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Transition towards sustainable mobility: the role of transport optimization

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Abstract

Although the concept of a transition towards sustainability has been introduced about 30 years ago, there is still a lack of progress. Transport emissions have not decreased in the last decade. However, they need to be reduced substantially to meet climate goals. The cornerstones of a transition can be summarized with the avoid-shift-improve paradigm: Traffic should be avoided as much as possible, any unavoidable traffic should be shifted to sustainable modes of transport and finally fuel and vehicle technologies should be improved. The goal of this paper is to find out how and where transport optimization can contribute to a transition towards sustainable mobility. It identifies concepts based on the avoid-shift-improve approach for which transport optimization can be used, describes the existing literature and points out research directions.

Keywords Sustainability · Transportation · Transition to sustainable mobility · Avoid-shift-improve

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1 Introduction

Globally, transport emissions grew faster than any other end-use sector from 1990 to 2021 at an annual average rate of nearly 1.7%. The transport sector largely relies on fossil fuels, and was responsible for 37% of CO_2 emissions from end-use sectors in 2021. The vast majority of the sectors' emissions are caused by road transport (about 75%), relying on oil products for 91% of its final energy. CO_2 emissions should decrease by 3% per year to 2030 to meet the Net Zero Emissions by 2050 Scenario (International Energy Agency 2022).

A common approach to respond to increasing mobility demand was the extension of existing road infrastructure. However, adding more roads often leads to induced traffic. In addition, gains in efficiency are often offset by an increase in demand. This is commonly known as the rebound effect. To shift the focus from the supply to the demand side, a new approach towards sustainable mobility is necessary (Global Climate Action Partnership 2016).

There is no common definition of sustainable mobility. It has been suggested (Foltỳnová et al. 2020) to derive the definition from the UN Brundtland Commission that defines sustainable development such that it "satisfies the needs of present generations without compromising future generations' ability to satisfy their own needs" (World Commission on Environment and Development 1987) and covers the economic, environmental and social pillar in the context of the triple bottom line. In 2015, the UN introduced 17 sustainable development goals, each associated with targets (United Nations 2015). Sustainable mobility is not represented as a goal itself but included in target 11.2 (Holden et al. 2019).

In German-speaking countries, a transition to sustainable mobility and energy is subsumed under the concept of "Verkehrswende", which first appeared in the 1990 s in reports of the German parliament, and which consists of the notion of "Mobilitätswende" and "Antriebswende" (Hesse 1993). Following the example of the energy transition, the cornerstones of the concept are based on reducing and optimizing traffic. The main goal of the approach is to significantly reduce greenhouse gas (GHG) emissions and create more livable cities by applying one of the three concepts: "Vermeiden, Verlagern, Verbessern" (*avoid/reduce*, *shift/maintain* and *improve*). While both passenger and freight traffic should be avoided as far as possible, mobility needs should still be satisfied. Any unavoidable traffic should be shifted to more environmentally friendly means of transport and finally improved through better organization and new technologies. The approach is hierarchical: *avoid* measures should be implemented first, then *shift* measures and finally *improve* (Bongardt et al. 2019).

The importance of the avoid-shift-improve approach is also highlighted by international organizations such as the OECD International Transport Forum, the International Energy Agency or the UN Emissions Gap Report (see for instance United Nations Environment Programme (2022)).

The European Union addresses these problems in the Sustainable and Smart Mobility Strategy, part of the European Green Deal presented in 2019 by the European Commission. Objectives of this strategy include increasing the number of zero-emission vehicles, making sustainable alternative solutions available to the public and businesses, using digitalization and automation and improving connectivity and access. The overarching target of the Green Deal is to reduce transport-related GHG emissions by 90% by 2050 (European Commission 2020).

Although the concept of transition towards sustainability was introduced about 30 years ago and has been on the agenda of governments and organizations, there is still a lack of progress. As outlined above, transport emissions have not decreased in the last decade, and they have to be reduced substantially to meet climate goals. Hence, these concepts are still highly relevant today. Many of them have been the subject of scientific publications or have been tried out in practice. However, the efficient planning of traffic flows and the coordination of deliveries are challenging tasks. To find efficient solutions with goals such as minimizing the number of vehicles, achieving a higher vehicle utilization, reducing the number of empty trips, and thus reducing the negative impact on the environment, models and methods of transport optimization can be used.

This article aims to find out how and where transport optimization can contribute to a transition towards sustainable mobility. The main task is to identify the concepts based on the avoid-shift-improve approach for which transport optimization can be used, describe the existing literature and point out research directions.

We organize the concepts based on whether they are used for freight or passenger transportation. However, some concepts are not exclusive to freight or people transport, such as the switch to alternatively fueled vehicles. The remainder of the paper is structured as follows. Section 2 provides a classification and sets the scope of the paper. Section 3 discusses concepts related to alternatively fueled vehicles. Section 4 and 5 review concepts that can be used for freight or passenger transport, respectively. Finally, Sect. 6 points out research directions, and Sect. 7 provides a discussion of the concepts and conclusions.

2 Classification and scope of the paper

Table 1 shows how the different concepts can be assigned to the three approaches. The *avoid/reduce* category relates to system efficiency. *Avoid/reduce* means that the need to travel is avoided, for instance, by consolidation, or the length of the trip is shortened, for instance, by route optimization. Examples of concepts that fit in this category are alternative delivery locations since they lead to a reduction in trip length. Also, finding the best refueling or recharging policies increases system efficiency. Vehicle sharing systems can lead to fewer trips because the costs per trip are higher than when owning a vehicle. Ridesharing additionally results in less vehicles on the streets and helps to reduce congestion.

Shift/maintain deals with trip efficiency and means that travel is shifted to less energy-consuming and more environmentally friendly modes, particularly non-motorized transport such as walking and cycling and rail or public transport. Rail is more environmentally friendly, depending on the utilization rate and drive technology. For public transport, emissions per user are less than individual motorized transport due to a higher occupancy rate. Bike sharing encourages a

Table 1 Classification of concepts for the transition towards sustainable mobility according to avoid-shift-improve approach

	A/R	S/M	I
Multi echelon delivery concepts			
With non-motorized vehicles		*	
With alternative fuel vehicles			*
Alternative delivery locations	*		
Autonomous vehicles	*	*	*
Vehicle sharing			
With non-motorized vehicles	*	*	
With alternative fuel vehicles	*		*
Ridesharing			
People and people	*		
People and freight	*		
Demand responsive transport system	*	*	
Freight on public transportation	*	*	
Alternative fuel vehicles			
Design of charging and/or fueling infrastructure			*
Best refueling and/or recharging policies	*		*
Public transport optimization	*	*	*

A/R (Avoid/Reduce - SystemEfficiency), S/M (Shift/Maintain- Trip Efficiency), I (Improve -Vehicle Efficency)

shift to non-motorized means of transport. Furthermore, multi-echelon delivery concepts, including non-motorized vehicles, are in the *shift* category. A shift to public transport is fostered by improving demand responsive transport systems or public transport optimization, making these systems more attractive.

Finally, the *improve* category is about vehicle efficiency. When motorized travel is necessary, energy use and emissions should be reduced, and fuel and vehicle technologies improved. Here, we consider the usage of vehicles with alternative fuels, such as electric and hydrogen vehicles. Part of the *improve* category are systems that use alternative fuel vehicles for multi-echelon delivery concepts or vehicle sharing. Also the design of recharging/refueling network or finding the best refueling/recharging policies is considered. These initiatives improve the conditions and hence make the usage of those vehicles more attractive which attracts new users.

The focus of this paper is on urban and rural areas. Long-distance and interurban transportation are out of scope. An overview of operations research (OR) for green freight transportation can be found in Bektaş et al. (2019). An important component of a transition to sustainable mobility is a shift to public transport and rail in general. However, since this is a very broad topic and would require a survey paper on its own, we refer to existing surveys (e.g. Borndörfer et al. (2018)). Maritime transportation also foresees the switch to environmentally friendly ships. As the field is also too broad, it is beyond the scope of this paper. Psaraftis (2019) provides an excellent overview of the challenges met within sustainable maritime transportation.

3 Alternatively fueled vehicles

One of the most obvious ways to reduce the transport sector's GHG emissions is to adopt alternatively fueled vehicles to replace fossil fuel vehicles. However, even though several technological breakthroughs have been achieved during the past decade, several challenges remain today when implementing vehicle fleets fueled by sources other than traditional diesel and gasoline. For electric vehicles, especially limitations in the vehicles' operational range and access to recharging infrastructure are mentioned as an inhibitor of the deployment. For hydrogen- and the various types of gas-driven vehicles, access to refueling infrastructure is paramount; for hydrogen, the distribution is complex and, therefore, challenging. The transformation from traditional diesel and gasoline stations to alternative fuels is far from simple, as the new supporting infrastructure is very costly. So far, the development has been hindered by a "hen and the egg"-like dilemma: the infrastructure needs to be in place before fleet owners start considering buying an alternatively fueled vehicle; however, infrastructure owners and investors are reluctant to invest in a market with only very few customers. Thus, development has been relatively slow in most parts of the world.

Methodologies from transport optimization are vital for supporting the deployment of alternative fuels. Tour planning with refueling has first been considered by Erdoğan and Miller-Hooks (2012). They introduced the Green-Vehicle Routing Problem (G-VRP), which includes range-limited alternatively fueled vehicles and charging station availability. They assume a constant refueling time. For setting up a network of charging or refueling stations, there are two classes of models: 1) node-based models, where customer demand is assigned to the nodes of the network, and 2) flow-based models, where demand is a set of origin–destination trips taken (Kchaou-Boujelben 2021).

Electric vehicles and charging infrastructure The limited driving range and long charging times must be considered when planning charging infrastructure for electric vehicles. For a recent review on the Electric Vehicle Routing Problem and its variants, see Kucukoglu et al. (2021). Sweda et al. (2017a) and Sweda et al. (2017b) address policies for efficient electric vehicle charging, thus minimizing the total cost. The impact of driving style, road and weather conditions on the driving range of electric vehicles is studied by Pelletier et al. (2019). The best size and mix of a fleet of both electric and conventional vehicles is studied by Malladi et al. (2022).

Electric vehicles and battery swapping

One of the limitations of using electric vehicles is their restricted driving range and long charging times. The development of swappable batteries has partially circumvented this problem. They can be exchanged quickly and recharged independently from the vehicle. Several interesting optimization problems have arisen in the field of battery swapping (Cui et al. 2022).

Yang et al. (2017) study battery service network design for shared electric vehicles and formulate the problem as a Mixed Integer Linear Program (MILP). A metaheuristic solution method is proposed and applied to a real-world network.

Widrick et al. (2018) formulate a battery-swap station management problem dealing with charging and discharging batteries at the stations by taking into account stochastic demand for batteries and prices for dis-/charging batteries. The problem is modeled as a Markov decision process, and the optimal strategy is found by using Dynamic Programming.

Although swappable batteries are used for many types of electric vehicles, some practitioners still see a potential danger in their usage, especially when it comes to smaller vehicles, such as e-scooters. Detachable batteries can be damaged or stolen more easily, and such e-scooter models are not as robust as conventional ones.

Hydrogen and refueling infrastructure

Fuel cell and green hydrogen technologies are considered to be among the most promising alternative fuels to replace diesel for heavy-duty vehicles such as large trucks (Rose and Neumann 2020). Hydrogen offers fast refueling and a long operational range, which makes hydrogen attractive to fleet owners supporting high fleet utilization. However, investments in refueling infrastructure are needed before hydrogen can be expected to gain reasonable market shares.

The complex dependencies between the production of green hydrogen, distribution to refueling stations, and location of these caused recent interest in research within hydrogen infrastructure planning. Multiple data sources, such as the existing petrol-refueling station network, demographic data and regional economic data, are used by Lin et al. (2020) to propose a combination of a greedy algorithm and simulated annealing to optimize the location of hydrogen refueling stations. Thiel (2020) apply agent-based modeling integrating a particle swarm optimization metaheuristic and a Geographic Information System (GIS) for Paris to locate new hydrogen refueling stations to complement existing stations and respond to the growing demand for hydrogen.

Rose and Neumann (2020) studies the interplay between refueling stations producing hydrogen locally and the power system, and a framework combining infrastructure location planning and propose an electricity optimization model.

4 Novel modes for freight transportation

Freight transport and logistics play a pivotal role in today's modern societies. Even though freight transport is responsible for only 2% of the vehicles on the roads in Europe, these are said to emit 23% of total CO_2 emissions originating from road transport (United Nations 2019). Thus, transitioning the road freight transport sector to align with the green agenda is essential in the mobility transition. Bektaş et al. (2019) suggest three directions for the transport optimization community to facilitate this transition, namely: 1) to help design effective transportation plans capturing the balance between environmental and economic objectives, 2) to inform and support policymakers about consequences of specific political measures to be taken and 3) to evaluate alternative "futuristic solutions for freight" by the use of OR-based models.

Besides the obvious challenge of emissions and local pollution, urban and suburban freight transport is also associated with externalities such as noise, traffic accidents and congestion. The notion of "the problem of the last mile" describes the issues faced by transport operators serving the last (and first) parts of the transport sequence within urban and suburban conditions (Larsen and Van Woensel 2019). A review dedicated to last-mile distribution is given by Boysen et al. (2021).

Cattaruzza et al. (2017) provide a survey on VRPs for city logistics categorizing the most critical challenges to be addressed as 1) time-dependency, 2) multi-level and multi-trip organization of the distribution and 3) dynamic information.

Alternative modes of freight transport have been emerging due the last decade. (Electric) cargo bikes and micro-vans are being deployed to efficiently handle last mile transport due to these vehicles' high degree of accessibility and more modest needs for parking. Integrating new transport modes often results in multi-echelon routing problems as these vehicles typically have limited operational ranges and capacities. Sluijk et al. (2022) and Cuda et al. (2015) present surveys on two-echelon routing problems.

A related topic is collaborative logistics in which, often competing, companies collaborate on sharing each other's vehicle capacities to achieve a, in theory, system optimum rather than a user optimum for each actor individually. Or in other words, freight operators carry out part of their transportation jointly by exchanging transportation requests with colleagues (or competitors). Reviews on collaborative urban transportation and vehicle routing are given in Cleophas et al. (2019) and Gansterer and Hartl (2018).

The freight transportation sector faces numerous challenges in reaching the goals defined by the green agenda. However, novel business models and new modes of transport may help achieve these goals. Such business models and modes of transport pose new and exciting problems for the transport optimization community to address. In this section, promising new areas of research will be reviewed and discussed.

4.1 Non-motorized freight transportation

Mobility transition also foresees a switch from standard delivery vans to low- or zero-emission modes of transport. A literature review (Oliveira et al. 2017) provides an overview of lightweight vehicles which could be used for the last mile delivery. They state that 47% of studies recommend using (cargo) bikes.

The (electric) cargo bike offers several advantages over delivery trucks, including lower purchase prices, tax, insurance, storage, and depreciation costs. Furthermore, they can use bike lanes to escape traffic congestion and can be parked more easily than vans; hence, proving to be more suitable for densely populated areas or areas with high traffic volumes than vans. However, cargo bikes have lower load capacity compared to delivery trucks and therefore more delivery activities per day are required to reach the required package volume. Furthermore, they are not suitable on steep roads and are not well suited for large and heavy packages. For a recent review of the advantages and disadvantages of using cargo bikes for urban delivery and the impacts of cargo bikes on urban logistics see Vasiutina et al. (2021).

The impact of load on the speed of cargo bikes and the resulting travel times is the focus of work proposed by Fontaine (2022). They show that neglecting load when estimating travel times can lead to violations of time windows.

Due to the limited capacities and travel distance, delivery by cargo bikes is often combined with (micro) city hubs - which are facilities typically located close to delivery areas. This makes the planning of distribution easier: Larger quantities can be brought to city hubs by (electric) vans, and the last mile delivery from a city hub to the final customer can be executed by a smaller vehicle, such as a cargo bike. The problem at hand can be modeled as a 2E-VRP where the routing of both inbound and outbound vehicles has to be optimized while the available inventory at the city hub is monitored.

A 2E-VRP with time windows and partial recharging is considered by Caggiani et al. (2021). For the first stage, they assume that delivery is executed by vans, and the second stage is done by electric vans and cargo bikes. Finding best city hub locations is the main focus for Büttgen et al. (2021). The 2E-VRP becomes more challenging when temporal and spatial synchronization between vehicles from different stages has to be guaranteed. Anderluh et al. (2017) consider transshipments between vehicles at satellite platforms without storage capacities. Fikar et al. (2018) let the transshipment points between vehicles be selected before planning the routes for vehicles. They propose a dynamic optimisation procedure to solve the problem and test their algorithm on real-world based data. Anderluh et al. (2020) investigate how time uncertainty impacts the quality of the solution for a two-echelon problem with synchronization.

Another option is to include walking couriers in the delivery tour. In a study for last-mile light goods vehicle activity in London (Allen et al. 2018), it is highlighted that walking as part of the delivery tour is already current practice. Walking can take up to 62% of the total vehicle round time while the vehicle is parked at the kerbside, and drivers walk about 8 km on a round. Vehicle routing with walking couriers is considered, for instance, by Le Colleter et al. (2023) and Bayliss et al. (2023).

4.2 Autonomous deliveries

Recent developments in sensor technologies, telecommunication and artificial intelligence have led to an increased interest in automated last-mile delivery technologies. Unmanned aerial vehicles (UAVs, drones) and robots have been investigated and tested by various companies in diverse settings. The first objective for using drones is to improve customer service by reducing delivery times and ensuring timeliness. Drones might play a role in improving traffic conditions in cities as they potentially reduce street traffic; however, if deployed at a large scale they might also lead to increased noise pollution. Urban settings with restricted access, such as pedestrian areas or a campus, might be the best areas for using delivery robots that might be driving on streets, bike lanes or even sidewalks. These vehicles are usually smaller, slower, quieter, and more environmentally friendly than classical delivery vans but may be similar to electric cargo bikes but without the need for a human rider/driver. For an overview of the topic and recent experiments, as well as a broad literature review, we refer to a recent article on automated deliveries for e-commerce applications Buldeo Rai et al. (2022). The CO_2 emissions of drones, sidewalk and road delivery robots are analysed and compared by Figliozzi (2020). The authors state that all three autonomous vehicle types have a significant potential to reduce emissions.

Direct drone deliveries have been considered for retail deliveries in Perera et al. (2020). The authors propose a stylized drone delivery system model in order to analyze its potential with regard to logistics parameters such as the number of warehouses and offered delivery-lead times. It is shown that increasingly cost-effective drones will lead to more decentralised systems with faster delivery speeds. In terms of route efficiency, such direct delivery systems are not beneficial, will increase the number of single deliveries, and potentially have negative environmental impacts. We therefore concentrate on the concepts involving flying drones or driving robots in combination with other transport modes in order to increase the efficiency of the overall delivery system. On the one hand, there are two-echelon delivery concepts (Bakach et al. 2021; Alfandari et al. 2022), where delivery robots are used for second echelon deliveries. On the other hand, there has been increased interest for hybrid delivery concepts combining unmanned or autonomous delivery vehicles with vans. In the following, we present an overview of selected recent scientific literature considering those combined problems.

Van-based drone delivery

The experiments of delivery companies have ignited the interest of the OR community. The combined problem of routing trucks and drones was the first time such a problem has been considered from a tour planning point of view (Murray and Chu 2015). The advantages in terms of improving efficiency are obvious as the drone can deliver to more remote areas while the van does not need to drive long distances for single deliveries that are far from its main route. In the existing literature, exact algorithms have been applied to solve smaller problem variants, while heuristics and meta-heuristics have been proposed to solve larger problem instances. Several problem variants as well as more theoretical considerations have appeared in the literature, for recent surveys on drone deliveries we refer to Li et al. (2021) as well as Moshref-Javadi and Winkenbach (2021). The considered problems are usually differentiated by different combinations of single or multiple trucks and single or multiple drones.

Van-based robot delivery

Van-based robot deliveries have some similarities with van based-drone deliveries. However, there are several differences based on their technical characteristics. For instance for drones the speed depends on the payload. Robots are travelling at lower speeds and may have interactions with pedestrians, bicycles, and cars. Robots will most often offer the possibility to serve several customers before needing to return to their base station or truck, leading to potentially more efficient route structures.

A combined concept is considered for the first time with regards to operational planning by Boysen et al. (2018). A problem with multiple robots per truck and each robot serving a single customer per route is considered. Two problem variants are investigated, one where the robot gets back to a dedicated robot depot and another one where the truck waits for all its robots before continuing its tour. The problems are modeled as MIP and solved using standard solvers as well as a specific local search approach. Managerial insights based on computational experiments on artificial test instances show the advantages of the model using dedicated robot depots as the truck does not have to wait for the low speed robots.

Robots with compartments are considered for allowing multiple drop-offs in a single tour in by Simoni et al. (2020). Besides an Integer Programming formulation, Local Search heuristics combined with Dynamic Programming for efficiently allocating robot routes to existing truck tours are proposed.

According to the presented experiment, such systems are beneficial if robots are employed in heavily congested areas and have the ability to serve multiple customers within a single route.

A problem version considering several complex practical characteristics is considered by Yu et al. (2022). A van-based robot pickup and delivery model is considered: Robots and vans can serve customers, however, not all customers can be reached by vans. In addition battery constraints for robots are considered. A MIP model as well as a Large Neighborhood approach for solving larger problem instances is proposed. Extensive numerical analysis based on artificial problem instances as well as a case study of the city of Xi'an is presented. The proposed model performs better than classical two-echelon distribution concepts with satellites depending on fixed and variable cost of the robots as well as the (infrastructural) cost of the satellites.

4.3 Parcel lockers and alternative delivery locations

In order to respond to the problem of failed deliveries and to reduce delivery costs by using consolidation opportunities, delivery companies consider alternative delivery locations such as parcel lockers. These lockers can be either white label or proprietary and can be in residential buildings or in easily accessible places throughout a city. Other options are to offer alternative delivery locations throughout the day or to deliver to the trunk of a car.

The problem of locating parcel lockers can be modeled by different types of location problems such as covering location problems or uncapacitated facility location problems (see Deutsch and Golany (2018)).

Mancini and Gansterer (2021) study a problem where the delivery company can decide whether the customer orders are delivered to a given address in a certain time window or to a locker box. The customer can indicate the subset of locker box stations that are acceptable. Furthermore, the customers receive compensation if the delivery goes to the locker box station. Matheuristic-based solution methods are proposed. Grabenschweiger et al. (2021) extend the problem by considering heterogeneous locker boxes. The authors propose a mathematical formulation and a metaheuristic. Different locker configurations and different demand scenarios were compared to derive managerial insights.

In the VRP with delivery options (VRPDO), customers can indicate alternative delivery locations, each associated with a time window and a preference level. The problem is an extension of the vehicle routing problem with time windows and the generalized vehicle routing problem. Constraints for the capacity at locker stations and the minimum preference level are included. An LNS approach for the problem was developed by Dumez et al. (2021) and a branch-price-and-cut algorithm by Tilk et al. (2021).

Reyes et al. (2017) present a problem where delivery to the trunk of a car is possible and is called the VRP with roaming delivery locations (VRPRDL). In contrast to the VRPDO, there are no preferences for delivery options nor capacity constraints at delivery options. The authors propose an ALNS heuristic. Ozbaygin et al. (2017) combine it with the possibility of home delivery and solve by a branch-and-price algorithm. A dynamic version is studied by Ozbaygin and Savelsbergh (2019).

Schwerdfeger and Boysen (2020) consider a system of mobile parcel lockers that can move autonomously or by a human driver. They define the mobile locker location problem (MLLP). Customers have different whereabouts in the planning horizon. A location and a time window define each whereabouts. Mobile parcel lockers move during the planning horizon and stop at locations selected from predefined potential parking locations. Customers can then pickup their parcels if the locker is within the maximum walking range. The objective is to minimize the fleet size, and a locker capacity constraint is considered. The authors propose different MIP models. They show in computational experiments that in the system of mobile parcel lockers, fewer lockers are necessary to serve the customers than in the stationary locker system. Schwerdfeger and Boysen (2022) compare mobile locker concepts such as human vs. robot-driven, mounted vs loaded lockers and mobile vs. stationary lockers.

In Orenstein et al. (2019), a delivery system is proposed in which customers may specify a number of different service points for potential delivery. These service points can be staffed or self-service points. Furthermore, delivery can be postponed to the subsequent period at the cost of a penalty payment. Limited capacity for different locker sizes is taken into account. The problem is solved by heuristics. The computational study shows that flexibility helps to reduce delivery costs.

Regarding the minimization of failed deliveries, Florio et al. (2018) propose an approach that optimizes hit rates where the likelihood of customer availability is modeled using availability profiles.

5 People transportation

An improvement in system efficiency is also reflected in the mobility and transportation of people in terms of ridesharing or renting a service.

5.1 Renting a service

Renting a service includes concepts such as carsharing, bikesharing, moped or scooter sharing, where an organization offers a fleet of vehicles which can be rented by private users for a certain amount of time. Users can typically book vehicles via an online platform, and each user pays a fee for booking and using a vehicle. Vehicles can either be picked up and dropped off at predefined stations or are free-floating in a defined operating area. In recent years there have been various reviews on bikesharing (e.g. Shui and Szeto (2020)) carsharing (e.g. Golalikhani et al. (2021)) or on vehicle sharing systems in general (Ataç et al. 2021).

An overview of shared mobility systems at the strategic, tactical and operational levels is presented by Laporte et al. (2018). The focus is on bicycle and carsharing systems and only those that use fixed stations for pickup and return.

Location of stations Several factors must be considered to determine the optimal number and locations of stations in a station-based system. Mix et al. (2022) propose a two-stage approach to determine the optimal locations for the stations. First, they estimate demand in different city areas, based on historical data, with the help of multiple linear regression. The real-world data are then used in a maximum coverage optimization model, which is solved with a commercial solver. Kabak et al. (2018) also evaluated their multi-criteria decision-making model on real-world data. They first identified twelve criteria they deemed essential for setting up bike stations: connectivity to the public transportation networks, population size or proximity of recreation areas. They identified potential locations using a geographic information system and ranked them using an analytic hierarchy process and multi-objective optimization.

Inventory level and fleet size Another optimisation problem is finding the optimal fleet size for sharing vehicles. Ströhle et al. (2019) addresses the issue of finding a trade-off between available supply in rental cars and customers' temporal and spatial flexibility. Yan et al. (2017) study a problem of combining decisions on locations of bike stations with the problem of fleet allocation. They formulate the problem as a MILP with both deterministic and stochastic demand. While the deterministic model can be solved to optimality by a commercial solver, the authors develop a two-stage heuristic solution method for the stochastic version of the problem. Liu et al. (2019) formulate a bi-level problem for optimal fleet allocation strategy for a mixed fleet of conventional and electric bikes. The model takes into account the impact of the electric bikes on the sharing system by estimating profits, demand for both types of bikes and the additional charging costs for the electric bike.

Station-based repositioning Due to the active rental of bikes throughout the day, an imbalance in the supply and demand at stations might occur. Therefore, it is necessary to reposition the bikes from locations with low and high demand to stations with low and high demand. The rebalancing problem belongs to the field of VRP with pickup and delivery. Many studies on repositioning assume that the available capacity at each station is also the optimal inventory level, and therefore propose rebalancing strategies based on fill-up rate (Maggioni et al. 2019). Datner et al. (2019) focus on the problem of defining a target number of bikes during the day at each station with the goal to minimize user inconvenience.

Brinkmann et al. (2019) consider dynamic repositioning strategies in their work. They formulate a stochastic-dynamic Inventory Routing Problem that minimizes the number of unsuccessful bike rentals. They simulate future demand with a dynamic look-ahead policy and solve the problem with approximate dynamic programming. Legros (2019) also consider a dynamic version of the problem with the goal to minimize the number of users who cannot be assigned to a bike. They show that more active or imbalanced locations should be given a higher priority if no rebalancing through rental actions is expected.

For a recent survey on rebalancing problems in the context of carsharing see Nansubuga and Kowalkowski (2021).

Free floating repositioning

In the free floating system there are no designated stations for shared vehicles, so finding the optimal rebalancing strategy is difficult. To overcome this problem, the practitioners and researchers typically divide the city into operating zones and define minimum and maximum inventory levels per zone. He et al. (2020) consider a repositioning problem which takes into account temporally dependent demands. They show that repositioning activities should be performed earlier in the day and only sporadically later on.

The rebalancing and repositioning problems in the case of car sharing are complex, especially in the case of one-way service. While bikes, scooters or mopeds can be moved by trucks, this strategy is less suitable for cars. Additionally, a problem arises of how many cars to provide at each gathering point, as several criteria, such as available parking spots and expected demand have to be taken into account. Illgen and Höck (2019) provides an overview of different optimization, simulation and multistage models on the strategic, tactical and operational levels.

Soppert et al. (2023) argue that the zoning approach in free floating rebalancing problem might lead to suboptimal solutions, as the literature typically assumes that a user can be assigned to any vehicle within a zone, even if the distance from a user to vehicle is long. They propose matching functions based on the distance users are willing to walk to the next available vehicle.

Electric rental vehicles

Sharing systems can also include electric vehicles but the limited driving range and the charging times must also be taken into consideration. Shen et al. (2019) give an overview of the literature on optimization models for service operations of electric vehicles. Narayanan et al. (2020) provide an overview of the literature where autonomous vehicles are used in the sharing concept.

Bruglieri et al. (2014) propose that the rebalancing of electric vehicles is done by company employees who might use bikes to drive the vehicle. Weikl and Bogenberger (2015) tackle the problem of repositioning, recharging and refueling electric and conventional vehicles in a free-floating carsharing system. The goal is to find the optimal rebalancing policy, by taking into account real-world historical data on time-dependent vehicle demand.

A big problem of small electric rental vehicles is their limited driving range. All vehicles which are not using swappable batteries are typically recharged at the depot during the night. An alternative to charging at the depot would be charging on board while vehicles are being relocated (see Osorio et al. (2021)).

5.2 Ridesharing

Carpooling, usually to and from work, with the objective to reduce costs has a long tradition. With the emergence of advanced information technologies, the idea can be extended to a general context where people with similar itineraries and time schedules can share rides. In dynamic ridesharing problems, drivers and riders are matched on short notice (or even en-route) (see Agatz et al. (2012) and Mourad et al. (2019) for surveys). Demand-responsive ridesharing systems can be modeled as a dial-a-ride problem (DARP). Each user has a specified origin and destination. The goal is to design efficient vehicle routes such that every request is covered (see Molenbruch et al. (2017); Parragh et al. (2006) for review papers on the DARP).

Obviously, ridesharing will have positive effects in scenarios where it is possible to match many trips without generating large detours, thereby increasing vehicle occupancy and in the long run decreasing car ownership. Negative effects can be generated by deadheading and out-of-service movements. Further, undesired effects are that the ridesharing trip replaces active mobility or a well-functioning public transport system or that it generates induced traffic.

Demand responsive transport systems

While public transport provides an efficient and hence environmentally friendly alternative in urban areas, occupancy rates in rural areas are low. One solution is to introduce demand-responsive transport systems. A recent overview is provided in Vansteenwegen et al. (2022). The authors suggest a classification along the degrees of responsiveness: dynamic online, dynamic offline and static. Furthermore, these systems can be stop-based, such that the stop can be selected from a predefined set of locations, or door-to-door based, where any location is possible. The system can be semi-flexible when it is in general based on a timetable from which it can deviate or be operated fully flexibly. Errico et al. (2013) provide a survey on such semi-flexible systems.

Combined passenger and freight ridesharing

In a combined delivery system, passengers and freight can be transported together. One option is to transport people and freight in the same taxi network. In this context, the share-a-ride problem was introduced in Li et al. (2014). A fleet of taxis serves passenger requests and can also take parcel requests as long as the passenger journey is not affected significantly. They study a dynamic and a static version.

Another suggested system is to use excess capacity on trips that already take place. In crowd-sourced delivery, also termed crowd-shipping, parcel deliveries can be performed by self-employed drivers. The idea is that extra money can be earned on trips that would be undertaken anyway for work or leisure. Arslan et al. (2019) propose a decentralized matching platform to match parcel requests with ad-hoc drivers. The vehicle routing problem with occasional drivers is introduced in Archetti et al. (2016) where a company uses ad-hoc drivers, called occasional drivers, in addition to their regular delivery fleet.

Freight on public transportation There are also works considering freight on public transport. Several different terms are used in the literature such as freight on transit, cargo-hitching or passenger-and-package sharing. Freight can be on public transportation in a cargo tram, so that only the infrastructure is shared, in a shared vehicle, i.e. in a separate wagon, or in the same wagon as the passengers (Elbert and Rentschler 2022).

Public transport can be incorporated in two-tiered models on the first level. Masson et al. (2017) study a two-tier model where buses are used on the first level and city freighters depart from bus stops for the second-tier delivery. The pickup and delivery problem with time windows and scheduled lines is studied in Ghilas et al. (2016); Mourad et al. (2021). Behiri et al. (2018) investigate relevant topics at the strategic, tactical and operational levels.

6 Research directions

In this section, we highlight the research directions for a transition towards sustainable mobility that is the most relevant according to the opinion and expertise of the authors.

Inland waterways In the past years, there have been many initiatives on including inland waterways in urban freight transportation. Many interesting optimization problems can be identified in transportation by ships, such as multi-echelon vehicle routing problems (Sarkar et al. 2022), however, there is still a lack of literature in this area. Delivery by ship might be even more sustainable if alternative fuels are used. Future research might help to investigate where the optimal recharging or refueling stations should be located, which transshipment points could be used to transfer the freight from ship to another mode of transportation and what is the optimal composition of the vehicle fleet.

Reserved parking: scheduling, scheduling loading bays Usually, last mile delivery models assume the availability of parking spaces at the customer location. Urban space is scarce and in the majority of cities, there is a lack of parking space. Additionally, city governments are faced with an increasing demand for a redistribution of public space suggesting a reallocation of streets and parking lots to parks, recreational spaces or bike lanes. Hence, it is important that the parking space is managed efficiently. Advanced parking or reservation systems for loading bays are considered in simulation (Comi et al. 2018) or allocation (Shao et al. 2016) models, but future research should consider the parking problem when designing delivery tours.

Mobility as a service, multimodal planning, on-demand transport in combination with active mobility and public transport The seamless combination of various transport modes for personal mobility is essential in order to achieve a successful multimodal offering for people. Besides further improving multimodal route planning in general, special emphasis is required on the integration of active mobility modes in such applications. Active mobility is key for transitioning towards a more sustainable transport system (Reyes Madrigal et al. 2022). Furthermore increasing attention is drawn to analysing the potential consequences of automated on-demand transport such as robo-taxis or automated shuttles via simulation (Chouaki et al. 2023). The first results indicate potential problematic situations where such innovative mobility modes might decrease the modal share of public transport and bicycles.

It is therefore imperative to investigate how to best connect on-demand transport with public transport and active mobility for increasing overall system sustainability.

Social sustainability in the last mile

In recent years numerous papers have addressed environmental in addition to economic components in transportation problems, however, there is a lack of research on the social component of sustainability. Anderluh et al. (2021) put focus on the disturbance caused by freight delivery as a part of a social objective in a two-echelon vehicle routing problem. Abdullahi et al. (2021) discuss a multi-objective VRP that considers all three pillars of sustainability.

Stochastic and dynamic two-echelon routing with synchronization In last mile urban freight transport, non-motorized modes of transport like cargo bikes or walking couriers can be used. One way of integrating these modes is to perform a temporal and spatial synchronization in a two-echelon system where replenishment is performed by vans at certain rendezvous points. This synchronization is a challenge in a highly dynamic city distribution environment. Especially motorized vehicles are usually subject to congestion, delays and disruption in a city. There are some works that include dynamic or stochastic aspects, such as Dayarian et al. (2020) and Anderluh et al. (2020), as highlighted in the very recent review by Soares et al. (2023). Future research should focus on including these aspects in a way that last mile delivery problems are modelled realistically. Dynamic routing, for instance, is particularly challenging with synchronization aspects since there are multiple interdependencies between the routes that have to be considered especially for problem instances requiring a high degree of synchronization. In this direction, timely and relevant contributions can be made since the deterministic and static solution might finally not be feasible, implementable or very poor in the real-life setting.

7 Discussion and Conclusion

This paper has been studying the problem of transition towards sustainable mobility with the help of the avoid-shift-improve approach. The focus was on different paths of transport optimization and how they can be used within this approach. The most promising concepts for sustainable mobility were selected and categorized based on their contribution to the avoid-shift-improve approach. Relevant literature on optimization techniques for proposed concepts has been discussed. Due to the limited space, the list of the concepts for transition to sustainable mobility addressed in this paper is neither exclusive nor exhaustive.

We identified substantial transport optimization contributions, especially in the area of the *avoid* measure. Transport optimization can help to reduce the number of kilometers travelled, to minimize the number of vehicles on the street and therefore reduce congestion and CO_2 emissions. Within the *shift* measure, where the primary foci are non-motorized vehicles and public transport, transport optimization could be used to efficiently plan freight distribution with cargo bikes, to solve the optimal location and rebalancing policies in vehicle sharing systems, or to decide how to use public transport for freight delivery. For the *improve* measure, which aims at improving vehicle efficiency, optimization techniques could be used to find the optimal refueling and recharging infrastructure for alternatively fueled vehicles or to help integrate autonomous vehicles in the freight delivery process.

Although the novel concepts for passenger and freight transportation typically help the transition to sustainable mobility, some issues still need to be addressed. Ridesharing and rental services with motorized vehicles can help reduce the number of vehicles moving on the streets, but they should not take away users from public transport. In the case of non-motorized sharing systems, a cannibalization effect with public transport can be observed. Still, it is not as alarming, as it helps promote active mobility, which was particularly important during the COVID-19 pandemic. There are, however, many downsides of free-floating sharing systems of non-motorized vehicles, such as vandalism, irregular parking or interference with the traffic flow. Cities must respond to these challenges by introducing regulations and monitoring services, e.g. geo-fencing.

In order to integrate the optimization models in practice, a shift in the way companies and organizations are operating is needed as well. A change in the operative mindset and willingness to accept novel ideas is crucial to successfully implement and test innovative solutions. Transparent communication and feedback from users and planers is essential in creating trust among stakeholder groups. Furthermore, the availability of data in digital (machine-readable) form is a prerequisite for a smooth integration of innovative software tools in companies' systems.

Likewise, politicians are asked to set up framework conditions for encouraging and also forcing more sustainable mobility solutions that will call for transport optimization to play an active role in the new framework conditions. It is vital to derive regulatory measures that will impact the way business is done in such a way that in order to have benefits companies need to change their operations. As long as being non-sustainable is more efficient and companies can earn more money, they will have no incentive of doing it differently. A combination of push and pull measures will be necessary. We saw that research on transport optimization plays a vital role in the avoid-shift-improve approach.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare.

References

Abdullahi H, Reyes-Rubiano L, Ouelhadj D et al (2021) Modelling and multi-criteria analysis of the sustainability dimensions for the green vehicle routing problem. Eur J Oper Res 292(1):143–154

Agatz N, Erera A, Savelsbergh M et al (2012) Optimization for dynamic ride-sharing: a review. Eur J Oper Res 223(2):295–303

Alfandari L, Ljubić I, da Silva MDM (2022) A tailored benders decomposition approach for last-mile delivery with autonomous robots. Eur J Oper Res 299(2):510–525

Allen J, Piecyk M, Piotrowska M et al (2018) Understanding the impact of e-commerce on last-mile light goods vehicle activity in urban areas: the case of london. Transp Res Part D: Transp Environ 61:325–338

Anderluh A, Hemmelmayr VC, Nolz PC (2017) Synchronizing vans and cargo bikes in a city distribution network. CEJOR 25:345–376

Anderluh A, Larsen R, Hemmelmayr VC et al (2020) Impact of travel time uncertainties on the solution cost of a two-echelon vehicle routing problem with synchronization. Flex Serv Manuf J 32:806–828

Anderluh A, Nolz PC, Hemmelmayr VC et al (2021) Multi-objective optimization of a two-echelon vehicle routing problem with vehicle synchronization and 'grey zone' customers arising in urban logistics. Eur J Oper Res 289(3):940–958

Archetti C, Savelsbergh M, Speranza MG (2016) The vehicle routing problem with occasional drivers. Eur J Oper Res 254(2):472–480

Arslan AM, Agatz N, Kroon L et al (2019) Crowdsourced delivery-a dynamic pickup and delivery problem with ad hoc drivers. Transp Sci 53(1):222–235

Ataç S, Obrenović N, Bierlaire M (2021) Vehicle sharing systems: a review and a holistic management framework. EURO J Trans Logist 10(100):033

Bakach I, Campbell AM, Ehmke JF (2021) A two-tier urban delivery network with robot-based deliveries. Networks 2021:1–23

Bayliss C, Bektaş T, Tjon-Soei-Len V et al (2023) Designing a multi-modal and variable-echelon delivery system for last-mile logistics. Eur J Oper Res 307(2):645–662

Behiri W, Belmokhtar-Berraf S, Chu C (2018) Urban freight transport using passenger rail network: scientific issues and quantitative analysis. Trans Res Part E Logist Trans Rev 115:227–245

Bektaş T, Ehmke JF, Psaraftis HN et al (2019) The role of operational research in green freight transportation. Eur J Oper Res 274(3):807–823

Bongardt D, Stiller L, Swart A, et al (2019) Sustainable urban transport: Avoid-shift-improve (asi). https://www.transformative-mobility.org/assets/publications/ASI_TUMI_SUTP_iNUA_No-9_April-2019.pdf, accessed: 2023-02-06

Borndörfer R, Klug T, Lamorgese L et al (2018) Handbook of optimization in the railway industry, vol 268. Springer

Boysen N, Schwerdfeger S, Weidinger F (2018) Scheduling last-mile deliveries with truck-based autonomous robots. Eur J Oper Res 271(3):1085–1099

Boysen N, Fedtke S, Schwerdfeger S (2021) Last-mile delivery concepts: a survey from an operational research perspective. OR Spectrum 43(1):1–58

Brinkmann J, Ulmer MW, Mattfeld DC (2019) Dynamic lookahead policies for stochastic-dynamic inventory routing in bike sharing systems. Comput Oper Res 106:260–279

Bruglieri M, Colorni A, Luè A (2014) The relocation problem for the one-way electric vehicle sharing. Networks 64(4):292–305

Buldeo Rai H, Touami S, Dablanc L (2022) Autonomous e-commerce delivery in ordinary and exceptional circumstances. the french case. Res Trans Bus Manage 45:100–774

Büttgen A, Turan B, Hemmelmayr V (2021) Evaluating distribution costs and co2-emissions of a two-stage distribution system with cargo bikes: A case study in the city of innsbruck. Sustainability 13(24):13–974

Caggiani L, Colovic A, Prencipe LP et al (2021) A green logistics solution for last-mile deliveries considering e-vans and e-cargo bikes. Trans Res Proced 52:75–82

Cattaruzza D, Absi N, Feillet D et al (2017) Vehicle routing problems for city logistics. EURO J Trans Logist 6(1):51–79

Chouaki T, Hörl S, Puchinger J (2023) Towards Reproducible Simulations of the Grand Paris Express and On-Demand Feeder Services. In: 102nd Annual Meeting of the Transportation Research Board (TRB 2023), Washington D.C, USA
Cleophas C, Cottrill C, Ehmke JF et al (2019) Collaborative urban transportation: Recent advances in theory and practice. Eur J Oper Res 273(3):801–816
Comi A, Schiraldi MM, Buttarazzi B (2018) Smart urban freight transport: tools for planning and optimising delivery operations. Simul Model Pract Theory 88:48–61
Cuda R, Guastaroba G, Speranza MG (2015) A survey on two-echelon routing problems. Comput Oper Res 55:185–199
Cui D, Wang Z, Liu P et al (2022) Operation optimization approaches of electric vehicle battery swapping and charging station: A literature review. Energy. https://doi.org/10.1016/j.energy.2022.126095
Datner S, Raviv T, Tzur M et al (2019) Setting inventory levels in a bike sharing network. Transp Sci 53(1):62–76
Dayarian I, Savelsbergh M, Clarke JP (2020) Same-day delivery with drone resupply. Transp Sci 54(1):229–249
Deutsch Y, Golany B (2018) A parcel locker network as a solution to the logistics last mile problem. Int J Prod Res 56(1–2):251–261
Dumez D, Lehuédé F, Péton O (2021) A large neighborhood search approach to the vehicle routing problem with delivery options. Trans Res Part B Methodol 144:103–132
Elbert R, Rentschler J (2022) Freight on urban public transportation: a systematic literature review. Res Trans Bus Manage 45(100):679
Erdoğan S, Miller-Hooks E (2012) A green vehicle routing problem. Trans Res Part E Logist Trans Rev 48(1):100–114
Errico F, Crainic TG, Malucelli F et al (2013) A survey on planning semi-flexible transit systems: methodological issues and a unifying framework. Trans Res Part C Emerg Technol 36:324–338
European Commission (2020) Sustainable and smart mobility strategy - putting european transport on track for the future. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions
Figliozzi MA (2020) Carbon emissions reductions in last mile and grocery deliveries utilizing air and ground autonomous vehicles. Transp Res Part D: Transp Environ 85(102):443
Fikar C, Hirsch P, Gronalt M (2018) A decision support system to investigate dynamic last-mile distribution facilitating cargo-bikes. Int J Log Res Appl 21(3):300–317
Florio AM, Feillet D, Hartl RF (2018) The delivery problem: optimizing hit rates in e-commerce deliveries. Trans Res Part B Methodol 117:455–472
Foltỳnová HB, Vejchodská E, Rybová K et al (2020) Sustainable urban mobility: one definition, different stakeholders' opinions. Transp Res Part D: Transp Environ 87(102):465
Fontaine P (2022) The vehicle routing problem with load-dependent travel times for cargo bicycles. Eur J Oper Res 300(3):1005–1016
Gansterer M, Hartl RF (2018) Collaborative vehicle routing: a survey. Eur J Oper Res 268(1):1–12
Ghilas V, Demir E, Van Woensel T (2016) An adaptive large neighborhood search heuristic for the pickup and delivery problem with time windows and scheduled lines. Comput Oper Res 72:12–30
Global Climate Action Partnership (2016) Sustainabe urban transport: Avoid-shift-improve (a-s-i). https://globalclimateactionpartnership.org/app/uploads/2016/01/SUTP_GIZ_FS_Avoid-Shift-Improve_EN.pdf, accessed: 2023-02-06
Golalikhani M, Oliveira BB, Carravilla MA et al (2021) Carsharing: a review of academic literature and business practices toward an integrated decision-support framework. Trans Res Part E logist Trans Rev 149(102):280
Grabenschweiger J, Doerner KF, Hartl RF et al (2021) The vehicle routing problem with heterogeneous locker boxes. CEJOR 29(1):113–142
He L, Hu Z, Zhang M (2020) Robust repositioning for vehicle sharing. Manufact Serv Oper Manage 22(2):241–256
Hesse M (1993) Verkehrswende : ökologisch-ökonomische Perspektiven für Stadt und Region. Ökologie und Wirtschaftsforschung, Metropolis-Verl, Marburg
Holden E, Gilpin G, Banister D (2019) Sustainable mobility at thirty. Sustainability 11(7):1965
Illgen S, Höck M (2019) Literature review of the vehicle relocation problem in one-way car sharing networks. Trans Res Part B Methodol 120:193–204
International Energy Agency (2022) Transport. https://www.iea.org/reports/transport

Kabak M, Erbaş M, Cetinkaya C et al (2018) A gis-based mcdm approach for the evaluation of bike-share stations. J Clean Prod 201:49–60

Kchaou-Boujelben M (2021) Charging station location problem: a comprehensive review on models and solution approaches. Trans Res Part C Emerg Technol 132(103):376

Kucukoglu I, Dewil R, Cattrysse D (2021) The electric vehicle routing problem and its variations: a literature review. Comput Ind Eng 161(107):650

Laporte G, Meunier F, Wolfler Calvo R (2018) Shared mobility systems: an updated survey. Ann Oper Res 271:105–126

Larsen A, Van Woensel T (2019) Freight, logistics and the delivery of goods in cities. In: DTU International Energy Report 2019: Transforming Urban Mobility. Technical University of Denmark, chap 8, p 62–71

Le Colleter T, Dumez D, Lehuédé F et al (2023) Small and large neighborhood search for the park-and-loop routing problem with parking selection. Eur J Oper Res 308(3):1233–1248

Legros B (2019) Dynamic repositioning strategy in a bike-sharing system; how to prioritize and how to rebalance a bike station. Eur J Oper Res 272(2):740–753

Li B, Krushinsky D, Reijers HA et al (2014) The share-a-ride problem: people and parcels sharing taxis. Eur J Oper Res 238(1):31–40

Li H, Chen J, Wang F et al (2021) Ground-vehicle and unmanned-aerial-vehicle routing problems from two-echelon scheme perspective: A review. Eur J Oper Res 294(3):1078–1095

Lin R, Ye Z, Guo Z et al (2020) Hydrogen station location optimization based on multiple data sources. Int J Hydrogen Energy 45(17):10,270-10,279

Liu L, Sun L, Chen Y et al (2019) Optimizing fleet size and scheduling of feeder transit services considering the influence of bike-sharing systems. J Clean Prod 236(117):550

Maggioni F, Cagnolari M, Bertazzi L et al (2019) Stochastic optimization models for a bike-sharing problem with transshipment. Eur J Oper Res 276(1):272–283

Malladi SS, Christensen JM, Ramírez D et al (2022) Stochastic fleet mix optimization: evaluating electromobility in urban logistics. Trans Res Part E Logist Trans Rev 158(102):554

Mancini S, Gansterer M (2021) Vehicle routing with private and shared delivery locations. Comput Oper Res 133(105):361

Masson R, Trentini A, Lehuédé F et al (2017) Optimization of a city logistics transportation system with mixed passengers and goods. EURO J Trans Logist 6(1):81–109

Mix R, Hurtubia R, Raveau S (2022) Optimal location of bike-sharing stations: a built environment and accessibility approach. Trans Res Part A Policy Pract 160:126–142

Molenbruch Y, Braekers K, Caris A (2017) Typology and literature review for dial-a-ride problems. Ann Oper Res 259:295–325

Moshref-Javadi M, Winkenbach M (2021) Applications and research avenues for drone-based models in logistics: a classification and review. Expert Syst Appl 177(114):854

Mourad A, Puchinger J, Chu C (2019) A survey of models and algorithms for optimizing shared mobility. Trans Res Part B Methodol 123:323–346

Mourad A, Puchinger J, Van Woensel T (2021) Integrating autonomous delivery service into a passenger transportation system. Int J Prod Res 59(7):2116–2139

Murray CC, Chu AG (2015) The flying sidekick traveling salesman problem: optimization of drone-assisted parcel delivery. Trans Res Part C Emerg Technol 54:86–109

Nansubuga B, Kowalkowski C (2021) Carsharing: a systematic literature review and research agenda. J Serv Manag 32(6):55–91

Narayanan S, Chaniotakis E, Antoniou C (2020) Shared autonomous vehicle services: a comprehensive review. Trans Res Part C Emerg Technol 111:255–293

Oliveira CMd, De Mello Albergaria, Bandeira R, Vasconcelos Goes G et al (2017) Sustainable vehicles-based alternatives in last mile distribution of urban freight transport: A systematic literature review. Sustainability 9(8):1324

Orenstein I, Raviv T, Sadan E (2019) Flexible parcel delivery to automated parcel lockers: models, solution methods and analysis. EURO J Trans Logist 8(5):683–711

Osorio J, Lei C, Ouyang Y (2021) Optimal rebalancing and on-board charging of shared electric scooters. Trans Res Part B Methodol 147:197–219

Ozbaygin G, Savelsbergh M (2019) An iterative re-optimization framework for the dynamic vehicle routing problem with roaming delivery locations. Trans Res Part B Methodol 128:207–235

Ozbaygin G, Karasan OE, Savelsbergh M et al (2017) A branch-and-price algorithm for the vehicle routing problem with roaming delivery locations. Trans Res Part B Methodol 100:115–137

Parragh SN, Doerner KF, Hartl RF (2006) A survey on pickup and delivery models part ii: transportation between pickup and delivery locations. J für Betriebswirtschaft 58:81–117
Pelletier S, Jabali O, Laporte G (2019) The electric vehicle routing problem with energy consumption uncertainty. Trans Res Part B Methodol 126:225–255
Perera S, Dawande M, Janakiraman G et al (2020) Retail deliveries by drones: how will logistics networks change? Prod Oper Manag 29(9):2019–2034
Psaraftis HN (ed) (2019) Sustainable shipping: a cross-disciplinary view. Springer, Cham
Reyes D, Savelsbergh M, Toriello A (2017) Vehicle routing with roaming delivery locations. Trans Res Part C Emerg Technol 80:71–91
Reyes Madrigal LM, Puchinger J, Nicolaï I, et al (2022) Walking in Mobility as a Service (MaaS): Exploring the Appraisal of Walking in MaaS in the Paris Region. Walk21, Ireland
Rose PK, Neumann F (2020) Hydrogen refueling station networks for heavy-duty vehicles in future power systems. Transp Res Part D: Transp Environ 83(102):358
Sarkar B, Ganguly B, Pareek S et al (2022) A three-echelon green supply chain management for biodegradable products with three transportation modes. Comput Ind Eng 174(108):727
Schwerdfeger S, Boysen N (2020) Optimizing the changing locations of mobile parcel lockers in last-mile distribution. Eur J Oper Res 285(3):1077–1094
Schwerdfeger S, Boysen N (2022) Who moves the locker? a benchmark study of alternative mobile parcel locker concepts. Trans Res Part C Emerg Technol 142(103):780
Shao C, Yang H, Zhang Y et al (2016) A simple reservation and allocation model of shared parking lots. Trans Res Part C Emerg Technol 71:303–312
Shen ZJM, Feng B, Mao C et al (2019) Optimization models for electric vehicle service operations: a literature review. Trans Res Part B Methodol 128:462–477
Shui C, Szeto W (2020) A review of bicycle-sharing service planning problems. Trans Res Part C Emerg Technol 117(102):648
Simoni MD, Kutanoglu E, Claudel CG (2020) Optimization and analysis of a robot-assisted last mile delivery system. Trans Res Part E Logist Trans Rev 142(102):049
Sluijk N, Florio AM, Kinable J et al (2022) Two-echelon vehicle routing problems: a literature review. Eur J Oper Res 304(3):865–886
Soares R, Marques A, Amorim P et al (2023) Synchronisation in vehicle routing: classification schema, modelling framework and literature review. Eur J Oper Res. https://doi.org/10.1016/j.ejor.2023.04.007
Soppert M, Steinhardt C, Müller C et al (2023) Matching functions for free-floating shared mobility system optimization to capture maximum walking distances. Eur J Oper Res 305(3):1194–1214
Ströhle P, Flath CM, Gärttner J (2019) Leveraging customer flexibility for car-sharing fleet optimization. Transp Sci 53(1):42–61
Sweda TM, Dolinskaya IS, Klabjan D (2017) Adaptive routing and recharging policies for electric vehicles. Transp Sci 51(4):1326–1348
Sweda TM, Dolinskaya IS, Klabjan D (2017) Optimal recharging policies for electric vehicles. Transp Sci 51(2):457–479
Thiel D (2020) A pricing-based location model for deploying a hydrogen fueling station network. Int J Hydrogen Energy 45(46):24,174-24,189
Tilk C, Olkis K, Irnich S (2021) The last-mile vehicle routing problem with delivery options. OR Spectrum 43(4):877–904
United Nations (2015) Transforming our world: the 2030 agenda for sustainable development
United Nations (2019) GHG data from UNFCCC (United Nations Framework Convention of Climate Change). https://transport.ec.europa.eu/transport-themes/clean-transport-urban-transport/urban-mobility/action-plan-urban-mobility_en
United Nations Environment Programme (2022) Emissions gap report 2022: The closing window – climate crisis calls for rapid transformation of societies. https://www.unep.org/emissions-gap-report-2022, license: CC BY 4.0
Vansteenwegen P, Melis L, Aktaş D et al (2022) A survey on demand-responsive public bus systems. Trans Res Part C Emerg Technol 137(103):573
Vasiutina H, Szarata A, Rybicki S (2021) Evaluating the environmental impact of using cargo bikes in cities: A comprehensive review of existing approaches. Energies 14(20):6462
Weikl S, Bogenberger K (2015) A practice-ready relocation model for free-floating carsharing systems with electric vehicles-mesoscopic approach and field trial results. Trans Res Part C Emerg Technol 57:206–223

Widrick RS, Nurre SG, Robbins MJ (2018) Optimal policies for the management of an electric vehicle battery swap station. Transp Sci 52(1):59–79
World Commission on Environment and Development (1987) Our common future-The Brundtland report. Oxford University Press, Oxford
Yan S, Lin JR, Chen YC et al (2017) Rental bike location and allocation under stochastic demands. Comput Ind Eng 107:1–11
Yang J, Guo F, Zhang M (2017) Optimal planning of swapping/charging station network with customer satisfaction. Trans Res Part E Logist Trans Rev 103:174–197
Yu S, Puchinger J, Sun S (2022) Van-based robot hybrid pickup and delivery routing problem. Eur J Oper Res 298(3):894–914