OPERATIONS OF ZERO-EMISSION BUSES: IMPACTS OF CHARGING METHODS AND MECHANISMS ON COSTS AND THE LEVEL OF SERVICE

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ABSTRACT (249 words)
To limit global warming and strive for more liveable and sustainable cities, innovative zero-emission busses are on the rise all around the world. For now, only trolley, battery and fuel-cell electric vehicles can be classified as (on the pipe) zero-emission vehicles. Different charging methods, including different charging systems and power, are available to charge battery electric vehicles. However, scientific literature focused on the operation and charging scheduling of electric vehicles is scarce.

In this study, a comparison of different applied charging methods for electric buses is obtained. A new ZE-bus station simulation method is developed to assess charging methods and charging regulations with regard to their impacts on costs and level of service.

The shift to zero emission bus transport is meant for achieving more sustainable and liveable cities. However, this research concludes that this is involved with higher costs and passenger disturbances. The investment costs increase substantially. Benefits of electric operations, including vehicle propulsion cost savings up to 70 percent, are not able to compensate these high investments. (Slow) depot charging offers opportunities for operations on short distance lines. The depot location should be close to a bus station and additional fleet is required. In order to prevent fleet overcapacity, vehicles should be recharged with high charging power along the line, preferably at combined bus stations and terminals in order to prevent charging related delays. Dynamic/In-motion charging - still in its infancy stage yet - offers opportunities to prevent these delays due to combined charging and operation time.

Keywords: Electric buses, charging methods, charging regulations, level of service, investment and operational costs, service reliability

1. INTRODUCTION

A goal of the Paris climate agreement of 2016 is to limit global warming to 2 degrees Celsius. According to Ou et al. *(*1*)*, the transport sector, a major oil consumer and greenhouse gas emitter worldwide, accounted for 26% of world's energy use and 23% of energy-related greenhouse gas emissions. Thus, the transportation sector has to contribute significantly to achieve the goals of the Paris climate agreement. The whole transport sector - also public transport - can make a difference here. Public bus transport is nowadays mostly performed by highly polluting diesel engine vehicles (79% of the total European transit fleet in 2013) *(*2*)*.

1.1. Zero-emission bus transport

The last couple of years, an ongoing shift towards more sustainable transport modes is taking place. The technological developments and the increasing awareness of environmental pollution, resulted in a more active attitude of different parties in the (public) transport stakeholder field. In order to limit global warming and strive for more liveable and sustainable cities, in the Netherlands, from 2025 onwards, all new transit buses should be zero-emission vehicles *(*3*)*. Several sustainable, alternative propulsion types exist, such as: compressed natural gas (CNG), liquid propane gas (LPG), methanol, dimethyl ether (DME), hydrogen and electricity *(*1, 4*)*. However, not all of them are on the pipe zero-emission. Overall, electric vehicles are considered to be the most promising zero-emission, alternative vehicles *(*4, 5, 6*)* .

1.2. Literature gap and research objective

Due to ongoing worldwide urbanization and its simultaneous need for sustainable mass transit, the interest in electrification in bus transit is growing. The number of electric vehicle pilots is growing rapidly – especially in Europe and China - however, scientific literature focused on the operation and charging scheduling of electric vehicles is scarce. Research on this topic lags, as far as known to the authors, behind practice. Where some charging methods are compared in literature, an assessment of the operations of different applied charging methods has - as known to the authors - never been made.

Our research objective is to provide insights into the impacts of charging method choices in different situations. Moreover, a first improvement in operation efficiency is obtained by providing charging process regulations.

1.3. Outline

After this introduction chapter, zero-emission bus transit is further elaborated on in chapter 2. Also the main research objectives are further specified here. In chapter 3, the research methodology is elaborated on, followed by a case study in chapter 4. Finally, in chapter 5, conclusions are drawn and discussed, and recommendations are rendered.

2. ZERO-EMISSION BUS TRANSPORT

2.1. Developments and charging methods

In 2015, approximately 173,000 electric buses were in operation worldwide. 98.3% of this total global electric fleet size operates in China, which makes it the leader in the electric public bus transport market *(*2*)*. Also in Europe, multiple cities are providing electric public bus transport services. The systems used in 90 different European cities, are analysed in E-bus Reports, published by UITP (Union Internationale des Transports Publics – International Association of Public Transport) *(*2, 7*)*. These reports are results of the ZeEUS (Zero Emission Urban bus System) project, wherein the electrification solutions of the urban bus system are tested and the European market of electric buses is facilitated.

The Netherlands are very progressive in the electrification of bus transit. The share of electric vehicles increased from 1% (61 vehicles) of the total fleet in 2016 to almost 6% (280 vehicles) in 2017 *(*8*)*. So far, China is the only country with faster developments in the electric bus transportation market.

In regards of pure electric vehicles, the following distinction can be made: (1) trolleybuses; (2) fuel cell (hydrogen) buses; (3) battery electric buses.

For electric bus transport, there is a trend that vehicles are developed in such a way that charging infrastructure can be adapted to specific customer needs *(*7*)*, which depends on certain battery limitations, differences in line characteristics and other local circumstances. This is shown by the different applied charging methods all over the world. A subdivision in charging methods for battery electric buses is shown in Figure 1.

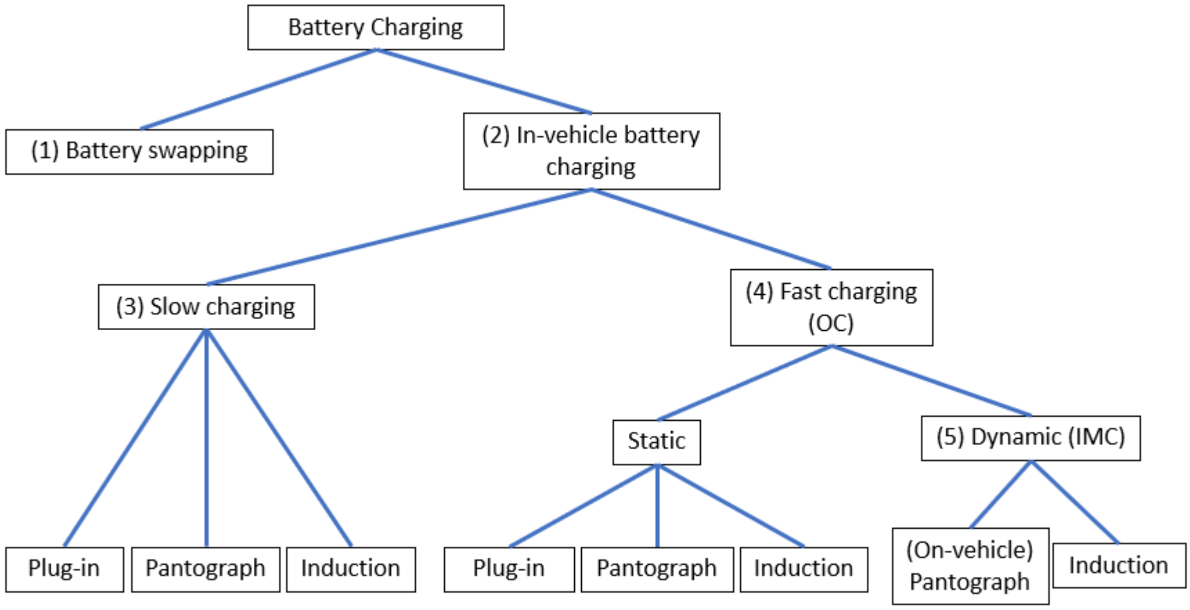

FIGURE 1 Subdivision of charging methods

The first division is made between battery swapping (1) and battery in-vehicle charging (2). Battery swapping means that drained batteries are replaced with freshly charged ones, which makes the charging duration basically irrelevant. In-vehicle battery charging is subdivided in slow (3) and fast charging (4). Slow charging often takes place at the depot during the night. The time to fully charge the battery is relatively long, especially when the battery storage power gets high *(*9*)*. This is different for fast charging – also called opportunity charging (OC). Higher charging powers are used in order to decrease the charging time. Another opportunity is the use of dynamic (in-motion) charging (5). In-motion charging (IMC) is a concept that is still in its infancy stage *(*10*)*, but is nonetheless a very promising option for the future. For a more detailed description of different charging methods, we refer to Wiercx *(*11*)*.

2.2. Problems for operations and planning

A technical problem of electric vehicle operations is that the current battery technologies are not sufficient to cover the same distances as a conventional diesel engine vehicle. For electric vehicles, (on-route) charging time should therefore be considered in the timetable planning and/or vehicle scheduling. This charging time depends specifically on the charging method and the amount of charging infrastructure. For most charging methods, the conventional timetables developed for the diesel engine vehicles, could not comply anymore. To what extend should those timetables be adjusted?

Furthermore, the energy consumption rate (and arrival time) of an electric vehicle depends on multiple factors, like number of passengers, weather conditions and traffic conditions *(*5*)*. For instance, heating and cooling the vehicle require extra energy: Suh et al. *(*12*)* tested an integrated HVAC (Heating, Ventilation and Air Conditioning) unit in an electric bus and found that the unit consumed 21,4% of the total energy for heating and 18,8% for cooling. How should such uncertainties be taken into account in timetable planning and/or vehicle scheduling?

Besides the charging time requirements, Topon and Hisashi *(*5*)* mentioned the high investment costs for buses as well as the installation cost of charging infrastructure, as major hurdle for large-scale adoption of electric vehicles. Purchasing an electric vehicle, cost about twice as much as a comparable diesel vehicle *(*13*)*. Especially the battery packs are expensive. The weight of the battery pack of a long-range all electric vehicle can be 26% of the total vehicle weight and the battery cost can be 39% of the total vehicle cost *(*14*)*. Both percentages decrease when batteries are downsized.

The main aspects determining the costs for a charging station, according to van Kooten Niekerk et al. *(*15*)* are: (1) Location: including ground prices, availability of a high-power electricity connection in the vicinity and possibility of cooperation of authorities; (2) Charging capacity: including space availability and energy connection capacity. Space availability determines the maximum number of vehicles that can be charged simultaneously and the energy capacity determines the charging speed. There will be a trade-off between the use of charging infrastructure and the efficiency of vehicle operations and scheduling. In other words, a balance between operating costs, travel time (experience) and level of service (LoS) should be found to optimize the system performance. Different charging process regulations can be complied in order to approach this optimal system performance. Which charging regulations result in the most efficient operations? Should vehicles only be charged when their battery load is almost empty or is it more efficient to completely recharge all arriving vehicles? And which charging process regulations in between are possible?

2.3. Main research question and research scope

Our main research objective is to provide insights into the charging method choice in different situations. Therefore, an assessment of the operations, the LoS and the costs of different charging methods for electric vehicles is obtained. By modelling different charging methods and discussing the results, first insights in the standardisation of charging methods are obtained. Furthermore, insights in improving operations efficiency by charging process regulations, are provided. This results in the following research question:

What will be the effect of the charging infrastructure choice at a public bus station on the operations, level of service and costs and how could the charging processes be regulated in an efficient way?

The research focuses on bus stations, since multiple lines pass there and charging infrastructure might be applied there efficiently. Bus lines will be described exogenously, by setting certain input parameters. More detailed line operations, like the amount of acceleration and deceleration, caused by multiple intersections, sharp curves and high I/C-ratios, are not considered in detail.

Moreover, only full electric, battery cell vehicles are included in this research. Other alternative-fuel alternatives still emit some polluting particles, so in fact, electric vehicles are the only zero-emission alternative. Fuel-cell (hydrogen) and trolleybuses are beyond the scope of this research.

In addition, the research focus is on the assessment of different charging methods. Therefore, only assessment criteria, based on the differences between charging methods (operations, LoS and costs) are considered. Thus, criteria based on differences between diesel engine and electric vehicles (like environmental aspects), are not included.

3. METHODOLOGY

3.1. Assessment Framework

In order to quantify the effects of the charging method choice on the operations, LoS and costs, a quantitative research is performed. In order to assess charging methods and mechanisms, a ZE(Zero-Emission)-bus station operations model that simulates the charging operations at a bus station, is developed. To assess different variants in a consistent way, an assessment framework is developed (Table 1). This assessment framework presents indicative (societal) costs and benefits, including (1) three important public transport criteria: operations, LoS and costs and (2) the distribution of different positive and negative effects of the most important stakeholders in this field: passengers, bus transit operators and transit authorities.

TABLE 1 Assessment Framework of the ZE-bus station operations model

Criterion	Variable		Unit	Explanation	Stakeholder(s)
Operations	1	Disruptions	%	Percentage of vehicles that have to wait on other vehicles at boarding, alighting and buffer places, per day	Operator Passengers
LoS	2	Delayed departure times	€	Daily costs for delayed departures (from passengers perspective)	Passengers Authority
	3	Dispersion in departure times	€	Daily costs for dispersion in departure time	Passengers
Costs	4	Operational delayed vehicle costs	€	Daily costs for inefficient vehicle use	Operator
	5	Operational energy/fuel consumption costs	€	Daily energy and fuel consumption costs	Operator
	6	Vehicle investment costs	€	Net present value of the total (electric and non-electric) fleet	Operator
	7	Charging infrastructure investment costs	€	Net present value of the charging infrastructure systems	Authority

To start, the operations are assessed by providing disruption percentages, which indicate how many vehicles must wait for other vehicles before boarding, alighting and/or charging activities can take place.

LoS is described by:

1) Delayed departure time, relative to non-electric operations, which expresses the waiting time of passengers due to the charging process, in costs, and

2) Dispersion in departure time, which indicate the societal costs of reliability of departure times from a passenger perspective.

Finally, the cost components are assessed by:

1) Operational delayed vehicle costs, which described the extra vehicle hours per scenario and expressed it into cost. The extra loss time at the station due to charging, is included here from an operators' perspective.

2) Operational energy/fuel consumption costs, which represents the daily vehicle propulsion costs for both electric and diesel engine vehicles.

3) Vehicle investments, which is expressed in the net present value (NPV) of the (minimum required) (electric and non-electric) fleet size.

4) Charging infrastructure investment, including its required surface area, which is also expressed in its NPV.

3.2. Research approach

First, a theoretical and practical literature review is performed. For a detailed overview, see Wiercx *(*11*)*. Secondly, a bus station, is modelled. During the model development stage, a case study was conducted in order to validate the model variables and determine other important model parameters, which could be implemented in the model as well. The model developed in an iterative way. Our model is developed in Excel and simulates the charging operations at a bus station in Simbus (further explained in section 3.2.2.). The conceptual model is shown in Figure 2.

Although the research object is a bus station, the charging time per vehicle depends on multiple time, network and vehicle characteristics. Therefore, all parameters affecting the charging time are described exogenously in a detailed way and are used as input variables. The network characteristics are case dependent and described in the Input Block, Line, Trip and Station boxes. These variables are derived from local AVL data (Automatic Vehicle Location data, see *(*16*)*). The Input Vehicle box links to an electric vehicle database, where several electric vehicles available in the European market *(*2, 7*)*, including some of their specifications, such as energy consumption and battery storage capacity, are listed.

In the Input General box, the season of the year is specified, which results in energy consumption factors for the heating and cooling system. Besides, a battery buffer and maximum fast charging (max OC) rate are specified. The battery buffer is considered to take the available risk in operations and the battery life time reduction by too much discharging the battery, into account. A maximum charging rate is considered for OC methods. High charging power should be reduced at a certain battery level in order to not overheat the battery *(*15*)*.

The ZE-bus station operations model consist of three different model modules. These are discussed in more detail in the remainder of this chapter.

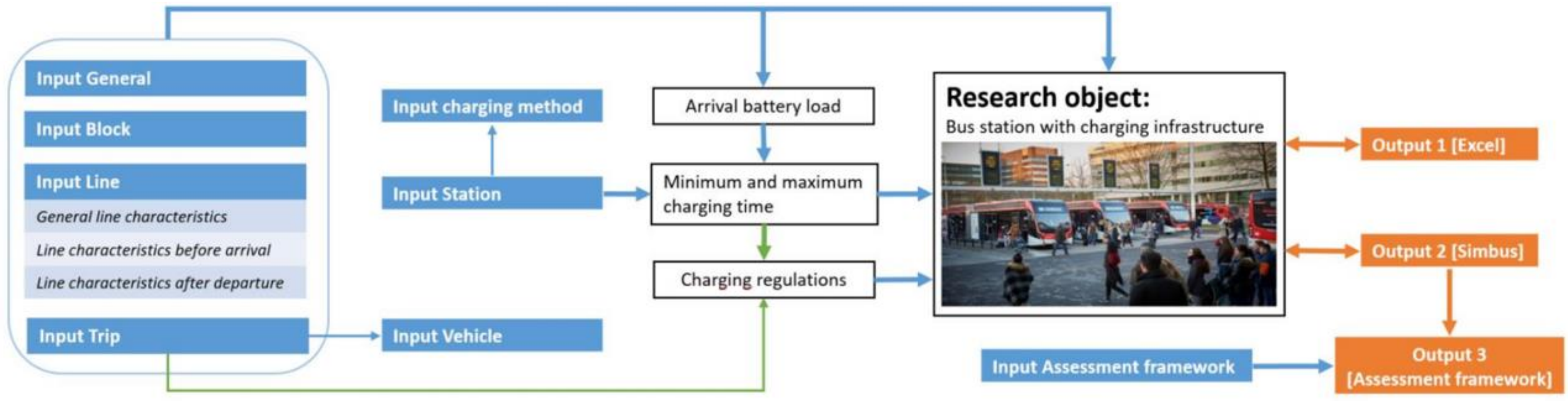

FIGURE 2 Conceptual model framework

3.2.1. Charging time calculation model

In the first model part, the minimum and maximum charging times are calculated. Based on the AVL data and several other input variables, classified in Figure 2, charging times for each trip arriving at the bus station, are derived in the following four steps:

1. Calculation of the battery load when the vehicle arrives at the station;

$$Batt\_load_{ar} = Batt\_load_{last} - \frac{EC * d_{covered} * F_{season}}{BSP} * 100\% \quad (1)$$

2. Calculation of the required battery load for performing the next trip;

$$Batt\_load_{req} = \frac{EC * d_{to\ cover} * F_{season}}{BSP} * 100\% \quad (2)$$

3. Calculation of the minimum battery recharging percentage;

$$Batt\_load_{charge,min} = MIN\ (-Batt\_load_{ar} + Batt\_load_{req} + BB\ ; - Batt\_load_{ar} + Max\ OC\ ;\ 0\ ) * 100\% \quad (3)$$

4. Calculation of the minimum and maximum charging time;

$$t_{charge,min} = \frac{Batt\_load_{charge,min} * BSP * Max\ OC * Eff}{CP} \quad (4)$$

$$t_{charge,max} = \frac{(Max\ OC - Batt\_load_{ar}) * BSP * Max\ OC * Eff}{CP} \quad (5)$$

Where:
$Batt\_load_{last}$: Last calculated/derived battery load (%);
BB: Battery buffer (%);
BSP: Battery storage power (kWh);
CP: Charging power (kW);
$d_{covered}$: Distance covered from previous charging location (km);
$d_{to\ cover}$: Distance to cover before the vehicle can be charged again (km);
EC: Energy consumption (kWh/km);
Eff: Charging efficiency (%);
F_{season}: Season factor;
$Max\ OC$: Maximum OC rate (%).

3.2.2. Bus station operations model

In the second model part, a Simbus simulation takes place. Simbus is a bus station simulation tool, developed by Goudappel Coffeng *(*11*)* and determines the optimal distribution of vehicles over the available boarding and/or alighting platforms and possibly to buffer places, in order to optimize the bus station operations. The derived charging times are used in the simulation in order to take the charging processes into account. Based on the AVL data, the calculated charging times and different reliability values, one final Simbus input sheet is developed. This sheet is saved as text-file, in order to import it in Prosim, the simulation application of Simbus. During the simulation, the results are written in an output text-file and then exported to an Excel file (Figure 3).

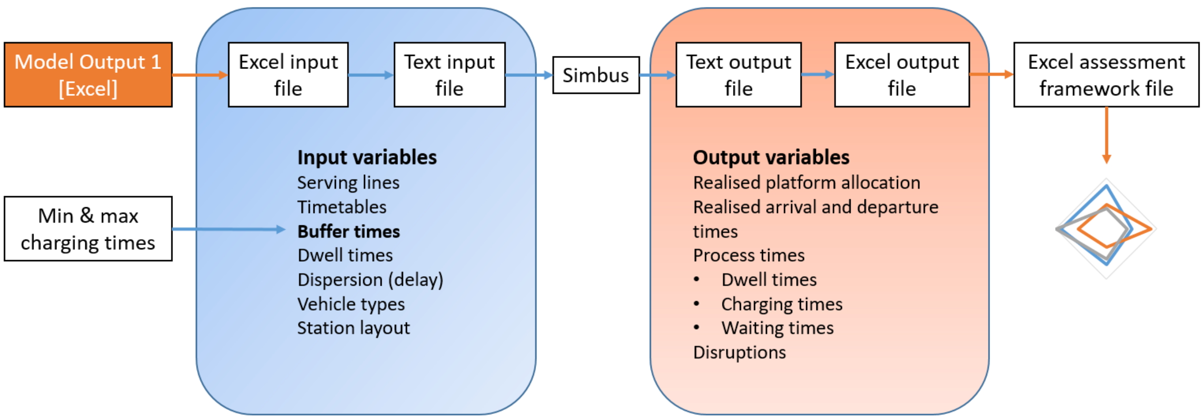

FIGURE 3 Tooling and data scheme for the ZE-bus station operations model

3.2.3. Cost/benefit calculation model

The last model part translates the Simbus simulation output into values for the multi-variable assessment framework criteria. Some of the variables are obtained from the Input boxes, shown in Figure 2, while others are retained from the first model part. The costs and/or benefits for the seven assessment criteria (see Table 1) are obtained, according to equations 6 up to and including 12.

1. Disruptions:

$$disr = \sum_{i=m}^{n} trips_{disrupted} / \sum_{i=m}^{n} trips * 100\% \qquad (6)$$

2. Delayed departure time:

$$C_{del\ dep} = \sum_{i=m}^{n} Delay_i * \#\ P_{i,on\ board} * VoT \qquad (7)$$

3. Dispersion in departure time:

$$C_{dispersion} = \sum_{j=m}^{n} St\ dev\ delay_j * \#\ P_{j,affected} * VoR \qquad (8)$$

4. Operational delayed vehicle costs:

$$C_{op,del} = \sum_{i=m}^{n} Delay_i * C_{veh\ hour} \qquad (9)$$

5. Operational energy/fuel consumption costs:

$$C_{op,c/f} = Price_{el} \left(CP * \sum_{i=m}^{n} t_{charge_i} + \left(1 - Av\ Batt\ load_{dep}\right) * BSP * \#Veh_{el} \right) + Price_{ds} * \sum_{k=m}^{d} (d_{covered} * FC) \qquad (10)$$

6. Vehicle investment costs:

$$C_{inv,veh} = NPV\left(Dr; \left(\#veh_{rig} * C_{veh,rig} + \#veh_{art} * C_{veh,art}\right)_{el} + \left(\#veh_{rig} * C_{veh,rig} + \#veh_{art} * C_{veh,art}\right)_{ds}\right) / Lt \qquad (11)$$

7. Charging infrastructure investment costs:

$$C_{inv,ci} = NPV\left(Dr; \#OCp * C_{OCi} + C_{land}\left(Surf_{cp} * \#OCp + Surf_{my}\right) + C_{SCi} * \#veh\right) / Lt \qquad (12)$$

Where:

$Av\ Batt\ load_{dep}$: Daily average battery load of vehicles when they depart at the charging station (%);
C_{land}: Costs for land (€/m^2);
C_{OCi}: Costs per opportunity charging point (€);
C_{SCi}: Costs per slow charging point (€);
$C_{veh\ hour}$: Operational costs per vehicle hour (€/hour);
$C_{veh,rig}$: Costs for a standard/rigid vehicle (€);
$C_{veh,art}$: Costs for an articulated vehicle (€);
Dr: Discount rate (%);
FC: Fuel consumption (litres diesel/km);
Lt: Life time of vehicles and/or charging infrastructure (# days);
NPV: Net Present Value (€);
$\#OCp$: Number of opportunity charging points;
$\#\ P_{i,on\ board}$: Number of on-board passengers;
$\#\ P_{j,affected}$: Number of passengers affected by delayed departures;
$St\ dev\ delay_j$: Standard deviation of delayed departures (min);
$Surf_{cp}$: Surface charging points (m^2);
$Surf_{my}$: Surface marshalling yard (m^2);
$\#Veh_{ds}$: Number of diesel engine vehicles;
$\#veh_{rig}$: Number of standard/rigid vehicles;
$\#veh_{art}$: Number of articulated vehicles;
$\#Veh_{el}$: Number of electric vehicles;

VoR: Value of reliability (€/hour);
VoT: Value of time (€/hour).
For missing abbreviations, see page 8.

4. CASE STUDY

To demonstrate our model and to find actual insights, we performed a case study, for which Schiphol airport was chosen. Schiphol is the third largest airport in Europe, located in the Netherlands, southwest of Amsterdam. BRT - branded as R-net - lines serve multiple bus stations and connect relatively large surrounded areas with each other and Schiphol. These lines have high frequencies, just like the Schiphol Sternet lines which connect the airport with multiple parking lots around it. This results in a high number of vehicle movements at Schiphol's bus stations. Furthermore, 100 electric vehicles have been introduced since 2017, which makes it Europe's largest electric fleet size in one concession. Two OC locations are considered: one at Knooppunt Schiphol Noord and one at P30 (Figure 4). Besides the two fast on-route charging locations, some OC points and multiple slow chargers are located at two depots. A new timetable was developed in order to optimize the charging-included planning *(*17*)*.

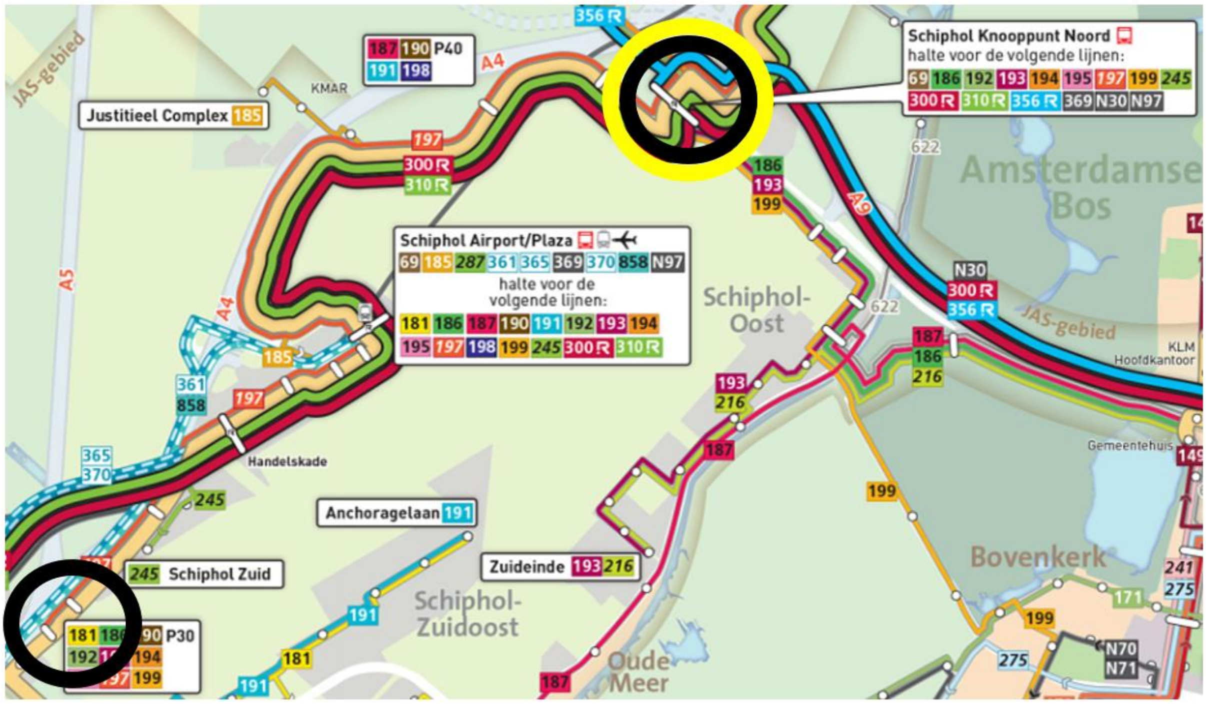

FIGURE 4 Bus line map around Schiphol (valid as of autumn 2017)

4.1. Variants and scenarios

In this case study, three charging methods are considered: Slow depot charging, OC by pantograph and OC by induction. For slow depot charging, a vehicle should be charged slowly in a couple of hours and another, fully charged vehicle replaces its operations. For OC, vehicles are charged faster and more often at (a) bus station(s) along the route. IMC is not a serious option for the transit operators (yet), so this charging method is not considered in this case study.

Besides the charging methods, four different configurations of electrification are considered:

1) No electrification at all (base case);
2) Only electric city (and Sternet) buses;
3) Only electric BRT-vehicles (R-net);
4) Full electrification.

Finally, different charging regulations are taken into account. The ZE-bus operations model calculates the minimum and maximum charging time per trip and applies this in a Simbus simulation. It is interesting to execute simulations for the boundary conditions of the charging times, however, simulations of charging conditions in between are interesting as well and could provide valuable insights for operational (charging) planners. Hence, some charging mechanisms, assigning the minimum or maximum charging time to a vehicle, depending on specific rules, are developed. Those charging mechanisms are shown in Table 2.

TABLE 2 Charging mechanisms

Charging mechanism	Charging time	Charging principle	Relevance
Min	Minimum	Minimum charging if charging is necessary	Determine the range of the charging times
Max	Maximum	Always charge the battery to its maximum	
Peak	Time of the day dependent	Minimum charging during the peak periods and maximum charging during off-peak periods	Unburden the busy peak periods
Place	Charging place dependent	Maximum charging if possible and minimum charging at the last available charging point	Limit waiting times before charging
Need	Necessity dependent	Maximum charging if charging is necessary	Limit the amount of charging activities

Based on all possible combinations of charging methods and electrification configurations, in combination with the charging mechanisms, a set of model variants is obtained. For slow depot charging, vehicle replacement takes place. Therefore, the most important question is: how many extra vehicles are required to perform the operations? In order to minimize this number, vehicles are completely charged only when it is necessary. Hence, only the Need charging mechanism is considered for slow depot charging.

4.2. Input variables

The model is developed to research one OC station in the network. In that way, the battery dynamics can be simulated in detail. Therefore, one OC station, is chosen for this research: Schiphol Knooppunt Noord (Figure 4). Instead of four OC points at two bus stations, eight OC points at Schiphol Knooppunt Noord are considered. At Schiphol Knooppunt Noord, eight boarding and alighting platforms are available.

The operating electric bus type (i.e. VDL Citea SLFA Electric) is not involved in the vehicle database of the model, because there are no real life energy consumption test results available yet. By filtering the vehicle database on the same vehicle length, charging method and charging power, one vehicle, the Solaris Urbino 18 electric PA (Length: 18 m, passenger capacity: 129; Energy consumption: 1.3 kWh/km, Battery storage power 240 kWh), remains, so this vehicle is chosen to resemble in this case.

The simulation day is Thursday 5 October 2017. The AVL data of this day contains non-electric operations. In general, Thursdays (and also Tuesdays) are considered as busiest travelling days, especially in peak periods *(*18*)*. This day takes place in autumn, so a season factor of 1 is considered. For the maximum OC rate and battery buffer the standard values are used, respectively 80% and 20% in order to use the battery as optimally as possible.

To translate delays into costs, the number of affected passengers is used. For our case study, the number of passengers inside the vehicles at the charging station and after departing at the charging station were estimated based on passenger counts.

4.3. Results

The daily assessment results of different charging methods and charging mechanisms, relative to the base case (only diesel engine vehicles), are represented in Figure 5 for respectively electric city vehicles, electric R-net vehicles and all electric vehicles. In this representation, the differences between charging methods (OC induction, OC pantograph and Slow depot charging) are visible. For slow depot charging, only one charging mechanism (Need) is considered, so the assessment of different criteria is represented by lines in the spider graphs. For the two OC methods, five charging mechanisms (Table 2) are considered. For each criterion, the assessment result of the minimum and maximum scoring charging mechanisms is represented. Therefore, a plane-shaped figure becomes visible in the spider graphs. At last, the disruptions are expressed as percentages. The outer circle of the spider graphs corresponds with 100% disruptions and reference value with 0%. The scales of Figures 5a and 5b are equal, while the scale of Figure 5c is different.

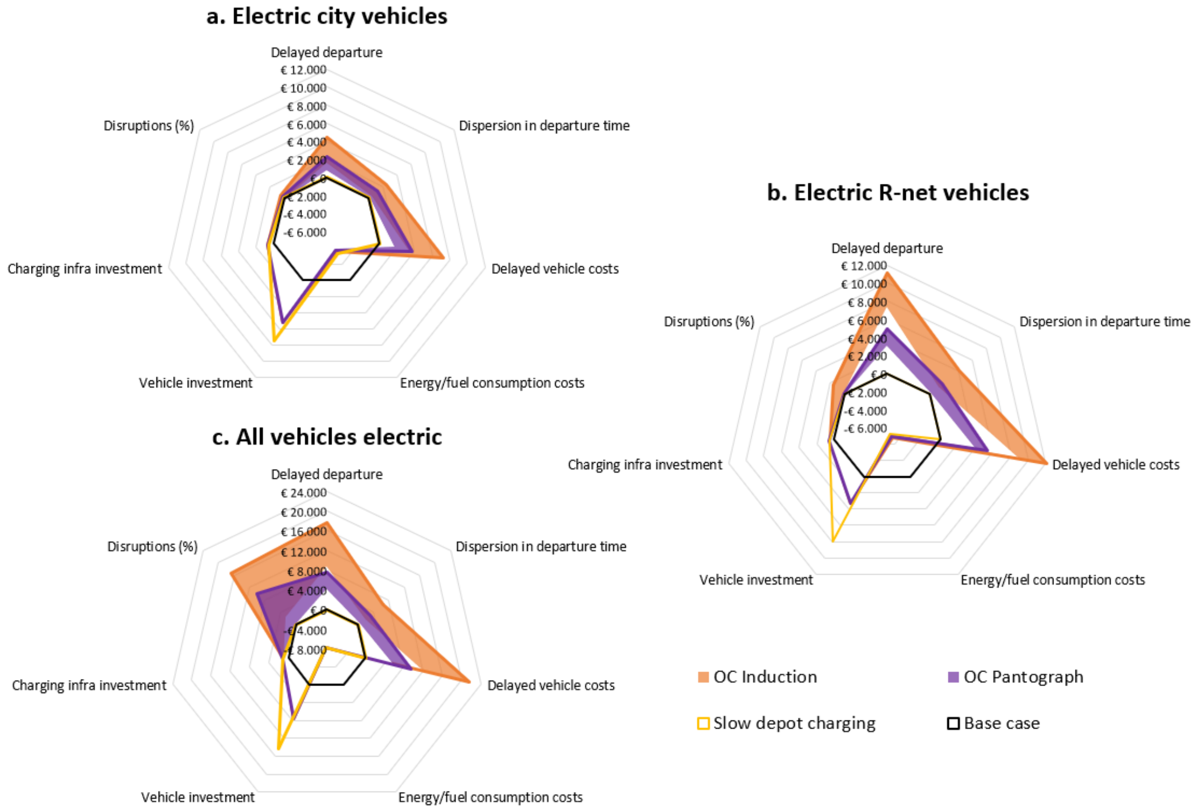

FIGURE 5 Daily scores relative to the base case for: a) electric city buses, b) electric R-net vehicles, and c) Completely electric fleet

According to Figures 5a, 5b and 5c, there is an important trade-off between high vehicle investment costs and large energy/fuel consumption cost savings, especially for slow depot charging. With respect to the base case, slow charging at the depot does not result in extra delays and disruptions, because the number of required vehicles is upgraded in order to be able to perform the trips according to conventional timetables. This is different for the OC methods. OC at the bus station results in delayed departures, since charging processes are not included in conventional timetables (AVL data). Comparing the two OC methods, the delay criteria and disruption criterion score structurally higher for OC by induction compared to OC by pantograph. This is caused by lower maximum charging power for induction systems.

Besides, electrifying R-net vehicles instead of the city and regional vehicles, results in lower vehicle investment costs due to the electrification of 56 vehicles instead of 78 vehicles. However, the delay costs (delayed departure and delayed vehicle costs) are significant higher, caused by longer and more frequent charging activities, needed to perform the trips on the relatively long R-net routes. Electrifying the city bus operations first, is therefore a deliberately decision.

Full electric operation results in the highest vehicle investments, delay costs and number of disruptions, but to the lowest energy/fuel consumption cost. The high number of disruptions represent a charging point scarcity. There are too little charging points for the amount and duration of charging activities.

5. CONCLUSIONS, DISCUSSION AND RECOMMENDATIONS

5.1. Conclusions

Overall, it can be concluded that the total costs increase for operations of electric vehicles compared to operations of conventional diesel engine vehicles. The main purpose of the implementation of Zero-emission vehicles is to improve sustainability and liveability and apparently higher costs are involved with that. Operators have to deal with higher investment costs: electric vehicles are 60 to 80 percent more expensive than diesel engine vehicles and also additional charging infrastructure is required. On the other hand, substantial operational benefits, up to 70 percent, could be realised, especially on BRT and long distance regional lines.

For charging electric vehicles, different charging methods are distinguished in this research. First, slow depot charging could be performed during the night (overnight charging), but also during the daily operations. By the deployment of extra vehicles during the charging processes, conventional timetables can be complied. The operation and LoS remain constant. Though, higher costs are involved, because an oversized fleet is necessary. For longer distance lines, a larger fleet overcapacity is required.

Secondly, OC is a fast (re)charging process during operations. Often, OC takes place at a bus station, preferably a combined bus station and bus terminal, because already available dwell times can be used for the charging processes. Still, slight charging related delays of departing vehicles could occur, especially when the number of charging systems is not sufficient and/or the charging times are relatively long. Purchasing enough charging infrastructure systems, providing matching charging power and considering charging times in timetable planning are necessary measures to keep operations and LoS on a high level.

IMC combines the charging and operational time, so no LoS problems could occur. However, substantial charging infrastructure investments are involved, since IMC is still in its infancy stage yet.

Finally, based on the assessment results of different charging mechanisms, specific charging regulations offer opportunities for different situations. A dynamic charging mechanism, varying between different charging mechanisms at the right moments, will result in a more efficient charging time planning.

5.2. Discussion

This research is valuable for policymakers and planners. To keep the LoS high and minimize investment costs, multiple decisions should be made by operators and authorities. Trade-offs and operators decisions are summarised in an operators decision tree, represented in Figure 6.

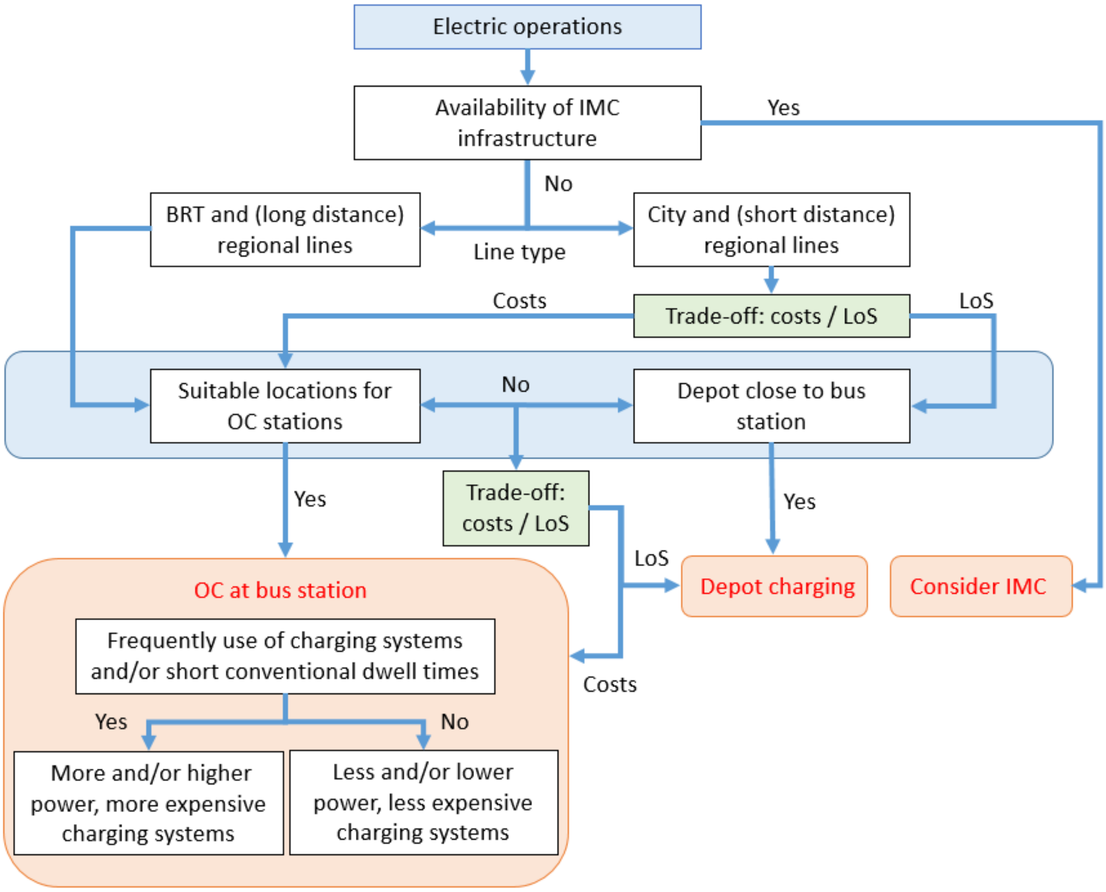

FIGURE 6 Charging method decision tree for operators

For now, IMC is only considered as realistic option if IMC infrastructure is already (partly) available. For the charging location choice, at a bus station or at the depot, a trade-off between LoS aspects and investment costs is considered. However, for longer distance lines, charging at a bus station is often preferred. Finally, the frequency of charging system usage, determines whether more expensive, higher power systems or cheaper, lower power systems are preferred.

Moreover, some model limitations, caused by simplifications and/or assumptions, influence the model results. Two model limitations, concerning some assumed battery loads at the start of vehicle operations and rough estimate battery loads for overnight charging, are showing model related shortcomings. Therefore, (especially minimum) charging times could be slightly over- or underestimated. Besides, the exclusion of the electricity grid make-up costs and the disqualification of the relationship between battery size and vehicle costs, are model limitations caused by a lack of detailed information. Solving those two limitations, result in structurally higher charging infrastructure costs and possibly lower vehicle investment costs.

5.3. Recommendations

First, for operators, it is recommended to limit delays for passengers, in order to confront the transit users only with positive effects of electric vehicles, such as travel comfort and more sustainable cities. In order to deal with increasing investment costs, it is recommended for authorities to financially support operators, by providing subsidies or maintain and manage the charging infrastructure.

Secondly, it is recommended to implement the model results of this research on line and network level, in order to analyse the electric bus station operations in regards to network planning. Besides, recommendations for further scientific research in individual, electric operation aspects, like battery downsizing, required battery buffer and maximum OC limits, are rendered. It is also recommended to use AVL data, concerning operations of electric vehicles in order to validate the modelled charging times and obtain results of adapted - charging time included - timetables.

Finally, for further model development, it is recommended to implement fuel-cell (hydrogen) and hybrid vehicles into the model, as well as the IMC method. In order to optimize the charging processes, more sophisticated charging mechanisms are recommended either.

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AUTHOR CONTRIBUTION STATEMENT

The authors confirm contribution to the paper as follows: study conception and design: M. Wiercx, R. Huisman, N. Van Oort, B. Van Arem; data collection: M. Wiercx; analysis and interpretation of results: M. Wiercx; draft manuscript preparation: R. Huisman, N. Van Oort, B. Van Arem. All authors reviewed the results and approved the final version of the manuscript.

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