

Olsen, Nils

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A Literature Overview on Scheduling Electric Vehicles in Public Transport and Location Planning of the Charging Infrastructure

Nils Olsen

School of Business & Economics

Discussion Paper

Information Systems

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A Literature Overview on Scheduling Electric Vehicles in Public Transport and Location Planning of the Charging Infrastructure

Nils Olsen

Freie Universität Berlin, School of Business and Economics,
Garystr. 21, 14195 Berlin, Germany

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The Vehicle Scheduling Problem (VSP) is a well-studied combinatorial optimization problem arising for bus companies in public transport. The objective is to cover a given set of timetabled trips by a set of buses at minimum costs. The Electric Vehicle Scheduling Problem (E-VSP) complicates traditional bus scheduling by considering electric buses with limited driving ranges. To compensate these limitations, detours to charging stations become necessary for charging the vehicle batteries during operations. To save costs, the charging stations must be located within the road network in such a way that required deadhead trips are as short as possible or even redundant. For solving the traditional VSP, a variety of solution approaches exist capable of solving even real-world instances with large networks and timetables to optimality. In contrast, the problem complexity increases significantly when considering limited ranges and chargings of the batteries. For this reason, there mainly exist solution approaches for the E-VSP which are based on heuristic procedures as exact methods do not provide solutions within a reasonable time. In this paper, we present a literature review of solution approaches for scheduling electric vehicles in public transport and location planning of charging stations. Since existing work differ in addition to the solution methodology also in the mapping of electric vehicles' technical aspects, we pay particular attention to these characteristics. To conclude, we provide a perspective for potential further research.

Keywords: Vehicle Scheduling, Public Transport, Electric Buses, Charging Stations, Location Planning

1 Introduction

Scheduling of vehicles is a task arising in the operational planning process of companies in public transport. The corresponding mathematical optimization problem is denoted as the *Vehicle Scheduling Problem* (VSP) which has been extensively studied in the research community. Within modern public transport systems, electric vehicles are increasingly being used to replace traditional combustion engine vehicles. However, the use of electric vehicles complicates traditional vehicle scheduling significantly since limited driving ranges and the possibility of charging the vehicle batteries have to be considered. This extension of the basic problem is denoted as the *Electric Vehicle Scheduling Problem* (E-VSP). In the following, we define both the VSP and E-VSP.

1.1 Traditional Vehicle Scheduling

The objective of the basic VSP is to cover a set of service trips contained in a timetable by a set of vehicles while minimizing the total costs. Service trips denote trips for transporting passengers from a departure location to an arrival location at specific times. A vehicle can perform deadhead trips without passengers in order to change its location. The set of all trips executed by a vehicle is denoted as its rotation. Vehicle rotations need to satisfy some basic constraints:

- (1) The trips of a vehicle rotation must be mutually compatible, that is, the trips have to be executable without time overlaps.
- (2) Every service trip is covered exactly once and
- (3) a vehicle begins and ends its rotation at the same depot.

The costs of a solution consist of fixed costs for buses used and operational costs for considering the covered distances and the drivers' working hours. Beside the basic problem, there exists a number of extensions such as multiple vehicle depots or heterogeneous fleets with multiple vehicle types.

The basic VSP and its extensions are well studied problems in the research community and have been widely analyzed. Hence, there exist a wide variety of solution approaches for the VSP at present time. Bunte and Kliwer (2009) give an overview of model approaches and solution methods for the VSP and

its extensions. The authors address several variants of the single and multi-depot VSP such as multiple vehicle types, vehicle type groups, time windows, or route constraints.

The runtime of the different solution methods strongly depends on the way of modeling and the problem features. It is a matter of common knowledge that the VSP with a single vehicle depot can be solved to optimality in polynomial time. In contrast, Bertossi et al. (1987) show that the VSP with multiple vehicle depots and/or multiple vehicle types becomes NP-hard. However, Kliwer et al. (2006) introduced a solution method based on a time-space network capable of solving even real-world instances with large networks and timetables to optimality considering multiple depots and multiple vehicle types. Generally, the problem complexity depends on numerous factors such as the number of timetabled service trips, the number of depots/vehicle types, and the size of the network. The latter aspect is of importance as larger networks lead to more possible connections between the service trips within a vehicle rotation and thus lead to higher problem complexities.

1.2 Scheduling Electric Vehicles

Within modern public transport systems, traditional combustion engine vehicles are increasingly substituted by electric vehicles. This is because electric vehicles are locally emission-free meaning that almost no greenhouse gases, fine dust, and nitrogen oxides are being emitted during operations. Beyond that, electric vehicles enable a significant reduction of noise (cf. Schalaböck (2012)). The advantages outlined are especially important for urban areas.

The term *electric vehicle* includes mainly three different types of electric propulsions: *hybrid electric vehicles* (HEV), *fuel cell electric vehicles* (FCEV), and *fully electric vehicles* (EV) (cf. Ogden et al. (1999) and Pihlatie et al. (2014)). A HEV contains a battery for powering an electric engine and a traditional combustion engine, that can be switched on in order to extend its range. A FCEV contains an electric engine powered by a fuel cell that generates electric energy directly from hydrogen or methanol. An EV merely contains an electric engine for movement. The electric energy needed for powering the engine is provided either by an electric battery or by overhead wires located within the road network. The first case corresponds to the term *battery electric vehicle* (BEV) and the second case to *trolley vehicle*.

Despite these advantages, the use of EVs complicates traditional vehicle scheduling since EVs have much shorter driving ranges compared to traditional vehicles due to limited battery capacities. To compensate these limita-

tions, detours to charging stations become necessary for charging the vehicle batteries during operations. The consideration of these additional challenges imposed by EVs leads to the E-VSP. Therefore, the following additional requirements have to be satisfied beside the traditional restrictions given by the VSP:

- (4) The residual energy of a vehicle battery cannot fall below zero and cannot exceed the battery capacity and
- (5) the vehicle batteries can only be recharged at specified charging stations.

The residual energy of a battery is often denoted as its *State-of-Charge* (SoC).

When considering EVs, specific technical aspects are of particular importance. Particularly worthwhile mentioning are different battery types, characteristics of the charging and discharging process of vehicle batteries, and energy consumption of the vehicles used. As things stand, there are a number of different battery types that are used in practice such as lithium-ion, nickel zinc, or lithium metal polymer batteries. In most practical operations lithium-ion batteries are used and mainly charged by fast charging technologies (cf. M. Wang et al. (2016)). The discharging process is mainly determined by the energy consumption of EVs. Factors that influence the energy consumption are line topologies, road gradients, weather and traffic conditions, or a vehicle's air conditioning (cf. De Cauwer et al. (2015) and Deflorio and Castello (2017)).

For charging a vehicle battery mainly three different options exist. First, a vehicle battery can be charged overnight during longer idle times at the depot. Second, a battery can be charged during smaller breaks within a vehicle's operation, which is called opportunity charging. Lastly, a vehicle battery can be swapped for a fully charged battery. Different charging technologies are available for transferring energy into the batteries. Nowadays, this transfer is mainly performed either by a wire (conductively) or inductively (cf. Young (2018)). Regardless of how a vehicle battery is charged, one mainly distinguishes between full and partial chargings. In general, battery charging is a complex process with regard to real conditions and has to be modeled in a precise way within solution methods for the E-VSP. Olsen and Kliewer (2020) demonstrate that imprecise models for representing battery charging processes lead to inconsistent solutions of the E-VSP and related optimization problems.

Haghani and Banihashemi (2002) show that the traditional VSP with route and time constraints is NP-hard. Consequently, the E-VSP is NP-hard as well because it is an extension of the basic problem.

1.3 Location Planning of Charging Stations

For a cost-efficient use of electric buses, the charging stations must be located within the road network in such a way that required deadhead trips are as short as possible or even redundant. This is due to the facts that longer deadhead trips increase the operational costs of the vehicles deployed and the probability of missing connections to subsequent trips which leads to higher demands for vehicle. However, attention must also be paid to construction costs and further restrictions such as local restrictions or constraints imposed by the energy supply. For instance, it is more expensive to build a charging station at a busy crossing than in a quiet side street. In contrast to vehicle scheduling, which is a more short-term planning task of public transport companies, location planning of charging stations is a long-term planning problem.

1.4 Research Objective and Outline

Due to the great complexity of the E-VSP and in order to be able to solve also real-world instances of the problem with extremely large road networks and timetables, heuristic solution methods have been predominantly established for solving the E-VSP. The existing contributions for the E-VSP differ in addition to the solution methodologies also in the mapping of electric vehicles' technical characteristics. Furthermore, location planning of charging stations is of central importance for the efficient deployment of EVs. In this paper, we provide a literature review of solution approaches for scheduling EVs in public transport and location planning of charging stations for EVs. We outline differences of the works with regard to the solution methodologies and particularly address the way of considering technical characteristics.

Therefore, the paper is structured as follows: In Section 2 we present solution approaches that consider limited driving ranges of vehicles within the traditional VSP. Following this, we discuss solution methods that consider recharging of the vehicle batteries in addition to limited driving ranges in Section 3. As the distribution of charging stations within the road network plays a major role for EVs, we present solution methods for location planning of charging stations within Section 4. A conclusion of this report and a perspective for potential further research is given by Section 5.

2 Vehicle Scheduling Problem with limited Driving Ranges

As a first approach towards a consideration of EVs within vehicle scheduling in public transport, the traditional VSP has been extended in order to reflect limited driving ranges of the vehicles used.

As one of the first contributions to consider limited operating ranges of the vehicles deployed, Freling and Paixão (1995) deal with the VSP with time constraints. Within this work, the maximum travel times of vehicles during their rotations are restricted. For solving this enhanced problem, the authors present a two-stage heuristic solution approach. First, initial solutions are generated, which are then improved by local search strategies. Although limited travel times of the vehicles are taken into account, the vehicles' driving ranges are not directly limited in this work. Furthermore, battery charging is not incorporated.

Desrosiers et al. (1995) and Haghani and Banihashemi (2002) introduce the *Time Window Constraint Scheduling Problem* as an extension of the traditional VSP. In contrast to the work of Freling and Paixão (1995), the authors restrict both the durations and lengths of vehicle rotations. Therefore, they add constraints to the traditional problem formulation of the VSP for incorporating restricted fuel consumptions of the vehicles used. For solving this enhanced optimization problem, the authors present an exact and two heuristic solution methods.

The exact solution method consists of an iterative procedure. First, the traditional VSP is solved to optimality. Therefore, standard optimization software libraries are used. In the second step, it is checked whether all vehicle rotations computed satisfy the newly added fuel constraints. If this is the case, the procedure stops and the current solution is returned. If at least one vehicle rotation violates the fuel constraints, additional constraints are added to the problem formulation in order to further reduce the solution space. Then, the solution procedure is repeated with the resulting extended problem formulation. The first heuristic solution approach is strongly based on the procedure of the exact solution method. The key difference is that for each vehicle rotation that violates fuel constraints the set of trips contained in the specific rotation is reduced until the rotation becomes feasible. The trips removed are inserted into a new vehicle rotation. The other steps of the exact procedure are retained. The second heuristic method is also based on the iterative procedure. The main idea of this approach is to build feasible integer solutions of the extended VSP formulation but without solving an integer optimization problem. Instead, feasible vehicle rotations are built

from integer and non-integer solutions of the problem.

In order to be able to solve even larger-scale instances by the solution methods presented, the authors propose two techniques for decreasing the problem size. First, they introduce an algorithm that aims at combining multiple trips into one trip. Within this procedure, the number of trips can be reduced up to about 20%. Second, they introduce a preprocessing algorithm for reducing the number of decision variables of the optimization problem. With this technique, a reduction of up to about 80% can be achieved. Within this work, the authors do not focus on further characteristics of EVs or related issues. In particular, the possibility of recharging a vehicle battery at charging stations is not considered.

3 Vehicle Scheduling Problem with limited Driving Ranges and Battery Recharging

Besides limited driving ranges of the vehicles the possibility of recharging the vehicle batteries is of particular importance. For that reason, a lot of research emerged that address both aspects of EVs. As described in Section 1, this problem refers the E-VSP.

The existing contributions differ particularly with regard to the way of reflecting the battery charging process. Basically, there is literature assuming battery chargings in constant and linear time. Charging in linear time refers to a linear increase in energy depending on the waiting time of a vehicle at a charging station. The assumption of charging in constant time implies that vehicles remain idle at a charging station for a fixed time period, whether or not the vehicle batteries have already been fully charged. In the following, we divide the literature into those that consider constant times and those that consider linear times for charging.

3.1 Battery Charging in Constant Time

As one of the first contributions that address both limited driving ranges of the vehicles and the opportunity to recharge the batteries, H. Wang and Shen (2007) define the *Vehicle Scheduling Problem with Route and Fueling Time Constraints*. The authors develop a heuristic solution method based on a multiple ant colony algorithm that incorporates route time constraints and generates vehicle rotations starting and ending at a depot. Subsequently, they introduce a bipartite graph model and an optimization algorithm in order to connect the rotations generated with respect to fuel time restrictions. Fueling times are assumed to be constant time windows within a full battery

charging is performed. Furthermore, charging is only possible within the depot. The algorithm aims at minimizing the number of vehicles deployed. Therefore, the maximum matching of the bipartite graph is determined by computing the maximum inflow with the Ford–Fulkerson algorithm.

Chao and Xiaohong (2013) propose a heuristic solution method for the E-VSP based on a Non-dominated Sorting Genetic Algorithm (NSGA-II). The authors focus on battery electric buses and consider the possibility of swapping the vehicle batteries at specific stop points besides the restricted driving ranges. The battery replacement is carried out within a constant time frame which is synonymous with a constant charging time. After the removal of the battery, a fully charged battery is inserted. The solution method aims at minimizing vehicle costs as well as the total charging demand. The solution procedure is analyzed using real-world data taken from a project in Shanghai. A problem instance with 119 service trips is being solved using the technical data of battery exchange systems that are deployed within this project.

Li (2014) consider another important aspect of EVs: battery swapping. Therefore, the authors propose a solution model for the E-VSP with either battery swapping or fast charging. Both options are performed within constant time frames; however, the time for fast charging depends on the stop point. The vehicle batteries are always fully charged. Furthermore, capacities of charging stations, the maximum number of simultaneous charging procedures, are incorporated. The author present a construction heuristic producing vehicle rotations which serve as initial solutions for different column-generation-based solution methods.

Adler and Mirchandani (2016) introduces the *Alternative-Fuel Multiple Depot Vehicle Scheduling Problem*. The proposed optimization problem extends the traditional VSP by incorporating a given set of fueling stations and fuel capacities for the vehicles. For solving the problem, the author presents an exact solution model and introduced a solution approach based on branch-and-price. In order to obtain initial solutions for the solution method the concurrent scheduler algorithm by Bodin et al. (1978) is extended to take into account the additional restrictions caused by BEVs. The charging procedures are carried out in constant time and the vehicle batteries are always charged to full capacity. An incorporation of additional characteristics of EVs was not made. The solution method is tested on real-world instances with up to 4,000 service trips taken from a real-world project in Phoenix, Arizona.

So far, homogeneous vehicle fleets consisting exclusively of EVs have been considered within the literature presented. Reuer et al. (2015) address the aspect of scheduling a mixed vehicle fleet. For that purpose, the authors extend the traditional VSP by considering a vehicle fleet consisting of EVs

and traditional combustion engine vehicles without range limitations. They denote this problem as the *Multi-Vehicle-Type Vehicle Scheduling Problem with Electric Vehicles*. This optimization problem aims at maximizing the proportion of feasible vehicle rotations for EVs within the full set of vehicle rotations while retaining optimal numbers of vehicles used and deadhead trips required obtained by solving the standard VSP without range limitations. Vehicle rotations that are infeasible for EVs are served by traditional combustion engine vehicles. To solve the problem, the authors use a time-space network based exact solution method for the VSP as introduced by Kliwer et al. (2006). As solutions to this problem comprise optimal flow values through the network, strategies for flow decomposition are necessary, in order to obtain vehicle rotations enabling additional degrees of freedom while generating multiple, all cost-minimal, vehicle rotations. Therefore, they develop strategies for flow decomposition. Within this work, constant time windows are assumed for charging the vehicle batteries.

3.2 Battery Charging in Linear Time

All of the solution approaches discussed so far have in common that charging processes are performed within constant time windows. This assumption leads to a substantial simplification of the battery charging process because the actual process of modern batteries is very complex (Montoya et al. (2017) or Olsen and Kliwer (2020)). For this reason, research has been done that incorporates charging procedures in linear time.

As one of the first contributions towards a more realistic reflection of battery charging processes, Kooten Niekerk et al. (2017) introduce a column-generation-based solution approach for the E-VSP with a single depot that incorporates chargings in linear time. Furthermore, they take into account the aspects of partial charging, battery aging effects, and time-dependent energy prizes. Battery aging effects are reflected by means of an exponential modeling. Since taking these technical aspects into account complicates the problem significantly, the authors propose two different solution models that differ in level of detail in terms of these aspects. Within the first model, energy prizes are assumed to be constant throughout the day and battery degradation is not considered. However, time-dependent energy prices and battery degradation are incorporated within the second model. In order to be able to solve the second model in a reasonable time, the linear charging process is approximated by assuming discrete states of the vehicle battery's SoC. For solving both optimization problems, standard optimization libraries are used for small and medium instances and the column-generation-based solution approach is used for larger instances. The authors show that in some

cases, the consideration of partial charging procedures leads to cost savings in comparison to full chargings of the vehicle batteries.

Janoveca and Kohánia (2019) present an exact solution approach for the E-VSP in the form of a mixed integer linear program. The authors extend an existing mathematical model for the E-VSP from Rogge et al. (2018) by incorporating partial charging in the depot and at terminal stops of the service trips. The charging infrastructure is assumed to be given in advance. For solving, they use standard optimization software libraries. Based on real-world data provided by a public transport company in the city of Žilina, Slovakia, the authors point out the correctness of the solution model but also the limits of the applicability due to the runtime required. They conclude that heuristic solution methods are generally more suitable in order to solve also larger instances arising within real-world applications.

Yao et al. (2020) propose a heuristic solution method based on a genetic algorithm for the E-VSP with multiple vehicle types. They particularly analyse the impact of different driving ranges, recharging durations, and energy consumptions that result from the vehicle types on the solution quality. Even though the authors consider a significant higher level of technical characteristics in comparison to previous work, they also assume that chargings are performed in linear time. Based on a computational study using public transport data taken from the district Daxing in Beijing, China, the authors show that the incorporation of different vehicle types reduces the total scheduling costs.

4 Location Planning of Charging Stations for Electric Vehicles

If we look at the literature presented so far, we can see that there is no work at all dealing with the impact of different scenarios of the charging infrastructure on resulting vehicle rotations when solving the E-VSP. At the present time, few publications exist that deal with location planning of charging stations for EVs in public transport. However, when regarding these publications location planning is considered as a separate optimization problem.

Kunith et al. (2014) propose a mixed integer linear optimization model for determining locations for charging stations for a bus line. The model is based on a set covering problem. The objective is to minimize the number of charging stations required. Within this solution model, the authors take into account constraints imposed by the buses' operation and the battery charging process. Furthermore, different energy consumption scenarios are

considered in order to reflect external influencing factors on the buses' energy consumption such as traffic volume and weather conditions. Standard optimization libraries are used for solving the problem.

Berthold et al. (2015) deal with the electrification of a single bus line in Mannheim, Germany. The authors present a mixed integer linear program in order to determine optimal locations of charging stations alongside the stops to be served by the buses. The sequences of stops that are operated by EVs are given in advance. Within this solution model, partial charging procedures, battery aging effects over multiple time periods, and different scenarios regarding the passenger volume and traffic density are considered. The objective is to minimize the total costs consisting of construction costs for the charging stations and the acquisition costs for the vehicles used. The problem is solved by using standard optimization libraries. Due to the consideration of multiple time periods and the technical characteristics, the optimization problem becomes very complex. As a consequence, the solution approach is not suitable for larger instances and larger public transportation networks respectively.

Xyliaa et al. (2017) develop a dynamic optimization model to establish a charging infrastructure for EVs in Stockholm, Sweden. Within this model, the authors consider restricted waiting times of the vehicles at intermediate stops of service trips that are given by the schedule and unrestricted waiting times at the depot. Furthermore, different currents of the charging systems imposed by local conditions and the technology type that is installed at a specific charging station is taken into account. Battery charging can either be performed conductively or inductively. Again, the problem is solved by using standard optimization libraries. In contrast to the previous work from Berthold et al. (2015), now multiple bus lines are optimized together. However, no line changes of the buses used are considered. Based on a computational study, the authors provide statements about the application possibilities of EVs in urban areas and effects on vehicle rotations. They point out that capacities of electricity grids in urban areas have a strong impact on the number of electrifiable bus lines.

Liu et al. (2018) take into account energy consumption uncertainties within location planning of charging stations for BEBs. To do this, the authors introduce a robust optimization approach represented by a mixed integer linear program. Using real-world data, the authors demonstrate that the proposed solution model can provide optimal locations for charging stations that are robust against uncertain energy consumption of BEBs.

Lin et al. (2019) introduce a spatial-temporal model for a large-scale planning of charging-stations for BEBs in public transport. The authors consider characteristics of BEBs' operation and plug-in fast charging technologies.

The model is represented by a mixed-integer second-order cone programming formulation with high computational efficiency. A case study using data from Shenzhen, China is used to analyse the robustness of the solution model to timetable changes.

With a view to other optimization problems in the scope of transportation, there are further contributions dealing with the charging infrastructure planning for EVs. Frade et al. (2011) deal with location planning of public charging stations for private transport with EVs. The authors introduced a solution model for planning the locations of charging stations in the city of Lisbon, Portugal based on a maximum coverage problem. The number of charging stations to be located is given in advance and the objective is to maximize the coverage rate of the demand. The charging demand for a day was approximated by the number of jobs and the charging demand for a night by the number of households per geographical unit. The problem is solved by standard optimization libraries.

Chen et al. (2013) propose a mixed integer programming model to determine locations for public charging stations for private EVs within the city of Seattle, Washington, USA. The authors use regression equations in order to estimate parking demands. Site accessibility, local job and population density, parking fees, and trip attributes are used as dependent variables for the regression analysis among others. The objective is to minimize walk distances from charging stations to destinations weighted by parking durations. For solving, standard optimization libraries are used.

Regarding *Vehicle Routing Problems* with electric vehicles, Worley et al. (2012) present a mixed integer linear program for the simultaneous determination of optimal locations for charging stations and vehicle routes. They show that this approach leads to lower total costs of the vehicle deployment by comparison to locations of charging stations being determined in advance.

5 Conclusion and Potential Future Research

Cost-efficient scheduling of EVs in public transport is essential for increasing sustainability in the transport sector. This applies particularly to urban areas where thresholds for greenhouse gases, fine particles, nitrogen oxides, and other emissions are largely being exceeded. Closely associated with scheduling of EVs is the planning of the charging infrastructure. This is because longer deadhead trips to charging stations during the vehicles' operation increase the operational costs and may lead to higher demands for vehicles. In this paper, we provided a first comprehensive overview of existing literature dealing with scheduling of EVs and location planning of charging stations in

public transport.

We structured the provided literature overview on the basis of the following aspects. First, we presented literature incorporating limited driving ranges within the traditional VSP. Second, we discussed contributions that consider battery charging in addition to limited driving ranges. This problem is generally denoted as the E-VSP within the scope of research. The works presented can be basically divided into those that assume charging in constant time and those that assume charging in linear time. Lastly, we presented literature that deal with location planning of charging stations. However, there are only publications that deal with location planning as a separate optimization problem at present time. Table 1 provides an overview about the contributions presented within this paper.

	reference	lim. driv. ranges	batt. chrg./ swap.	purely e-veh. fleet	fixed chrg. infra.	fixed veh. rotat.	part. chrg.
Scheduling Electric Vehicles	Freling and Paixão (1995)	•		•	•		
	Desrosiers et al. (1995)	•		•	•		
	Haghani and Banihashemi (2002)	•		•	•		
	H. Wang and Shen (2007)	•	•	•	•		
	Chao and Xiaohong (2013)	•	•	•	•		
	Li (2014)	•	•	•	•		
	Reuer et al. (2015)	•	•		•		
	Adler and Mirchandani (2016)	•	•	•	•		
	Kooten Niekerk et al. (2017)	•	•	•	•		•
	Janoveca and Kohánia (2019)	•	•	•	•		•
Charging Infrastructure	Yao et al. (2020)	•	•	•	•		•
	Frade et al. (2011)	•	•	•			
	Worley et al. (2012)	•	•	•			
	Chen et al. (2013)	•	•	•			
	Kunith et al. (2014)	•	•	•		•	•
	Berthold et al. (2015)	•	•	•		•	•
	Xyliaa et al. (2017)	•	•	•		•	•
	Liu et al. (2018)	•	•	•		•	•
	Lin et al. (2019)	•	•	•		•	•

Table 1: Overview of the main characteristics of the literature presented.

Based on the provided literature overview, there are a number of interesting future research avenues. Basically, most of the work presented involve heuristic solution methods. Only few contributions provide exact methods which, however, are only applicable for small problem instances. The development of exact solution methods for the E-VSP capable of solving also

larger real-world instances would be of great interest. Regarding technical characteristics of EVs, it would be interesting to see how more precise models for the charging and discharging process of vehicle batteries might affect the solutions of the E-VSP. Furthermore, battery aging effects are particularly important for the deployment of EVs. So far, these technical aspects have been insufficiently considered within existing solution approaches and should be better reflected within future models. Likewise, external factors that influence the operation of EVs should also be taken into account. To be mentioned here are energy consumption depending on the traffic volume and energy prizes that may depend on the demand or utilization of the electricity grid. Finally, the task of location planning for charging stations has been addressed as a standalone optimization problem, so far. However, as vehicle scheduling and location planning mutually depend on each other, location planning may be integrated into vehicle scheduling.

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