studies

This section presents a set of case studies focused on analyzing different ridesharing systems and their performance and potential impacts. We consider case studies on systems that operate conventional vehicles or AVs, and classify them according to their research objectives and the approaches used. Research objectives have focused on studying either the performances, efficiencies and deficiencies of the ridesharing systems, or their impact on peoples' lives and future transport infrastructure. On the other hand, we also observe that the studies considered have used either optimization-based, simulation-based or data-analysis-based approaches to achieve the intended research objectives. We discuss the different studies and their outcomes, and provide a table classifying them into different categories.

There have been a number of recent case studies conducted to test the viability of ridesharing systems and evaluate their proposed solution approaches. Agatz et al. (2011) led a study based on 2008 travel demand data from metropolitan Atlanta, and the results suggested that advanced optimization approaches have the potential to increase the participant matching rates and system-wide travel cost savings obtained in dynamic ridesharing systems. Ma and Zhang (2017) studied traffic flow patterns in a single bottleneck corridor using a dynamic ridesharing mode and dynamic parking charges, and the results showed that system performance over the traditional morning commute may not be significantly improved when ridesharing fees and parking charges are fixed. Nonetheless, dynamic parking charges with appropriately set ridesharing fees can improve system performance in terms of vehicle miles and hours traveled and in terms of allied travel costs. Jiang et al. (2017) proposed a large-scale nationwide ridesharing system called CountryRoads which was deployed in three different years to assess system performance improvement through a case study of the 'Chunyun' spring festival travel season in China. Results indicate that the proposed system was able to attract more users, achieve a higher success matching rate, and thus contribute to an increasingly successful ridesharing experience. Ferreira and D'Orey (2015) proposed a dynamic and distributed taxi-sharing system that was evaluated using a simulation modeling approach based on realistic taxi trips in Porto (Portugal). Simulation results showed that the system has the potential to reduce taxi fares, operation costs and total travel distance (up to 9%). Furthermore, Maciejewski et al. (2016) conducted a study to evaluate a rule-based dispatching algorithm that manages a fleet of shared taxis based on data collected by local taxi services in Berlin and Barcelona. Results indicated that despite its simplicity and efficiency, rule-based dispatching suffers from a limited planning horizon. Linares et al. (2017) studied a dynamic ridesharing system architecture that considers the Metropolitan area of Barcelona as a case study, and.

results showed that this transportation mode has the potential to reduce traffic flow and pollution levels in big cities while offering travelers shorter travel times.

Using data collected by surveying more than 500 respondents in Turin and Rome, Gargiulo et al. (2015) tested and evaluate a dynamic ridesharing service called VirtualBus. They found that users' main concerns were privacy, trust, and reliability of planning. More recently, Wang et al. (2017) investigated the cost and benefits of ridesharing with friends through a study on travel demands in the Yarra Ranges (Australia). Their study revealed that limiting ridesharing to friends while rejecting strangers might reduce ride choices and increase detour distances but it does not generate significantly higher costs. Furthermore, prioritizing friends can substantially increase matching rate. In an effort to understand how urban parameters affect the fraction of individual trips that can be shared (or 'shareability'), Tachet et al. (2017) conducted a study based on millions of taxi trip records in New York City, San Francisco, Singapore and Vienna with the aim of computing the shareability curves for each city.

Other case studies have focused on studying ridesharing system impacts on existing transportation systems. Martinez (2015) used a simulation-based procedure to evaluate the impacts of introducing a shared-taxi system in Lisbon. Barann et al. (2017) conducted another study using more than 5 million taxi trips in New York City and found that ridesharing could potentially save over 2 million kilometers of travel distance per week, which would significantly decrease CO_2 emissions. Similarly, Yu et al. (2017) evaluated the direct environmental benefits of ridesharing in Beijing, and found that it enabled energy savings, distance savings, and lower CO_2 emissions. Stiglic et al. (2016b) studied the impact of driver and rider flexibility in an enhanced dynamic ridesharing experience and found that suggested driver and rider flexibility on departure/arrival times was important to ridesharing system success, but that driver flexibility in terms of accepting detours was even more important. Thus, the benefits and positive impacts of ridesharing are linearly correlated to the flexibility of ridesharing participants. Table 3 gives a roll-up summary of the case studies presented.

Method \ Scope	Assessing system performance	Studying impacts
Optimization-based	Agatz et al. (2011) Jiang et al. (2017)	Stiglic et al. (2016b) Lee and Savelsbergh (2015)
Simulation-based	Agatz et al. (2011) Maciejewski et al. (2016) Ferreira and D'Orey (2015) Linares et al. (2017) Ma and Zhang (2017)	Martinez (2015)
Data-analysis-based	Tachet et al. (2017) Liu and Li (2017) Sanchez et al. (2016) Gargiulo et al. (2015) Wang et al. (2017)	Barann et al. (2017) Yu et al. (2017)

Table 3: Case studies - Ridesharing systems

Case studies on ridesharing systems (see Table 3) have mainly focused on assessing their performance and giving cues and clues for further research to increase their efficiency and maximize their benefits. Studies have since been conducted using optimization, simulation or data-analysis approaches, but there have been fewer recent case studies analyzing the impacts of ridesharing on transportation systems, possibly because ridesharing is not a new concept, and so the bulk of research is focused either on improving existing ridesharing systems or operating new ones rather than studying their potential impacts, which are assumed to be net-positive.

We now have two decades of extensive research into ridesharing systems, but little research on autonomous mobility services for future transportation systems. To fill this gap, a number of recent studies have focused on new driverless services and their potential impacts on urban mobility. Gruel and Stanford (2016) identified the long-term effects of introducing driverless cars and explored the conditions that would make them beneficial or damaging in transportation systems. The study also investigated how automation could increase the attractiveness of traveling by car. Smolnicki and Sołtys (2016) studied different autonomous mobility solutions and discussed their impacts on metropolitan spatial structures. Talebpour and Mahmassani (2016) studied the influence of AVs on traffic flow stability and throughput and found that AVs can improve stability and be more effective in preventing shockwave formation and propagation. Meyer et al. (2017) simulated the influence of AVs on the accessibility of Swiss municipalities, and concluded that AVs could dramatically increase accessibility rates and even replace public transport outside dense urban areas. Correia and van Arem (2016) explored the possibility of replacing individually-owned conventional vehicles with autonomous ones and what it would mean for traffic flow and parking demand in a city. Considering the city of Delft in the Netherlands as case setting, they showed that despite increased traffic congestion due to empty vehicle relocation trips, vehicle automation could lead to more trip requests satisfied while reducing travel costs. Milakis et al. (2017) investigated future development opportunities for AVs in the Netherlands and gave estimates for the potential impacts on transport planning, traffic management and travel behavior over time horizons up to 2030 and 2050. Exploring the impact of shared AVs on urban parking demand, Zhang et al. (2015) suggested that for AV adopter-users, up to 90% of parking demand might be eliminated (also see Le Vine et al. (2015)). Harper et al. (2016) studied the influence of travel with AVs for the elderly and people with travel-restrictive medical conditions and found a 14% increase in annual vehicle miles traveled for the United States population 19 and older. Furthermore, Aria et al. (2016) investigated AV effects on driver behavior and traffic performance, and the simulation results revealed that the positive effects of AV on roads are especially highlighted when the road network is crowded. Diels and Bos (2016) discussed a potential increase of motion sickness issues in AVs. Wadud (2017) focused on identifying which vehicle sectors would likely be the earliest adopters of full automation in the UK, and their findings suggests that households with the highest income will get higher gains from automations as they travel higher distances.

Studies on the deployment of AVs in shared mobility systems include Chen et al. (2016a) who ran a simulation study on the city of Austin, Texas. The results suggested that AVs offer a viable alternative to private vehicle travel (also see Fagnant and Kockelman (2014, 2016); Chen et al. (2016b)). The study revealed that each shared AV can replace 5–9 privately owned vehicles while serving 96–98% of trip requests. Bischoff and Maciejewski (2016b) led a similar study on the city of Berlin, Germany, simulating the replacement of hundreds of thousands of vehicles all around the city by a fleet of autonomous taxis. Results suggested that the car fleet in Berlin can be replaced by a fleet of 100,000 autonomous taxis while maintaining high service quality for customers (also see Bischoff and Maciejewski (2016c)). Another study, by Scheltes and de Almeida Correia (2017), simulated a system in which the last-mile segment of train trips was carried out by a fleet of fully autonomous vehicles. Results obtained from applying the simulation model on Delft, Netherlands, argue that such a system is able to compete with walking mode but needs to improve its performance to be competitive with cycling. Through a case study using taxicab trip data from New York City, Ma and Zhang (2017) concluded that an AV sharing and reservation system can significantly increase vehicle mileage rates while reducing their ownership rates. Another case study by Lokhandwala and Cai (2018)

Method \ Scope	Assessing system performance	Studying impacts
Optimization-based	Ma et al. (2017)	Correia and van Arem (2016)
Simulation-based	Bischoff and Maciejewski (2016a) Fagnant and Kockelman (2016) Chen et al. (2016b) Bischoff and Maciejewski (2016c) Chen and Kockelman (2016) Levin and Boyles (2015) Scheltes and de Almeida Correia (2017) Lokhandwala and Cai (2018)	Gruel and Stanford (2016) Zhang et al. (2015) Talebpour and Mahmassani (2016) Fagnant and Kockelman (2014) Milakis et al. (2017) Harper et al. (2016) Meyer et al. (2017) Diels and Bos (2016) Aria et al. (2016) Smolnicki and Sołtys (2016)
Data-analysis-based	-	Alessandrini et al. (2015) Fagnant and Kockelman (2015) Wadud (2017)

Table 4: Case studies - Shared autonomous mobility

suggested that replacing traditional taxis by shared AVs in New York City could potentially reduce the fleet size by 59% while maintaining the sale service quality. The study concluded that sharing AVs can increase occupancy rate (from 1.2 to 3) and decrease system-wide vehicle distance (up to 55%) (case studies are classified in Table 4).

Unlike for ridesharing systems, case studies on shared autonomous mobility systems have mainly focused on studying their expected outcomes and effects on people mobility and on existing transportation systems. This may be due to the fact that the introduction of autonomous mobility services in transportation systems is a new trend in transportation research, and so its potential impacts need to be studied and carefully analyzed before it can be widely adopted. However, most of studies reviewed have used simulation-based approaches, which is evidence that these new systems are still in an early stage of research. As a result, more research studies will be directed towards studying their operational performance as soon as they are widely deployed.

4. People and goods sharing rides

This section focuses on introducing shared mobility systems that combine both passenger and freight transportation. First, we set the context by reviewing the most recent concepts and trends in city logistics (Section 4.1). Then, the opportunities and challenges that can result from combining people and freight flows are discussed and their modeling and solution approaches are investigated (Section 4.2). Table 5 summarizes the papers reviewed with their different characteristics and methods used.

4.1. Setting the context: planning city logistics

The demand for freight transportation basically results from the need to transport goods from producers to consumers who are geographically apart. In general, this transportation chain consists of a pickup process (pre-haul or first-mile), a transportation process (long haul), and a delivery process (end-haul or last-mile) (Steadieseifi et al. (2014)). While freight transportation can take place in widespread geographical areas, city logistics considers the transportation of goods and their potential effects on traffic flow and congestion in urban areas (Savelsbergh and Van Woensel (2016)). However, both freight transportation and city logistics aim to provide customers with the products they need at the right time and place and at low cost.

Increasing global population, and thus increasing demand for goods, together with digital revolution and technological advances are creating both opportunities and challenges for planning and improving the sustainability of urban freight systems. Given their fundamental role in providing for people's daily needs, efficient city logistics have the potential to improve quality of life for more and more people. Recent studies in this direction have focused on anticipating the future opportunities and challenges facing city logistics. In their recent review on city logistics, Savelsbergh and Van Woensel (2016) identified the trends driving changes in city logistics: growing urban populations, increasing importance of e-commerce and swift supply chains, and the rise of the sharing economy and sustainability aspects. They claimed that sharing assets and capacities can enable higher capacity utilization, and thus reduce fleet sizes and numbers of freight movements. Besides studying the impacts of the information revolution on city logistics, Taniguchi et al. (2016) also described applications of big data and decision-support systems that can be used to enhance the design and evaluation of city logistics schemes, and gave illustrations of the need for new innovations that can help reduce the impact of freight in urban areas. One of the most common scenarios for reducing the number of freight vehicles going into cities is to consolidate goods volume at urban distribution centers, called consolidated distribution centers (CDC), which are usually located a city's borders (Allen et al. (2012)). In this scenario, cargo is delivered to a CDC by different supply chain operators, consolidated at the center, and then shipped to final customers using clean and highly utilized vehicles (Alessandrini et al. (2015); Figure 2). The main advantage of using CDCs is that shipments can be grouped by destination into packages where every package will be transported using a vehicle. This way, the number of vehicle trips and the need for parking bays can be reduced, this affording a more efficient delivery service.

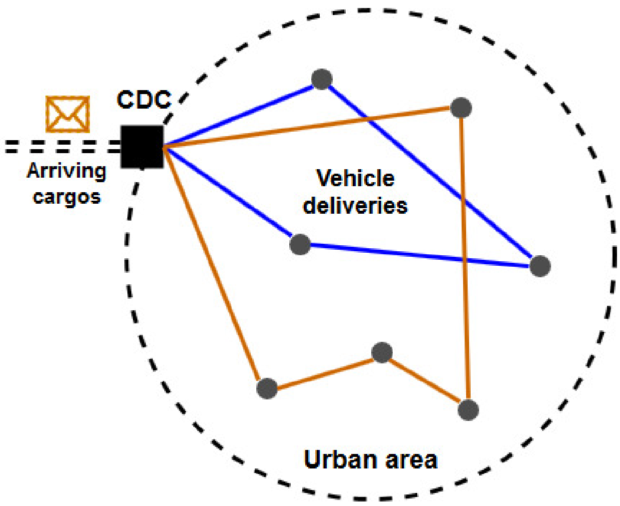

Figure 2: Consolidated Distribution Center (CDC) with vehicle deliveries

In order to make it efficient, these vehicles have to be small, agile, have large enough loading capacity and comply with the environmental requirements governing energy consumption, CO_2 emissions, and noise. The problem of planning and optimizing itineraries of such a fleet, in which vehicles operate round trips, is called the vehicle routing problem (VRP) (see Cattaruzza et al. (2015) for a review of VRPs for city logistics and Koç and Laporte (2018) for a review of VRPs with backhauls). Solving a VRP is about defining routes that respect a number of constraints, including pickup and delivery locations, time windows, vehicle capacity, narrow streets with limited accessibility, and other constraints. For example, Simoni et al. (2018) proposed a heuristic approach for routing vehicles carrying parcels from CDCs to their final destinations within an urban area, and identified the most efficient and environment-friendly strategies and regulations for this delivery.

Another promising opportunity in city logistics is the deployment of autonomous mobility services. With their potential application in future freight transportation systems, AVs might be used for refilling shops from remote warehouses, performing last-mile deliveries to clients, and collecting and transporting waste and products (CityMobil (2011);Alessandrini et al. (2015)). However, assessing the benefits of AVs and their efficient employment and impacts on city logistics is an important topic in today's research, and still requires further investigation. Many freight transportation companies have started using unmanned ground vehicles and unmanned aerial vehicles (drones) for small parcel deliveries (see Otto et al. (2018) for a recent review). The idea is that these relatively small unmanned vehicles will depart from warehouses or delivery trucks carrying small deliveries for individual customers. For example, Murray and Chu (2015) studied a problem in which delivery trucks carrying drones depart from and return to a depot. In their settings, customers are served either by delivery trucks or by drones that operate in coordination with the delivery trucks. Depending on its flight endurance, a drone has to deliver the customer's order and return to either the truck or a depot, the aim being to minimize the time required to deliver all customer orders. Such a system is thought to provide a more efficient delivery service at lower cost and with reduced environmental impacts.

Furthermore, another important innovation is the potential for delivering customer orders to more convenient locations than the home (e.g. direct delivery to a customer's car trunk (Savelsbergh and Van Woensel (2016)). Thanks to new technologies, a one-time access to customer a car trunk can be granted during a specific time-period and revoked as soon as the delivery is completed. In their recent paper, Reyes et al. (2017) modeled this last-mile trunk delivery as a VRP with roaming delivery locations (VRPRDL). In their approach, the delivery locations are first optimized for a fixed customer delivery sequence in order to generate an initial route. Then, the initial route is improved by switching a predecessor's or successor's delivery location once a customer is inserted or deleted. Results reveal that trunk delivery could potentially cut distance traveled in tests with realistic instances.

In such systems, some locations may change or move as the delivery process starts (like the location of a delivery truck a drone is to return to in Murray and Chu (2015), and the roaming delivery locations in Reyes et al. (2017)). Although this feature might lead to more flexible deliveries, it requires more complex models and sophisticated heuristic approaches, due to the layer of complexity added by the synchronization constraints required to adapt different departure and arrival times to these roaming locations. Reyes et al. (2017), for example, proposed a neighborhood search heuristic with a set of insertion and deletion operators, and considered the roaming delivery locations when building routes by enhancing the classical VRP insertion and deletion operators by including customer shifts to different delivery locations and consequently different time-windows within them. Thus, at each a time a new route is built, a set of alternative routes, where precisely one customer delivery location is different to the original route, are generated. However, due to the added complexity, generating these alternative routes requires additional computational effort. Building on this review of the latest trends in city logistics, we focus in the following subsection on the promising concept of integrating people and freight flows for future transportation systems development.

4.2. Combining people and freight transportation

Since both people and goods move in the urban environment, an efficient and effective transport network that ensures smooth sharing of passengers and freights is an essential element in city life (Cochrane et al. (2017)). There is ample literature on the problem of passengers or goods transport using dedicated networks, but far less research on joint use of transport resources between passengers and goods flows. However, combined transportation systems are starting to garner increasing attention.

A combined transportation system aims to use the underused assets in public mass-transport modes such as urban rail, buses or in people private-car trips to bring loads to a central station or take loads from that station to distribute it to the local neighborhood (Crainic and Montreuil (2016)). In such a system, we have a set of passengers and parcels, each having an origin location from where it should be picked up, and a destination location to where it should be carried and dropped off. We also have a transportation system, having both private and public transportation modes, which is able to transport both passengers and parcels simultaneously. Thus, the aim is to satisfy the demand of both passengers and parcels while minimizing costs and distances traveled, and therefore reduce congestion and pollution levels in urban areas. Of course, the transportation of goods must not disturb passenger trips. In other words, a passenger would accept only small deviations and short extra times for transporting parcels in the same trip. Thus, trip times that significantly exceed a passenger's usual route times in order to load and deliver parcels would likely be unacceptable. Although most problems dealing with passengers and goods transportation are NP-hard, so very difficult to solve, many studies have attempted to tackle them with different models and solution approaches. These models fall into two broad categories: single-tiered and two-tiered models (see Figure 3). A single-tiered model considers a set of vehicles each having specific capacity. These vehicles are able to transport passengers and goods to their destinations while accommodating certain like passenger and parcel time windows and vehicle capacity and service time (see Li et al. (2014)). In a two-tiered model, combined transport of passengers and goods is achieved via the contribution of a first-tier, generally composed of a public transport line with a set of transfer points or stations, and a second tier, composed of a range of vehicles being able to transport both passengers and goods (or only goods depending on the model studied) from transfer points to their final destinations (see Trentini et al. (2015)). Strict synchronization between the two tiers is therefore necessary. For planning and operating such combined systems, different models and solution approaches have recently been proposed, most of which aim to minimize their operational costs, or put differently, maximize their benefits. However, some studies have considered other objectives like minimizing the number of vehicles required for making deliveries, minimizing total distance traveled, or minimizing the wait time for deliveries. Below we take a deeper look at the existing models in the literature.

Li et al. (2014) extended the classical DARP formulation by introducing a new class of models called the share-a-ride problem (SARP). The SARP refers to the fact that people and parcels are transported using a set of taxis driving around in a city. The proposed model is therefore single-tiered. In this problem, passenger requests are served by a fleet of taxis, and some parcels are delivered during these taxi trips as long as delivery does not affect the passengers significantly. Passengers thus have priority over parcels. Furthermore, the SARP assumes that a taxi cannot serve two passengers simultaneously and that a parcel cannot be served by more than one taxi, i.e. it is either served by one taxi or not served at all. Another basic assumption in SARP is that parcel transportation requests are known beforehand whereas passenger requests arrive dynamically. In addition to the SARP, the authors propose a second model, which has similar settings but with the assumption that the assignments of passengers to taxis and their delivery sequences are also given. In this case, dubbed the freight insertion problem (FIP), the problem becomes static (see Figure 4). Solving the FIP is about finding a way to insert parcel requests without significantly extending passenger travel times. Since routing is given, the FIP has less complexity than the SARP, and can thus be solved relatively fast, at least fast enough for solving real-life instances. To solve this problem, authors present MILP formulations for both SARP and FIP and conduct a numerical study of both static and dynamic scenarios. Given the complexity of the problem, the authors proposed an ALNS to solve it (Li et al. (2016a)). The proposed approach was able to return solutions that are within 2.24% of the best results compared to

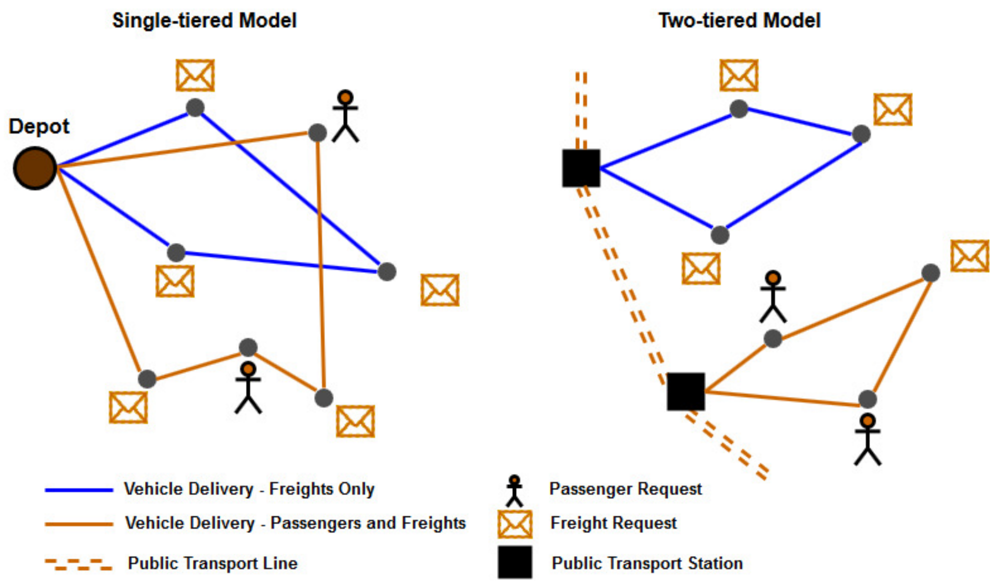

Figure 3: Single-tiered and two-tiered transportation systems

a mixed integer programming (MIP) solver and DARP test benchmarks from the literature. Beirigo et al. (2018) introduced another SARP formulation where a fleet of SAVs is used to serve both passenger and freight requests. The paper extends the original SARP formulation by allowing vehicles (in this case SAVs) to carry one or more passengers and different-sized parcels in the same trip. To solve the extended problem, the authors proposed a MILP formulation and analyzed it on a wide set of transportation scenarios. The SARP study was further extended by considering two stochastic variants; one with stochastic travel times and another with stochastic delivery locations (Li et al. (2016b)). In both cases, a two-stage stochastic programming model with recourse is used with the ALNS heuristic and a scenario generator. Results obtained from testing both stochastic models demonstrate that even though the convergence rate is faster, the SARP is less sensitive to the stochastic delivery locations than the stochastic travel times. The study thus concluded that considering stochastic information when modeling and planning real-life taxi-sharing systems can dramatically improve their performance over deterministic solutions.

Arslan et al. (2016) proposed another single-tiered model in a study on the concept of crowd-sourcing delivery, which aims to make parcel deliveries using excess capacity on trips that already take place (see Mladenow et al. (2015); Goetting and Handover (2016) for recent reviews of the latest crowd-sourced delivery models). For this purpose, the paper considered a decentralized model that automatically matches parcel delivery requests to potential ad-hoc drivers. Parcel deliveries are made by self-employed drivers who are willing to earn extra money on their way to home or work. The drivers indicate their origin and destination locations, their vehicle capacity, and a time window. Likewise, parcel delivery requests also have time windows that state when they should be picked up and delivered. Thus, a delivery is possible if there is a feasible match between driver's time window and parcel's time window. A set of backup vehicles is operated to cover parcel requests that cannot be delivered by ad-hoc drivers. Furthermore, the paper presents an event-based rolling horizon framework that dynamically matches tasks to drivers at each time a new delivery request or driver arrives throughout the day, as well as exact and heuristic recursive algorithms for solving the routing subproblem. Results show that using ad-hoc drivers can potentially reduce last-mile delivery costs as well as system-wide vehicle mileage. Archetti et al. (2016) considered a similar problem to Arslan et al. (2016) but in their setting, a service provider uses not only a fleet of delivery vehicles

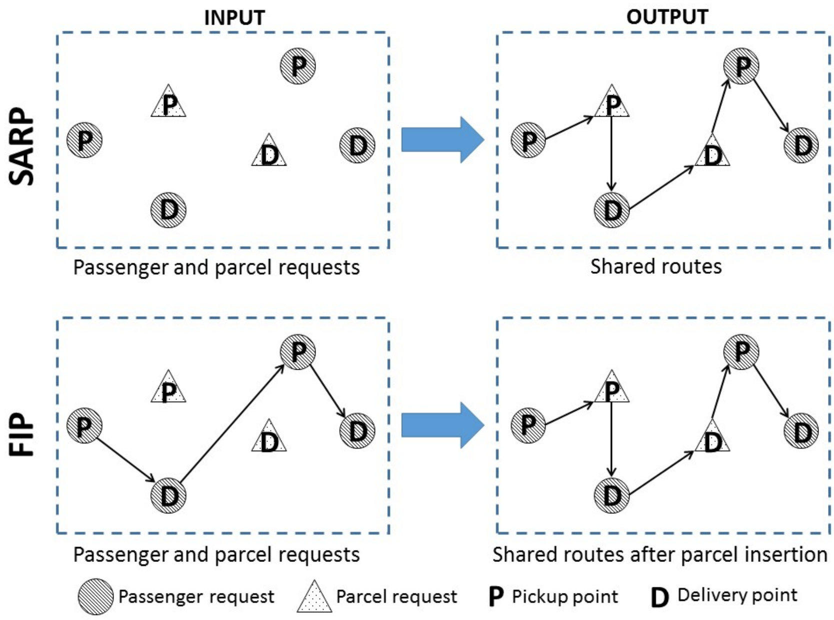

Figure 4: An illustrative example of the SARP and the FIP (Li et al. (2014))

and dedicated drivers but also a set of occasional drivers who are willing to make a single delivery using their own vehicle. Making these deliveries should not significantly extend the trip time for the occasional driver, who can then receive a small cost compensation for each delivery they perform.. To model the problem, Archetti et al. (2016) introduced a new variant of the classical capacitated VRP called the 'vehicle routing problem with occasional drivers'. The paper also presents a heuristic approach in which variable neighborhood and tabu search strategies are combined to produce good quality solutions. Wang et al. (2016) presented a crowd-tasking model in which last-mile deliveries are performed by a crowd of citizen workers, and proposed to formulate the model as a network min-cost flow problem and use an iterative pruning technique to make the network manageably small. Dayarian and Savelsbergh (2017) proposed another crowd-sourced service in which customers can deliver some online orders. Potential customers express an interest to participate in making deliveries on their way home, and thus supplement a set of dedicated drivers performing the service, with vehicle routes generated using a tabu search heuristic. A number of papers have considered transporting freight by the same rail network as passengers (see Steadieseifi et al. (2014); Cochrane et al. (2017); Ozturk and Patrick (2017)), but they are outside our scope as the models do not integrate passengers and freight in the same trip (i.e. rail is used during passenger off-hours).

Recent research has also focused on two-tiered models. Trentini et al. (2015) introduced a combined system that uses the available capacity in a passenger bus line to transport parcels (also see Trentini et al. (2013)). In their problem settings, all incoming goods are stored in CDCs, then loaded on buses operating through the bus line when there is spare capacity, and finally unloaded at specific bus stops and delivered to customers using a fleet of low-emission city freighters. The proposed problem is modeled as a VRP with transfers, and a mathematical formulation is given, along with an ALNS to solve it (see Masson et al. (2017), for a similar system). Fatnassi et al. (2015) proposed another two-tiered shared passengers and goods model with a first tier (train, bus or truck line) transporting passengers or goods to connection points where a second tier, consisting of a set of small electric and AVs moving on a specific guideway then transport them to their final destinations. The paper uses a forward periodic-optimization approach to solve this dynamic problem.

Behiri et al. (2018) studied the freight-rail transport scheduling problem in which existing urban rail is used for transporting freight. In their model, one rail line is considered. On this line, there are several stations where freight can be loaded and unloaded. Freights are brought to these stations by truck at different time windows in a day. To solve this problem, the paper proposes two heuristic approaches: a dispatching rule-based heuristic and a single-train decomposition-based heuristic. Similarly, Ghilas et al. (2016a) considered a system in which freight requests are delivered by a set of vehicles such that a part of the transportation process is carried out on a scheduled public transport line. To model this two-tiered system, the paper introduces the pickup and delivery problem with time windows and scheduled lines (PDPTW-SL). In this problem, two options are considered for transporting freight: direct and indirect shipments. In a direct shipment, a freight request is picked up at its origin and delivered to its destination using one vehicle, i.e. the scheduled line is not used. In an indirect shipment, a freight request is picked up by a vehicle, transferred to a nearby transfer node, transported between two transfer nodes by a scheduled public transport line, and finally picked up by another vehicle and delivered to its final destination. Thus, solving the problem is about defining routes and schedules for both freight requests and delivery vehicles. In order to solve this problem, the authors proposed a branch-and-price algorithm where the pricing problem is a variant of the elementary shortest path problem with resource and precedence constraints (ESPPRPC). Due to the complexity of the problem, an ALNS-based algorithm is also proposed (see Ghilas et al. (2016b)). Moreover, a stochastic version of the problem in which the demand quantity of each freight request is only revealed when the vehicle arrives at its pickup location was considered (Ghilas et al. (2016c)). To consider this uncertainty, a scenario-based sample average approximation approach is introduced. Another two-tiered crowd-sourced delivery system (Kafle et al. (2017)) suggested that a set of cyclists and pedestrians, called crowd-sources, might be willing to deliver small-size parcels from a delivery truck to customers living in the same neighborhood. A set of carrier trucks transport parcels to intermediate transfer points (first-tier) and then potential crowd-sources perform the last-mile delivery. To solve this problem, the paper proposes a tabu search algorithm. Results show that crowd-sourcing the service can lead to lower operational costs compared with a pure-truck delivery service.

This review on systems that combine people and freight transportation shows that the topic is gaining increasing interest (see Table 5 for a summary). Models and algorithms for both single-tiered and two-tiered systems have been explored. Although some papers have introduced exact approaches for solving this type of problem, the bulk of the research has focused on developing heuristic approaches. This is due to the complexity of such problems which require fast optimization approaches to tackle them in short computation times. We also find that most of the papers reviewed have focused on profitability. Nevertheless, other objectives have also been considered, such as minimizing the number of vehicles needed to operate the system and the distances covered. Thus, an useful direction for future research would be to also address the environmental issues which have not yet been considered in the literature. We would prone the following broad areas for future research: *(i)* developing efficient solution algorithms (exact and heuristic) for combined people-and-freight systems, *(ii)* extending the existing models by introducing multiple objectives related to profit, operational costs, environmental impacts, etc., *(iii)* developing more flexible models and efficient algorithms that consider the different sources of stochastic information (travel times, traffic jams, freight demands etc.), *(iv)* improving the dynamic (real-time) framework of such systems by adding new techniques and strategies (leading to shorter service times, strong synchronization between different tiers in two-tiered models, etc.), *(v)* introducing new public policies to regulate the potential integration of goods delivery in existing public transport systems, *(vi)* focusing more on increasing passenger satisfaction and reducing the potential inconvenience that might arise in such systems, and finally *(vii)* studying the potential

Reference	Problem variant	Method	Objective	Constraints					Characteristic
				RC	TC	CC	OC	SC	
Trentini et al. (2013)	Combined Del.	H	N, D	✓	✓	✓		✓	Two-tiered
Trentini et al. (2015)	Combined Del.	H	N, C	✓	✓	✓		✓	Two-tiered
Fatnassi et al. (2015)	Combined Del.	H	C	✓	✓	✓		✓	Two-tiered
Li et al. (2016a)	SARP	H	C	✓	✓	✓			Single-tiered
Li et al. (2016b)	Stochastic SARP	H	C	✓	✓	✓			Single-tiered
Arslan et al. (2016)	Crowd-sourcing	E	C	✓	✓	✓			Single-tiered
Archetti et al. (2016)	Crowd-sourcing	H	C	✓	✓	✓			Single-tiered
Ghilas et al. (2016a)	Combined Del.	E, H	C	✓	✓	✓		✓	Two-tiered
Ghilas et al. (2016b)	Combined Del.	H	C	✓	✓	✓		✓	Two-tiered
Ghilas et al. (2016c)	Combined Del.	H	C	✓	✓	✓		✓	Two-tiered
Wang et al. (2016)	Crowd-sourcing	H	C	✓	✓	✓		✓	Single-tiered
Kafle et al. (2017)	Crowd-sourcing	H	C	✓	✓	✓		✓	Two-tiered
Dayarian and Savelsbergh (2017)	Crowd-sourcing	H	W	✓	✓	✓			Single-tiered
Masson et al. (2017)	Combined Del.	H	N, C	✓	✓	✓		✓	Two-tiered
Behiri et al. (2018)	Combined Del.	H	T	✓	✓	✓		✓	Two-tiered
Beirigo et al. (2018)	SARP	E	C	✓	✓	✓		✓	Single-tiered

Method: **E**: Exact approach, **H**: Heuristic approach.

Objectives: **D**: Min. Travel Distance, **T**: Min. Waiting Time, **N**: Min. Number of Vehicles, **C**: Min. Operational Cost, **W**: Max. Collected Weight.

Table 5: Shared mobility - Combined people-and-freight systems

deployment of automated services and their impacts on the future development of such combined systems.

4.3. *Case studies*

Given its potential benefits, the integration of passenger and freight transportation streams has been assessed in a number of studies in the last three years. Most of these studies have focused on analyzing the performance of such integrated systems and evaluating their operational gains compared to the existing transportation systems. A good example can be found in Fatnassi et al. (2015) which considers a case study on the town of Corby (UK). The results demonstrate potential benefit of implementing a combined system in terms of service time, energy consumed, noise and carbon emissions compared to classical transportation systems. Ghilas et al. (2016c) suggested these combined systems can bring up to 16% savings on overall operational cost. Considering real taxi trips in the San-Francesco area, Li et al. (2016a) showed that a mixed-taxi service can outperform the other transportation systems available in the local urban area, but also highlighted two key factors to help maximize the gain obtained by such a service: analysis of the spatial characteristics of requests before implementing the service, and availability of a traditional freight service to ensure that all requests are delivered. Gonzalez-Feliu and Mercier (2013) studied the potential deployment of a combined people-freight approach in the city of Lyon (France) and found that it was crucial to apply an accessibility analysis that shows the attractiveness of different urban zones before this combined system can take place. Thus, the difficulty for households living at different city zones to reach their retailers should be considered when deploying the system. Wang et al. (2016) evaluated their crowd-tasking model using datasets from bus and taxi services in Singapore, and their results demonstrate that crowd-sourcing can be efficiently used in large-scale problems with real-time deliveries where this kind of service can be profitable to logistic companies as well as crowd-workers. More recently, Masson et al. (2017) led a case study based on a dataset derived from the city of La Rochelle (France) and found that efficient transshipment of freight from buses to city freighters is a major concern in a mixed system, as inefficient transshipment of freight between the two tiers might delay deliveries and significantly affect passenger trips. Although most case studies are ultimately optimistic over the future of combining passenger and freight flows, some of the allied concerns and practical issues still need to be investigated. These issues involve, among others, *(i)* security concerns, *(ii)* confidentiality and data privacy (like using only a barcode with limited personal information to identify parcels), *(iii)* the redesign of parcels with different sizes to fit in the shared transportation compartments, and *(iv)* uncertainties during deliveries (e.g. freight order modifications and cancellations). We would thus advocate more studies to evaluate these issues and study their impacts on the future deployment of these integrated systems.

5. Conclusions

This survey reviewed different variants of shared mobility systems along with their modeling choices and solution approaches. The papers reviewed covered mobility systems where people share their rides and mobility systems where people and goods are combined. We presented a set of case studies either analyzing shared mobility system performances or studying their potential impacts on people's lives and future transportation systems.

New shared mobility systems for both people and freight transportation have the potential to provide major societal, economic and environmental benefits. The development of algorithms for planning and operating such systems is at the heart of the shared mobility concept. This survey highlighted a number of promising optimization opportunities and challenges that arise when developing new systems to support shared mobility. Relevant operations research models in this area have also been reviewed. Although ridesharing is not a new concept, we have seen that the interest in enhancing dynamic ridesharing systems and developing new systems for matching passengers on-the-fly continues to grow. More research is now needed on systems that consider trip synchronization and traveler cost aspects, or more generally the quality of the provided service. One of the latest big trends appears to be research on deploying new autonomous mobility services. We now need more research on how these new services can operate and how they can impact future transportation systems, and there is also a need to introduce new models and algorithms that consider vehicle charging and maintenance operations. The potential integration of passenger and freight transportation is another promising opportunity that is steadily gaining currency. As such, more studies on developing realistic models and efficient algorithms that consider different objectives (including environmental issues) and different sources of uncertainty are also needed, along with new public policies to regulate this integration. We believe that these challenges and new innovations provide a rich vein of research opportunities, and we anticipate that this review could spur more contributions in this emerging area of transportation science.

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