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Different Charging Strategies for Electric Vehicle Fleets in Urban Freight Transport

Bram Kin [1,2,*], Meike Hopman [1] and Hans Quak [1,3]

1 Sustainable Transport and Logistics Department, Netherlands Organisation for Applied Scientific Research (TNO), 2496 RZ The Hague, The Netherlands; meike.hopman@tno.nl (M.H.); hans.quak@tno.nl (H.Q.)
2 Research Group Logistics and Alliances, HAN University of Applied Sciences, 6826 CC Arnhem, The Netherlands
3 Breda University of Applied Sciences (BUas), 4817 JS Breda, The Netherlands
* Correspondence: bram.kin@tno.nl

Abstract: The transition from diesel-driven urban freight transport towards more electric urban freight transport turns out to be challenging in practice. A major concern for transport operators is how to find a reliable charging strategy for a larger electric vehicle fleet that provides flexibility based on different daily mission profiles within that fleet, while also minimizing costs. This contribution assesses the trade-off between a large battery pack and opportunity charging with regard to costs and operational constraints. Based on a case study with 39 electric freight vehicles that have been used by a parcel delivery company and a courier company in daily operations for over a year, various scenarios have been analyzed by means of a TCO analysis. Although a large battery allows for more flexibility in planning, opportunity charging can provide a feasible alternative, especially in the case of varying mission profiles. Additional personnel costs during opportunity charging can be avoided as much as possible by a well-integrated charging strategy, which can be realized by a reservation system that minimizes the risk of occupied charging stations and a dense network of charging stations.

Keywords: urban freight transport; city logistics; electrification; zero emission zone; sustainability; charging strategy; charging infrastructure

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1. Introduction

The negative impact of freight vehicles in urban areas in terms of CO_2 as well as other air-polluting emissions, is widely addressed [1,2]. Freight vehicles—light commercial vehicles and trucks—are typically responsible for 10–15% of vehicle kilometers in cities but the share in traffic-related emissions comprises up to one-third [3–5]. Consequently, urban freight transport is addressed to become cleaner and eventually decarbonized. In order to decarbonize urban freight transport, some freight flows can shift to small vehicles such as cargo bikes [6,7]. Due to transport volumes and distances, most freight vehicle movements are, however, not eligible to move to such vehicles and the electrification of current vehicles is proposed to be the most applicable technology [8–10]. The deployment of electric freight vehicles is slow and limited to light commercial vehicles. While OEMs are slowly starting to produce electric freight vehicles, the price, operational constraints, and the lack of necessity to replace a conventional freight vehicle impede a large scale take-off [8,11,12].

To improve urban freight transport's sustainability and to accelerate this take-off, many European cities are starting to or have already started implementing more stringent admission requirements based on vehicle technologies, in line with the goal by the European Union to have zero emission city logistics by 2030 in major urban centers [13]. London is a front runner with its ultra-low emission zone [14]. In the Netherlands, the

Dutch climate agreement even plans to implement zero emission zones in city centers in 30–40 cities in the Netherlands from 2025 to accelerate the usage of more sustainable freight vehicles and reduce the logistics' carbon footprint by a total yearly CO_2-reduction of 1 Mton in 2030. These zero emission zones could be a potential game changer for the large scale usage of electric freight vehicles [15,16]. While the effect of low emission zones on vehicles and emissions is extensively studied, there are hardly any studies that address the challenges of a full electrification of urban freight transport vehicle fleets, as opposed to many demonstrations where electric freight vehicles are used for routes that fit the battery range (see e.g., [17–19]).

With the imminent implementation of zero emission zones, various concerns about the feasibility of the use of electric freight vehicles are arising for transport companies that have to replace their vehicle fleets. A limited driving range and the potential disruption of operations when charging en-route (opportunity charging) is a recurring issue (e.g., [20,21]). Another concern is the price. Even though battery prices have been falling in the past decade, high purchase costs are still an important price differentiator in the total cost of ownership (TCO), which impedes the switch from a conventional to an electric vehicle [22–25]. A potential trade-off to reduce the costs of an electric vehicle is a smaller battery that suffices in the majority of the operations supplemented with opportunity charging in rare cases [21,26–28]. A major concern for transport operators is how to find a reliable charging strategy when a larger vehicle fleet becomes electric, which provides flexibility based on different daily mission profiles within that fleet, while also minimizing costs [27]. Despite the transition in urban freight transport and the importance of different charging strategies to facilitate decarbonization, the integration of charging in day-to-day operations has hardly been researched or experimented with [21,27,28].

This study addresses various charging strategies with regard to the different aspects of feasibility. The objective is to investigate different charging strategies for large vehicle fleets with different mission profiles in order to allow for more flexible day-to-day operations at the lowest possible cost. Based on a real-life case study in which 39 electric freight vehicles have been monitored, the integration of opportunity charging in daily operations is studied with different transport operators. The case study includes three small OEM-produced light commercial vehicles, 34 retrofitted large vans, two retrofitted small trucks and a high capacity charging station in the Rotterdam area. Charging en-route furthermore provides the possibility of testing the reservation of a time slot, which takes into account the effect of queuing [29].

In order to position this case study, the next section provides a literature review on the transition towards decarbonized urban freight transport by addressing the context and the state of affairs of electric freight vehicle technology (Section 2.1), charging infrastructure (Section 2.2) and charging strategies (Section 2.3). Next, Section 3 describes the followed methodology: a case study with a quantitative and qualitative evaluation approach. Section 4 describes the results of the qualitative part, which is based on interviews and process evaluations with the involved companies. Section 5 describes the results of the total cost of ownership analysis. Based on the findings, the implications for upscaling electric freight vehicle fleets are discussed for both companies and policy makers in Section 6. Section 7 concludes the study.

2. Literature: Electrification of Urban Freight Transport

When addressing the challenges in the transition towards zero emission urban freight transport for transport operators, the diversity in types of freight vehicle movements in urban areas needs to be considered. There is not one comprehensive solution in this transition. Section 2.1 first elaborates briefly upon this diversity in urban freight transport fleets and trips and the state of affairs of electric freight vehicles. Furthermore, this section elaborates on charging infrastructure and charging strategies.

2.1. Diversity in the Electrification of Urban Freight Transport and State of Affairs

The term 'urban freight transport' or 'city logistics' is being used for commercial transport within, into and out of cities. A considerable part of commercial vehicles, mostly light ones, is primarily used to provide a service rather than the transport of goods [30,31]. Even if such vehicles do not primarily transport goods, the fact that these are commercial means that the zero emission requirement holds under the announced implementation of zero emission zones in the Netherlands. To structure this heterogeneity, different so-called city logistical segments, with different operational requirements with regard to vehicle capacity, trip distance and number of stops, can be distinguished [27,32–34]. Table 1 provides an overview of the different city logistical segments with the main characteristics per segment and the electrification requirements.

Table 1. Overview of city logistical segments and electrification requirements (based on [18,28]).

Logistical Segment	Electrification Requirements
Temperature-controlled (retail and horeca)	Temperature-controlled heavy duty vehicles and a mix of short range (city distribution by wholesalers) and long range (national distribution by specialists or supermarkets).
General cargo and retail	Heavy duty vehicles with a long range for national distribution trips.
Parcels and express	Light commercial vehicles for short distances and a large number of stops. Small trucks with a longer range for two-men distribution (e.g., appliances and furniture).
Waste logistics	Specialized heavy duty vehicles for short distances.
Facility logistics (supply)	Trucks and light commercial vehicles with varying mission profiles (local and national), stops at (large) institutions and ad hoc addresses.
Service logistics	Light commercial vehicles with daily varying mission profiles of which a proportion is not planned in advance. Mostly used to transport personnel with tools.
Construction logistics	Diverse segment with vehicles ranging from very heavy specialized vehicles with a high energy demand to light commercial vehicles with varying mission profiles.

Light commercial vehicles, that is, vans with a gross vehicle weight (GVW) under 3.5 tons, are responsible for 85–90% of freight vehicle kilometers in cities [35,36]. In the Netherlands, there are around 940,000 light commercial vehicles, of which 91% are owned by companies [37]. Out of these vehicles, only 0.60% of all registered light commercial vehicles were electric in the beginning of 2021 [38]. This means that there is a serious task ahead for the owners of these vehicles in light of the introduction of zero-emission zones.

In recent years, electrically-assisted cargo bikes and light electric freight vehicles (LEFVs) appear on the streets. Such vehicles are suitable for local trips with short distances and a light payload [6,7,39]. These LEFVs can be utilized to take over a part of today's freight and service trips that are being carried out by vans. The majority of the trips do, however, require at least a van because of the load capacity and distance constraint. With the impending transition towards carbon-free urban freight transport, the development of electric vehicle technology has been accelerated. Different aspects have been tested in demonstrations, including the reliability, user-friendliness and the integration in daily operations [11,18,40]. Whereas light electric vehicles are becoming available as OEM-product, this is hardly the case for electric trucks (all commercial freight vehicles with a GVW over 3.5 tons). The few operating electric trucks are often retrofitted and are a part of trials [8,17,41,42].

Increasing battery capacity becomes increasingly viable as the prices of batteries decline; from $668/kWh in 2013 to $137/kWh in 2020 and an estimated $58/kWh in 2030 [43] (mentioned prices are related to battery electric passenger cars). Falling prices are the main reason electric freight vehicles are becoming more cost-effective compared to conventional vehicles [22,27,44]. In some countries, this is partly enhanced by tax exemptions and subsidies [10,32]. Contrary to higher purchase costs, the depreciation and maintenance of electric vehicles are typically lower [22]. Compared to conventional vehicles, electric ones are well equipped for distribution in urban areas as energy usage is more efficient. Contrariwise, a disadvantage of electric vehicles is the gross vehicle weight that increases because of the battery, which diminishes the load capacity [11,21,32]. This becomes especially relevant for light commercial vehicles that have a maximum payload of 3.5 tons. The larger the battery, the lower the additional load that can be transported. In the Netherlands and Germany, the maximum GVW of electric light commercial vehicles has been (temporarily) increased to 4.250 kg [10].

2.2. Charging Infrastructure

In line with electric vehicle technology, corresponding charging infrastructure is being developed. Low capacity charging stations are widely commercially available. Charging stations with a capacity of 3.7 kW to 22 kW are mostly used for overnight charging for both passenger cars and light commercial vehicles. High capacity chargers with a capacity of 50 kW or higher are also commercially available and are often located in public places. For heavy duty transport, high capacity chargers of 350 kW or even 1 MW are being developed [27]. High capacity chargers are not only expensive, but also lead to issues with regard to the upgrading of the electricity network and grid anxiety by users [11].

Altogether, there is a difference between type of charging station: low capacity (often used overnight) and high capacity (for opportunity charging). Another distinction can be made between four types of charging locations. This, in turn, has an effect on the type of charging station, the moment to charge, electricity costs and investment costs. Table 2 provides an overview of the main characteristics regarding charging infrastructure at different locations in the Netherlands as well as the most pressing issues. It must be noted that, currently, not every charging station fits every vehicle. In the future this could result in different charging stations at the same locations.

Table 2. Overview of charging infrastructure at different locations in the Netherlands and the main issues (based on [8,17,22]).

	Home (Private)	**Depot (Private)**	**Road (Public)**	**At Premises (Semi-Public)**
Charging Type	**Low Capacity**	**Low Capacity**	**High Capacity**	**High Capacity**
Application light commercial vehicles	Suitable for overnight charging at or around the premises of the driver by using the same infrastructure as used for passenger cars. Can also take place on public roads.	Suitable to install multiple charging stations for a vehicle fleet.	Suitable, but only desired if range is too limited. There are various commercial high capacity charging stations at traffic nodes.	Only during long stops (i.e., not for parcel deliveries) during a drop/pick-up/service activity. Requires a high coverage.
Application trucks	Not applicable at the moment.	Suitable to install multiple charging stations for a vehicle fleet. Increasing grid capacity might be necessary.	Considered in the development of charging stations.	Not applicable at the moment.
Costs for vehicle operator	Relatively low investment costs and electricity costs when installing a charging station at home.	Dependent on the number of charging stations, high capacity chargers and grid capacity. Electricity costs relatively low due to large consumption. Depreciation costs low when used intensively.	No investment costs for transport companies, but high electricity costs as well as higher driver costs in case of queuing.	High investment costs when only used on a limited basis (e.g., once a day at a supermarket when unloading).

Table 2. *Cont.*

	Home (Private)	Depot (Private)	Road (Public)	At Premises (Semi-Public)
Charging Type	**Low Capacity**	**Low Capacity**	**High Capacity**	**High Capacity**
Current issues	Electricity demand for light commercial vehicles must be considered when upscaling the number of charging stations in residential areas.	Optimal use of charging stations with a large and varied fleet ('smart charging'), and grid anxiety. Including opportunity charging in the logistical planning for a second shift.	Minimizing driver costs (integration in planning) and the density of charging stations.	Costs and the charging station that matches a certain type of vehicle. Shared use of the charging stations.

2.3. Charging Strategies

The mission profile, vehicle type, size of the battery package and the charging infrastructure (and location) all relate to the charging strategy, which is a prerequisite for conducting daily operations. Overnight charging—at home or at a depot—has been demonstrated as the most cost-effective charging strategy as long as daily operations fit within the battery range since it hardly affects the conventional (diesel-based) way of operating [27]. There are various reasons, both financial and operational, why opportunity charging en-route, is not the preferred strategy:

- Electricity costs are higher when charging en-route (compared to charging at the premises);
- Increase in driver costs—which is the main cost aspect for freight transport (can comprise more than 60% of a TCO according to [41])—because the driver is inactive during charging, unless it takes place during unloading or a break;
- Exceeding working hours of a driver on long routes because charging time is added;
- Potential queuing time when using charging infrastructure [11,40];
- Detour kilometers, and hence additional time, when charging infrastructure is occupied or at a low network density of fast chargers in an area [40];
- Challenging to integrate opportunity charging in daily routes, so that it only disrupts operations minimally [8,11,19].

Despite these constraints, there can be situations in which it is worthwhile to investigate whether opportunity charging is cost-effective:

- Limited driving range, even with the largest possible battery package;
- Impact of the battery price, particularly when a large battery package is only required in rare cases [26,28];
- Occupied (private) charging infrastructure (in neighborhoods and at depots);
- Distribution of peak demand (at depots) to avoid grid problems [28].

In most cases it is justifiable to analyze a charging strategy in which the charging locations and the size of the battery package play a vital role in minimizing costs [28]. This topic has been studied in a demonstration with 39 electric freight vehicles as elaborated in the next section.

3. Methodology and Research Set-Up

This contribution addresses the technological, operational and financial feasibility of electrifying larger vehicle fleets with varying operational requirements. A mixed methodology is applied, using both qualitative and quantitative data collection in a case study with 39 electric freight vehicles in the Rotterdam area. The qualitative part is composed of interviews and process evaluations with the involved companies. The quantitative part is based on data monitoring of the daily operations of the vehicles and the charging operations. Both types of data collection serve as input for a total cost of ownership (TCO) scenario analysis to study the feasibility of different charging strategies in vehicle fleets. Figure 1 shows this research approach.

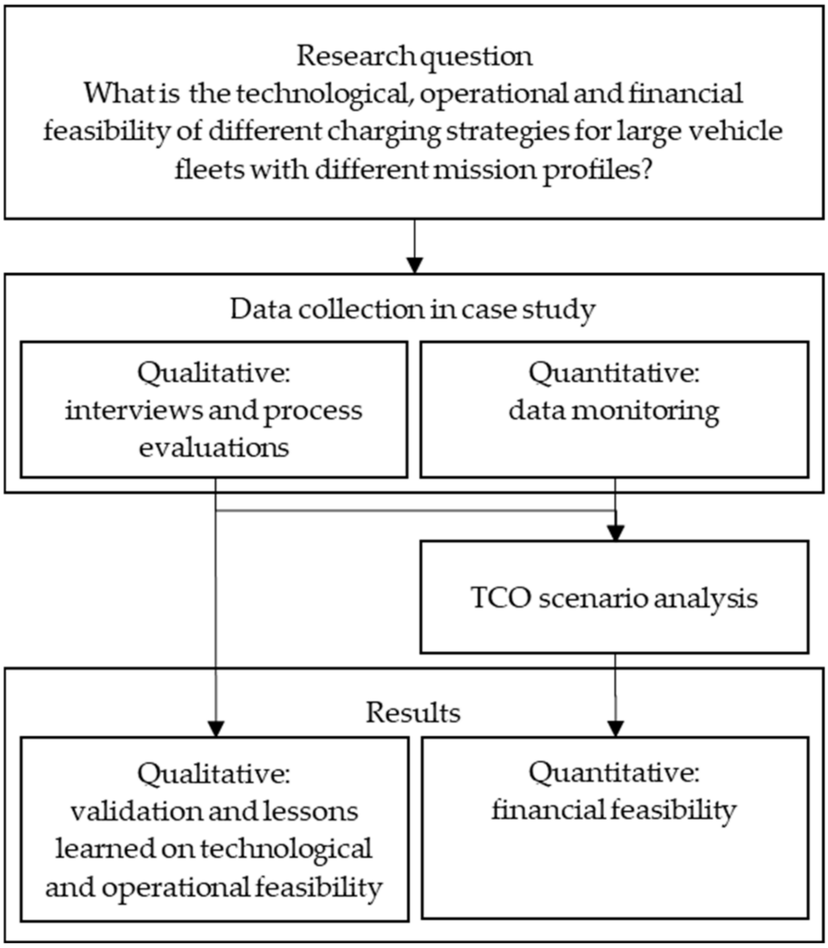

Figure 1. Schematic overview of the research steps.

3.1. Case Study Set-Up

The developed case study, the demonstration in the Rotterdam area, includes the operations of two transport operators during 2020; a large parcel delivery company that operates in a dense network (with ad hoc and planned deliveries and pickups with time constraints) and a small courier company with planned as well as ad hoc trips, both within the city and between cities. In addition to the transport companies, a charging infrastructure company provides a high capacity charging station (for which the transporting companies can book a time-slot to guarantee availability) in the Rotterdam area where the demonstration takes place. Table 3 provides an overview of the vehicles that are operating and being monitored in the case study. Monitoring data are collected for all 39 vehicles for the period of one year (2020). The vehicles used in this demonstration were purchased and delivered in 2018–2019. This case study has been developed based on practical challenges and opportunities for fleet operators when replacing conventional vehicles with electric ones on a larger scale than experimenting with just one or a few electric vehicles in daily operation (see also [29]). These challenges only come up when larger fleets are replaced and not just the routes that fit the electric vehicle characteristics best:

1. Limited driving range and, as a result, opportunity charging is possibly required during operations, as also routes that exceed the range are in scope when entire fleets are electrified.
2. Ad hoc trips and varying mission profiles (non-predictable or repetitive trips) are more difficult to plan. This complicates planning and requires charging infrastructure along routes [27].

3. A large vehicle fleet with different vehicles and varying mission profiles complicates the planning. Based on cost considerations, fleets might include conventional vehicles and vehicles with different battery sizes [45,46].

Table 3. Overview of the vehicles used in the case study.

	Small Van	Large Van	Small Truck
Number of vehicles	3	34	2
Vehicle type	Nissan eNV200	Fiat eDucato	EMOSS 1420
Gross vehicle weight (tons)	0.75	3.5	12
Battery capacity (kWh)	40	62	200
Energy consumption (kWh/100 km)	17	37	82
Range (km)	235	167	243
Production	OEM-product	Retrofit	Retrofit

3.2. Data Collection Plan

The case study in Rotterdam is used to collect qualitative and quantitative data according to a data collection plan. The qualitative data are collected via standardized process evaluation forms and interviews with the two transport operators and the charging infrastructure company. Every company completed the process evaluation form four times during the 18 month case study: once before, twice during and once after the 12-month quantitative data monitoring period in 2020. The process evaluation forms focus on general lessons learned, on technological, organizational and legal barriers, and on how these were overcome during the evaluation period. Interviews with the companies were used to elaborate on the results of the standardized process evaluation forms. The quantitative data are collected monthly for the period of one year (2020) using data templates that are specified per company in the case study. Table 4 provides an overview of the indicators that were monitored in the case study. A detailed description of the monitoring results can be found in [47].

Table 4. Overview of indicators monitored in the case study.

Indicator	Unit
Distance per day	km
Range	km
Usage per day	min
Time per stop	min
Energy use	kWh/km
Use of charging station	%
Required energy per vehicle per day	kWh
CO_2 emission reduction	kg

3.3. Scenario Definition in TCO Analysis

Based on a TCO scenario analysis, the financial feasibility of various charging strategies for electric freight vehicles has been assessed. The TCO composes the following elements: purchase costs for the vehicle and the charging infrastructure; yearly costs for maintenance, taxes and insurance; and operational costs for energy and the driver. For each of the three vehicle types in the case study, four base scenarios have been analyzed based on the qualitative and the quantitative data collection: a reference scenario for a conventional vehicle, that is, a diesel vehicle (scenario 1); an electric freight vehicle without opportunity charging (scenario 2); an electric freight vehicle with well-integrated opportunity charging (scenario 3); and an electric freight vehicle with moderately-integrated opportunity charging (scenario 4). The three electric vehicle-scenarios have different charging strategies. In scenario 2, the battery capacity is sufficient to cover the daily distance. Scenarios 3 and 4 have the same mission profile, but a smaller battery package, so opportunity charging is required. The difference between scenarios 3 and 4—well- versus moderately-integrated opportunity charging—is created to analyze the impact of better integration of opportunity charging, which is represented by a dense network of high capacity charging stations and by a reservation system to increase insight into the availability of and reduce waiting times for high capacity charging stations. In the current situation, high capacity charging stations are widely spread for (small) vans along the highway in contrast to the availability for trucks and the availability for vans in city centers and rural areas. These different strategies provide insight into the trade-off between a more expensive vehicle with a larger battery capacity and no opportunity charging on the one hand and a less expensive vehicle with a smaller battery capacity and additional costs for opportunity charging on the other hand. Table 5 provides an overview of the main parameters in the TCO scenarios per vehicle type. In addition, sensitivity analyses provide more insight into the effect of specific TCO parameters for the four scenarios per vehicle type. Section 5 provides the results of the sensitivity analyses for a lower purchase price for electric freight vehicles and for varying mission profiles.

Table 5. Overview of scenarios per vehicle type.

	Small Van	Large Van	Small Truck
Mission profile for all scenarios	130 km per day	100 km per day	200 km per day
Scenario 1: conventional freight vehicle	0.065 L/km	0.093 L/km	0.20 L/km
Scenario 2: electric freight vehicle without opportunity charging	40 kWh battery, 0.26 kWh/km, range of 131 km	47 kWh battery, 0.38 kWh/km, range of 105 km	200 kWh battery, 0.82 kWh/km, range of 207 km
Scenario 3: electric freight vehicle with well-integrated opportunity charging	24 kWh battery, 0.26 kWh/km, range of 78 km, 20 min charging time	35 kWh battery, 0.38 kWh/km, range of 78 km, 30 min charging time	120 kWh battery, 0.82 kWh/km, range of 124 km, 40 min charging time
Scenario 4: electric freight vehicle with moderately-integrated opportunity charging	24 kWh battery, 0.26 kWh/km, range of 78 km, 20 min charging time, 30 min queuing time, 10 min detour time	35 kWh battery, 0.38 kWh/km, range of 78 km, 30 min charging time, 30 min queuing time, 15 min detour time	120 kWh battery, 0.82 kWh/km, range of 124 km, 40 min charging time, 30 min queuing time, 15 min detour time

4. Results Qualitative Analysis

A detailed description of the analysis and the results of the case study can be found in [29,47]; this contribution focusses on the case study's learnings. During the monitoring period, process evaluations and interviews were conducted to perform a qualitative analysis. The results of the qualitative analysis are structured based on four aspects of the demonstration in the Rotterdam area: the electric vehicles, the charging strategy, the high capacity charging infrastructure, and the (developed) reservation system. The main lessons from the demonstrations, according to the demonstration participants, are discussed in the following four sections.

4.1. Electric Vehicles

Based on the interviews and process evaluations during and after the one-year demonstration, we found that small electric vans are available as OEM-products and are (relatively) easy to purchase, reliable in daily operations and have lower maintenance costs than comparable conventional vehicles. This leads to broad acceptance by drivers and other employees at the transport operator. The case study shows that the practical range of electric freight vehicles is influenced a lot by driving behavior and can be increased by training drivers on how to use electric vehicles. Besides, we found that range anxiety decreases when drivers are getting used to electric vehicles.

Large electric vans were not widely available as OEM-products (during the purchasing period in the case study) and in this case study, the parcel company purchased 34 retrofitted conventional freight vehicles with a battery capacity of 62 kWh and a range of 170 km. The retrofitted large vans experienced technical issues during the demonstration (which was surprising, as the parcel company already had positive experiences with similar retrofitted vehicles at the same converting company). As several (subcontracting) companies were involved in the producing and retrofitting the vehicles, it turned out hard to figure out the cause of the malfunctions. Trust in electric vehicles is essential for a wide uptake and technical issues had a huge impact on this, as the drivers were really reluctant to operate these electric vehicles after malfunctions were improved.

In the case study two small retrofitted Emoss trucks (see Table 3) with a battery capacity of 200 kWh and a range of 240 km were used. Besides some software-related issues in the start-up phase, these vehicles were reliable in the daily operations. For both types of vehicles—large vans and small trucks—the parcel company decided to purchase the largest available battery package to decrease the dependency on opportunity charging. In general, it is more convenient for a transport operator to pick one specific battery capacity for a certain vehicle type instead of adjusting the battery capacities to the varying mission profiles, as this adds planning constraints in comparison to common ways of working with planning diesel vehicles.

4.2. Charging Strategy

The transport companies in the case study state in the interviews that they prefer, from a cost perspective, low capacity charging at the depot over opportunity charging. Charging at the depot uses cheaper electricity, the planning of trips is easier, and it does not require any additional time and costs for a driver. For the financial and operational feasibility, it is important that the battery capacity (the range) fits the length of the roundtrip.

The moment and the location of charging needs to fit the daily operations when using opportunity charging. In this case study, the planners of the small courier company got used to taking this into account in their daily work and also started to plan the electric vehicles on ad hoc deliveries/pickups. They were able to use electric vehicles including opportunity charging similar to conventional ones due to a high density and availability of high capacity charging infrastructure (that fits small vans) along their routes (that also go between cities via highways). The process evaluations of the small courier company show that finding a suitable high capacity charging station is no longer a barrier for light commercial vehicles on highways in the Netherlands. From the process evaluations and the interviews with the parcel delivery company, it becomes clear that the coverage of the high capacity charging network is not sufficient for inner cities and rural areas. For distribution trips in these areas, vehicles need to make a detour to charge, which results in additional time and costs for the driver, as the large parcel deliverer was confronted with.

4.3. Public Opportunity Charging Infrastructure

Based on the process evaluations and the interviews with the charging infrastructure company, we conclude that the exploitation of the public opportunity charging station in this case study does not have a positive business case at the start due to an insufficient number of customers. The location of this charging station was determined based on the routes of the parcel company and does not fit the small transport operator’s operational region. The parcel company procured a larger battery capacity for their vehicles than initially planned, which reduced the need for opportunity charging at the charging station during the demonstration. Another barrier that was stated in the process evaluation forms is that customers outside the case study hardly used the charging station because it could only be used via a reservation system, which created a barrier for customers who did not count on this.

The interviews with the charging infrastructure company result in several lessons on developing a new opportunity charging station: it is important that it is easily accessible from different routes and for (larger) freight vehicles, that it has attractive facilities for drivers when taking a break, and that the charging infrastructure (including the reservation system) is easy to use and easy to access. Besides the choice of a good location, the following lessons were learned from the process evaluations and interviews in this case study on the process of starting a new high capacity charging station: check local rules and regulations on the exploitation of opportunity charging infrastructure, establish good collaboration with the electricity network operator, and check the compatibility between charging infrastructure and different vehicle types.

4.4. Reservation System

The charging infrastructure company in the case study states that a reservation system to guarantee availability could increase the attractiveness of a public charging point for users as it avoids queuing. The technology is available and has been implemented in the case study for one high capacity charging station in the Rotterdam area. For a wider uptake, a reservation system has to match practical requirements from users. In the interviews with the charging infrastructure company, it becomes clear that, when developing a technical service, it is important to involve end users in the process. At first, the reservation system in this demonstration was hardly used by the transport operators because reserving a spot at least two hours in advance appeared to be inconvenient during daily operations. During the case study, this period was changed from two hours to 15 min in advance, to make it more suitable for courier services and other ad-hoc operations. Despite this shorter registration period, transport operators in the case study state that they want to be able to use an opportunity charging point without reservation at all. At the same time, visibility of the availability is preferred.

At the time of the case study (2020) the need for a reservation system was very low, because in general there were hardly any waiting times for electric freight vehicles at high capacity charging stations. This was partly caused by the lower transport activity due to the COVID-19 crisis. As soon as the transport activity and the share of electric vehicles increases, the need for a reservation system might increase as well. This study showed that a reservation system was preferred by the users, especially if this allows for making sure a spot is free at the time required, but that the system should not be adding a barrier.

5. Results TCO Scenario Analysis

In order to estimate the impact of different choices in charging strategies and the corresponding battery-procurement strategy, we performed a TCO analysis in which different scenarios were examined, based on the case study and the data collected during the demonstration. During the one year data collection period, data were collected for a total number of 2381 vehicle days: 634 vehicle days were driven by the three small vans, 1628 by the 34 large vans and 119 by the two small trucks. The average distance per day was 121 km for the small vans, 107 km for the large vans and 135 km for the small trucks. A detailed description of all TCO scenarios and sensitivity analysis, including all results, can be found in [29]. Here, we present the most interesting results of this analysis only.

5.1. Results Base Scenario

The driver costs form the largest share of the TCO (i.e., between 60% and 90% depending on the vehicle type). We excluded general driver costs from the analysis since these are the same for electric and conventional vehicles. Only additional driver costs, for detours to charging areas or waiting time for charging, are added to the TCO. Figure 2 provides an overview of the TCO results of the four base scenarios for a small van, a large van and a small truck. The TCO of a small electric van without opportunity charging (scenario 2) is already 2% lower than the TCO of a conventional small van. For larger vehicles, it is the other way around: 4% higher for large vans and 57% higher for small trucks. This major difference between an electric and conventional truck can be explained by the (costly) large battery pack and by the fact that these vehicles were not yet commercially available as OEM-products (at the time of this demonstration).

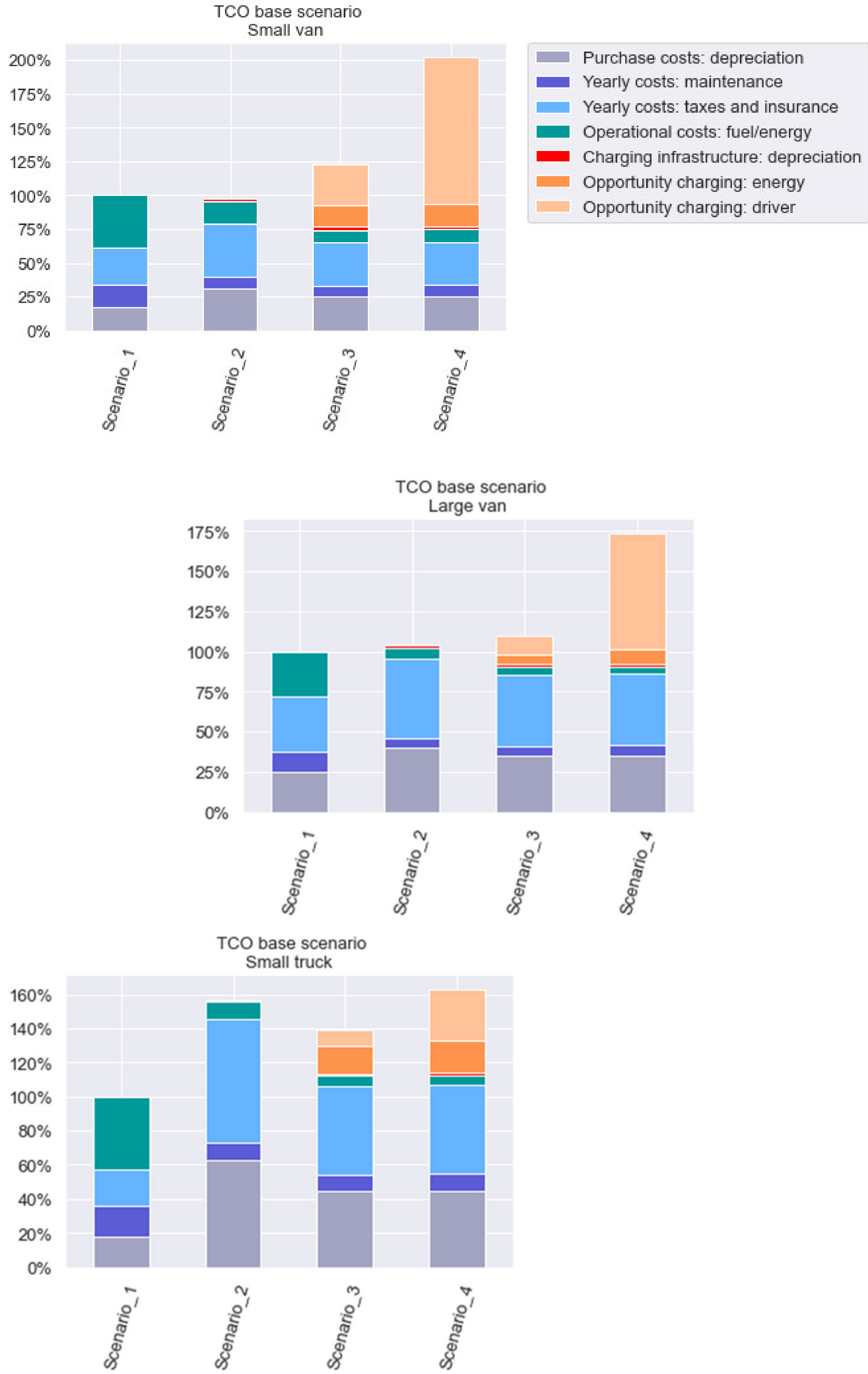

Figure 2. Results of TCO analysis base scenario small van, large van and small truck (For the scenarios, see Table 5).

When opportunity charging is required and well-integrated, the TCO of a small electric van is 25% higher compared to the TCO of a small conventional van, mainly due to the large share of driver costs. For a small van, moderately-integrated opportunity charging—represented by additional driving time and waiting time based on the available charging infrastructure at the time of the demonstration—leads to a TCO that is even 107% higher than the TCO of an electric vehicle without opportunity charging. This emphasizes the importance of a good operational integration of opportunity charging.

5.2. Results Sensitivity Analysis Mass Production

The battery is an important part of the purchase price and it is expected to decrease over time. In the base scenarios, the purchase price of the vehicles is based on websites of manufacturers and the derived battery price (the derived battery price (€/kWh) is the difference between the purchase price (€) of an electric and conventional vehicle of the same type divided by the battery capacity (kWh)) is 407 €/kWh for a small van, 577 €/kWh for a large van and 903 €/kWh for a small truck (which turns out to be much higher than the estimate for passenger vehicles [43]). In the sensitivity analysis on the mass production of electric freight vehicles, the battery prices are lowered to 166 €/kWh for all vehicle types based on cost development estimates (and converting dollars into euros at rates February 2021) in [48], which results in a lower TCO for all scenarios.

The biggest effect occurs in the TCO analysis of the small van; Figure 3's left parts show the TCO results for the four base scenarios and the three right bars show the updated TCO results for the three electric scenarios after applying a lower battery price. The graph in Figure 3 shows that for mass produced small vans the TCO of an electric vehicle compared to a conventional one can be 24% lower without opportunity charging and 9% lower with well-integrated charging.

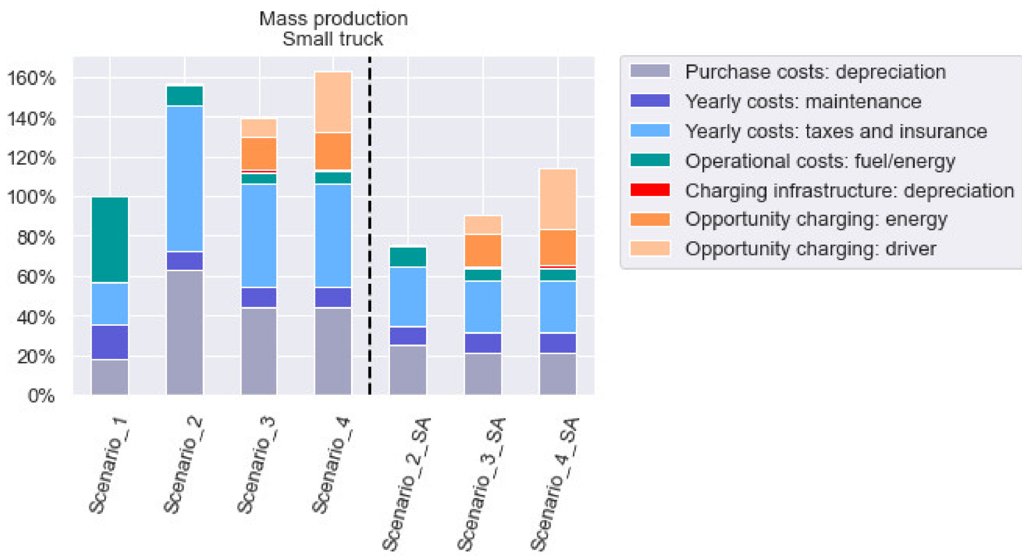

Figure 3. Results TCO sensitivity analysis mass production small truck.

5.3. Results Sensitivity Analysis Varying Mission Profiles

Mission profiles can vary on a day-to-day basis, depending on the type of operations. When purchasing an electric vehicle, a trade-off is made between a larger battery capacity (higher purchase costs) and using opportunity charging (higher operational costs). In the base scenarios the mission profile (distance per day) is fixed per vehicle type and based on using 85% of the battery capacity of the electric vehicle with the large battery (scenario 2). This results in a daily mission profile of 130 km for a small van, 100 km for a large van and 200 km for a small truck. In the sensitivity analysis we vary the mission profile so that it is similar to the base scenario for one day per week, and for four days per week the routes are shorter. As a result, the vehicles with the small battery capacity (scenarios 3 and 4) no longer require opportunity charging on these days. On 80% of the days the mission profile is 75 km for the small and the large van and 120 km for the small truck. On one day, opportunity charging is required. This scenario corresponds to the situation in which the battery pack no longer fits the worst case day, but the mission profile that occurs most frequently.

This modification results in a TCO of a conventional vehicle that is lower than the TCO of an electric one for all vehicle types. Figure 4 shows that the difference between the scenarios is relatively small for the large van. The most important tipping point that is shown by this analysis is that, for both the small and the large van, a smaller battery capacity and well-integrated charging (scenario 3) has a lower TCO than a larger battery capacity without opportunity charging (scenario 2). Opportunity charging is only required for 20% of the trips and, in that case, it is financially not attractive to invest in a lager battery capacity that is 'too big' for 80% of the trips.

Figure 4. Results TCO sensitivity (large van) analysis varying mission profile.

6. Discussion: Upscaling Full Electric Urban Freight Transport Fleets

In this section we discuss the main implications when upscaling from a single or a few electric vehicles to a full vehicle fleet. Based on the analyses in Sections 4 and 5, the implications for a wide scale electrification in other freight and service related sectors are discussed. In Section 6.2, the policy implications for the electrification of all freight vehicles in urban areas is discussed. Future trends, such as the zero emission zones and the potential out phasing of conventional vehicles, are also considered.

6.1. Implications for Electrification of Transport in Other Urban Freight Transport Sectors

In the demonstration the focus has been on the parcel delivery segment. In general, this segment is characterized by a high stop density, small vehicles and relatively short distances. When it comes to decarbonization of urban freight transport, this is one of the least challenging segments (because the characteristics of this sector largely correspond to the possibilities of an electric freight vehicle). This segment has been growing dramatically since the Covid-19 lockdown [49], but as part of all freight vehicle movements in urban areas, it is relatively small; it amounts to an estimated 3% of all vans in the Netherlands [50], 6% of all light vehicle kilometers and less than 1% of all truck kilometers in urban areas [36]. The remaining kilometers in urban freight transport cover a high diversity in terms of mission profiles and subsequent operational requirements in charging strategies as shown in Table 1. Overall, a twofold distinction across the segments can be made that leads to different challenges regarding charging strategies. On the one hand, there are *professional transport companies* that are active in retail distribution and the food sector (horeca) as well as companies with heavy duty trucks in waste collection and the construction sector. On the other hand, the majority of what we consider as logistics is actually rather *service-related*. It consists mostly of companies with light vehicles that are present in the construction (e.g., plasterer), small retail (e.g., local liquor store that delivers to clients) and service sectors. The latter varies from a security company with a van to landscaping companies.

For professional transport companies, this study shows five aspects for the transition towards zero emission transport. First, a fleet of multiple heavy vehicles requires *heavy duty charging infrastructure*—which is expensive—but might also lead to capacity issues at the local grid around charging locations [27,51]. Even though 2030 is still almost a decade away, *network aggravation* is a relevant issue today. Third, vehicles in several sectors drive relatively long distances. Even the largest battery is (currently) not sufficient to cover the required driving range. Particularly, when it concerns trucks, *public heavy duty charging stations* need to be developed. Next, despite dropping battery prices, the difference in the TCO between a small and large battery is high for heavy duty vehicles. An accurate *analysis of the costs related to various strategies*—as listed in Table 2—is important. In this regard, a different approach to how logistics is organized is an inevitable part of the change from a conventional to an electric vehicle. Finally, a *decoupling point* for swap bodies or a trailer at the city border to enable conventional transport towards and zero emission transport within the city, is an interesting alternative to further explore for various sectors [52].

When it comes to the electrification and charging strategies of companies in the service-driven sectors, six implications can be derived from this study. A lot of commercial vehicle movements have more varying *mission profiles*, which complicates the choice of a charging strategy. Mission profiles might vary from 20 km on one day to 300 km the next day [27]. As battery prices drop, it seems straightforward to choose the light commercial vehicle with the *largest battery package available* (the results of the TCO also show that the price difference for different battery sizes in small vehicles is negligible). Nonetheless, on some days, *opportunity charging en-route* is inevitable [53,54]. As shown in this as well as other studies, the amount of charging stations needs to grow considerably in order to facilitate the transition towards electrifying vehicle fleets [10,11,18,45,55]. Occupied charging stations are found to be a considerable barrier that lowers trust to use an electric vehicles in general. A requirement is therefore that public charging stations are accessible and easy to use [55]. In this regard, *flexible use of charging infrastructure* that takes into account user needs is required for public charging station operators [51]. More flexible use of a reservation system, real time occupancy updates of charging stations, a virtual queue, flexible pricing and a penalty for not showing up (at the right time) are found important in the considered case study. *Charging during breaks* or at (longer) stops can minimize the costs and shown in this and other studies [17,24,52]. Note that a proportion of the trips are mostly related to commuting, which means that vehicles can be parked on regular parking spots with charging infrastructure. Whereas the companies in this study conduct overnight charging at depots, in other segments the vehicle is parked at the private address of the driver. This requires a considerable *growth of charging points in residential areas*. An estimation for the wider Amsterdam area shows that for light commercial vehicles alone, more than 11,000 charging points in residential areas are required when the city implements a zero emission zone [27]. This comes in addition to charging infrastructure for passenger cars. In the TCO-analysis a scenario with home charging has been explored. Based on slightly higher energy prices compared to the lower tariffs for electricity for depot charging, the TCO increased by 5%.

6.2. Implications for Authorities

In the eventual inevitable decarbonization of urban freight transport, policies regarding charging infrastructure are essential. The results of this contribution lead to several policy implications. As opportunity charging is a necessity for numerous trips, *public charging locations must geographically grow* throughout the country [39]. Whereas charging locations are increasingly available at nodes along highways, such locations need to grow in areas where there is currently not directly a viable business case. Companies compete on a micro level at high demand locations (e.g., in the Netherlands around Schiphol airport and around larger cities), whereas expansion of infrastructure is lacking in other areas. A nation-wide network is required to stimulate the growth of electric freight vehicles in other parts of the country as well. There is a need for a *higher network density with charging locations in cities* to avoid detours and disrupted operations. Other transport segments, in particular passenger cars and taxis, are also showing an increase in electrifications. Therefore, a conflict by way of occupied stations can be expected. Another conflict that results from growing transport-electrification is the fact that more charging locations might go at the expense of public parking. As reported during the demonstration, conventional vehicles occupy charging locations. The same arguments hold for the growth of charging stations in residential neighborhoods. The growth of electric freight vehicles is also applicable to areas with distribution centers, where *aggravation of the electricity grid* is required to facilitate the vehicle operations. To stimulate the growth of electric vehicles, small (often one man) businesses require special attention. A lot of these operators are only slowly becoming aware of the transition to zero emission transport. If they procure a new vehicle on the short term and decide to opt for a conventional vehicle, the depreciation costs may be higher than expected. As analyzed in the sensitivity analyses, the TCO for light commercial conventional vehicles increases by 4–6% with a shorter depreciation period taking into account the access regulations from 2025 on. This is key to overcome anxiety [53,55,56]. Even though it is not within the scope of this study, it is important to mention that only electrification is undesirable from a societal perspective. Apart from the costs, freight vehicles have a considerable spatial footprint, which remains if they become zero emission. Policies must therefore also be directed at *other logistical models* that include decoupling and other vehicle modes such as cargo bikes.

7. Conclusions

The transition from diesel-driven urban freight transport towards more electric urban freight transport turns out to be challenging in practice. As the range of electric freight vehicles is relatively small and the price of battery packs is high, this study examined different charging strategies in order to operate electric freight vehicles in real life.

For smaller vehicles with relatively small batteries, opportunity charging becomes less of a necessity as battery prices start to drop. This is, however, based on current trends, which include uncertainty with regard to sufficient electric vehicle types, availability of natural resources and geopolitical tensions over these resources only to a limited extent. The case study and the analyses show that a larger battery pack leads to a lower TCO than a smaller battery pack including opportunity charging for the different vehicle types. The additional driver costs for waiting and charging during operations currently cannot outweigh the additional costs for a larger battery pack. Furthermore, a larger battery provides more flexibility in planning for transport operators and overcoming range anxiety. Despite dropping battery prices, for companies with (heavy duty) trucks the difference between a small and large battery provides an important trade-off with opportunity charging. Integrating opportunity charging as good as possible in daily operations, for example by using a reservation system or by charging during the breaks of the driver, can reduce costs. Results of the demonstration show that opportunity charging—regardless of the size of the battery—along the route is feasible if several conditions hold.

First and foremost, additional personnel costs for the driver must be avoided as much as possible. This comes down to charging during breaks, no or limited detour kilometers and avoid queuing. A dense network of (public) charging stations, as well as the availability of charging stations when necessary, are important. The main challenge revealed in the demonstration is that charging during an urban delivery trip is difficult. Most charging stations for light commercial vehicles are located along nodes, particularly next to highways. This led to the problem that vehicles had to interrupt their trip (as most stops are not along the highway) to make a detour to a charging station after which the delivery trip could be continued. Especially in urban areas this is a problem due to congestion, which leads to additional time lost. Outside cities, the growth of charging stations in locations with a lower demand lags behind as it is currently difficult to have a viable business case. The availability and density of public charging stations therefore need to grow both within urban areas and along highways that are less busy. This is particularly important for facilitating the growth in the number of electric (freight) vehicles. The availability of charging stations also relates to occupancy. In the demonstration, a reservation system at a specific location has been tested. By reserving a time slot, queuing can be avoided. Whereas this has a high potential, several improvements are required in this regard. First of all, flexibility and immediate availability is required. This relates to the second improvement; real time updates on the occupancy of charging stations. Several suggestions to improve the effectiveness of a reservation system with real time visibility of the occupancy that came from the demonstration include: visibility of the occupancy during the day, a virtual queue, limited charging time, flexible pricing and a penalty for not showing up. The need for a reservation system is especially high in areas with a high occupancy of charging stations (e.g., in city centers where charging stations are also used by passenger cars and taxis).

Overall, the transition towards electric transport demands a different way of thinking. Currently, companies mostly approach the shift towards electric vehicles from the paradigm of conventional vehicles. In this regard, it is considered that everything remains business as usual, except the vehicle type. The upcoming changes need a different perspective on the way the logistics are organized and planned. This includes strategies to reduce the number of vehicle kilometers and the use of transshipment points. Whereas the focus of this case study has been on predictable urban freight transport trips, future research on charging strategies should include sectors that have more ad-hoc trips. Another aspect to further investigate is the interference between commercial vehicles and charging requirements in passenger transport. This is particularly relevant when it comes to charging in residential neighborhoods and at public charging stations. Finally, sites, such as depots where large vehicle fleets have to be charged, lead to various implications for charging strategies that need to be included in future research.

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