Max Wiercx

# The operations of zero-emission bus transport

## How different charging methods and mechanisms at bus stations affect the level of service of public bus transport


TU Delft

adviseurs mobiliteit
Goudappel Coffeng

# The operations of zero-emission bus transport

## Master Thesis

By

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# Preface

This Master Thesis report is the final piece of my graduation research. After a little more than two years, I finish the Master Civil Engineering: Transport & Planning at the Delft University of Technology, with this research. In my research, I provided insights in the charging method choice for operations of electric public bus transport.

First of all, I want to thank the Thesis Committee, Bart van Arem, Niels van Oort, Wijnand Veeneman and Raymond Huisman, for their feedback and suggestions during my research. Special thanks to Niels van Oort for giving me the opportunity to perform my Master Thesis at Goudappel Coffeng. Also special thanks to Raymond Huisman for always keeping the practical as well as the scientific parts of the research in mind, despite of the company supervisor role, he had.

I would like to thank André Veenendaal and Gert Naber (Arriva), Hugo Visser (RET) and Allart Lensvelt (Schiphol Group), for their time and valuable insights provided during the interviews. I also want to thank the 'CROW-NDOV loket' for providing trip data, with permission of Vervoerregio Amsterdam and Connexxion.

Furthermore, I would like to thank the colleagues at Goudappel Coffeng, especially the members of the 'PT-team'. In the beginning of my research, I have spoken to most team members individually, in order to meet each other and get inspired for my research. During several (PT-team) meetings, I got feedback of different PT experts included in the PT-team, which was very helpful. Overall, I had a great time and learned a lot during my internship.

Besides, I want to name some more individuals contributed to my Master Thesis report. I want to thank Freek Verhoof for helping me exploring and using Simbus. During my whole research, he was always interested in the model development and the research progress. Thanks to Arthur Scheltes, Roland Buysse and Ellen van der Werff for reading (parts) of my final Thesis and gave helpful feedback. Also colleagues from other teams contributed to my research: Niels Voogt gave my some helpful advice during my research (he did research in electric private car charging) and Karin de Regt helped me with her advanced Excel skills. Finally, I want to pay tribute to a friend, Dieuwertje Boonstra, who did a spelling and grammar check on my whole Thesis.

*Max Wiercx*

*Den Haag, April 2018*

# Executive summary


In order to limit global warming and strive for more liveable and sustainable cities, innovative zero-emission busses should be implemented in the Netherlands from 2025 onwards. Different alternative vehicle propulsion methods have been introduced during the last decades. However, for now, only electric vehicles can be classified as (on the pipe) zero-emission vehicles. An important limitation of a battery electric vehicle is the limited range due to capacity restrictions of current batteries. Therefore, batteries should be (re)charged before, during and after the daily operations.

Different charging methods, including different charging systems and power, are available and some applied. However, there is no standardization of charging infrastructure yet. This study provides insights in the choice for a charging method, including corresponding trade-offs, in order to get insights in advantages and disadvantages of each method in different, specific situations. A comparison study of different applied charging methods for electric buses is obtained, which has, as far as known to the author, never been done before. The main research question is:

**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?**

This research focusses on bus stations, which are, from operators perspective, seen as efficient locations to install (fast) charging infrastructure. However, such stations are often located in dense and expensive inner city areas. Besides the effects of different charging methods, a first step in optimising the charging activities by developing charging mechanisms, is provided in this research.

**The operations of zero-emission bus transport**

The share of electric buses is growing worldwide and despite of the battery technology improvements, a paradigm shift from long range electric vehicles towards fast charging (opportunity charging/OC) techniques, resulting in shorter charging times and lighter and cheaper batteries and vehicles, has started in Europe. For OC, mostly performed by pantograph or by the induction technique, different charging power systems are available. OC activities result in longer dwell times of electric vehicles at the charging stations. Therefore, the charging activities should be scheduled appropriately in order to prevent structural delays. Combined bus stations and bus terminals are considered as suitable locations for OC, because multiple vehicles arrive there, buses often wait/buffer there for a certain time and the vehicles are often empty during this waiting time.

For in motion charging (IMC) techniques, no charging related delays are caused. However, IMC, as well as battery swapping techniques, are charging methods requiring substantial infrastructure investments. Slow charging at the depot occurs with substantial lower charging power, mostly during the night. In practice, overnight, slow charging is often combined with OC. For large scale electric operations, a high power electricity grid is required, especially if a large number of vehicles is charged at the same time and/or high power fast charging stations are built.

**(Z)E-bus station operations model: development and variants**

In order to chart the main problems for electric operations, to determine the current state of the art, and to derive several model settings, parameters and charging mechanisms (charging regulations), a literature study was performed and important stakeholders in the public bus transport field were interviewed. Based on automated vehicle location (AVL) data, trip data sheets are developed in order

to calculate the charging times and perform bus station simulations in Simbus, a bus station simulation tool developed and used at Goudappel Coffeng. Depending on the charging mechanism, the calculated minimum and/or maximum charging times are implemented in the Simbus simulation. The simulation output is translated into values for the assessment framework. In the assessment framework, seven criteria considered as opportunity or thread of one or some of the charging methods, are included. They are summarised in Table i.

*Table i - Assessment criteria and its corresponding affected stakeholders*

| Criterion | Variable | Unit | Affected stakeholder(s) |
|---|---|---|---|
| **Operations** | Disruptions | % | Operator, Passengers |
| **Level of service** | Delayed departure | € | Passengers, Authority |
| | Dispersion in departure times | € | Passengers |
| **Costs** | Operational delayed vehicle costs | € | Operator |
| | Operational energy/fuel consumption costs | € | Operator |
| | Vehicle investment | € | Operator |
| | Charging infrastructure investment | € | Authority |

Besides two charging mechanisms considering the minimum and maximum charging times, three other charging mechanisms, determining the charging time based on a specific set of rules as indicated in Table ii, are developed.

*Table ii - Charging mechanisms*

| Mechanism | Charging time | Charging principle |
|---|---|---|
| **Min** | Minimum | Minimum charging, if charging is necessary |
| **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 |
| **Place** | Charging place dependent | Maximum charging in general and minimum charging at the last available charging point |
| **Need** | Necessity dependent | Maximum charging if charging is necessary |

Based on these charging mechanisms and predefined development paths, including three different charging methods (slow depot charging, OC by pantograph and OC by induction) and electrification distributions (electric city and/or regional buses, electric BRT vehicles, and all electric vehicles), a set of model variants is obtained. After modelling these variants, location specific and/or extreme model scenarios are modelled as well. Finally, the influence of several individually, slightly changed variables is analysed in the sensitivity analysis.

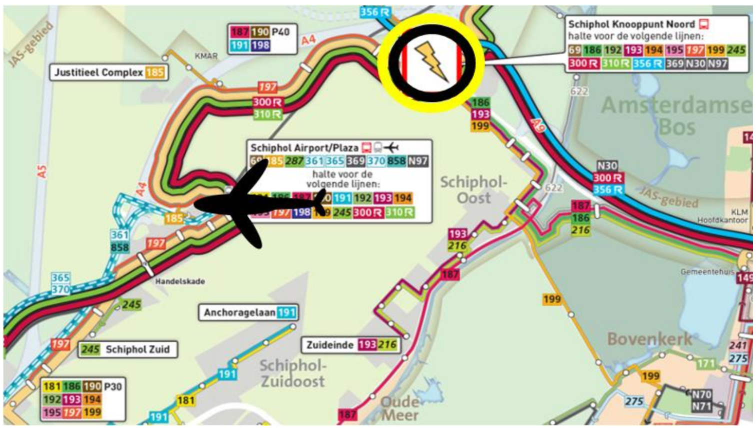

*Figure i - Electric operations at Schiphol*

**Model results for application Schiphol**

Amsterdam airport Schiphol has been used as an application to test and validate the model. Schiphol is interesting, because there are large bus stations served by multiple lines of different operators, including both city and BRT (R-net) vehicles. In addition, 100 electric vehicles will be implemented in April 2018. Considering Schiphol Knooppunt Noord as a sole fast charging location (Figure i), result in the values for the assessment criteria compared to a situation with only diesel engine vehicles, as indicated in Figure ii. In this graph, results of the relevant charging mechanisms for three different charging methods concerning a pre-defined electrification share (only electric city buses), are represented relative to the base case. In the base case, only conventional diesel engine vehicles are considered. The bandwidths represent the highest and lowest scoring charging mechanisms per criterion.

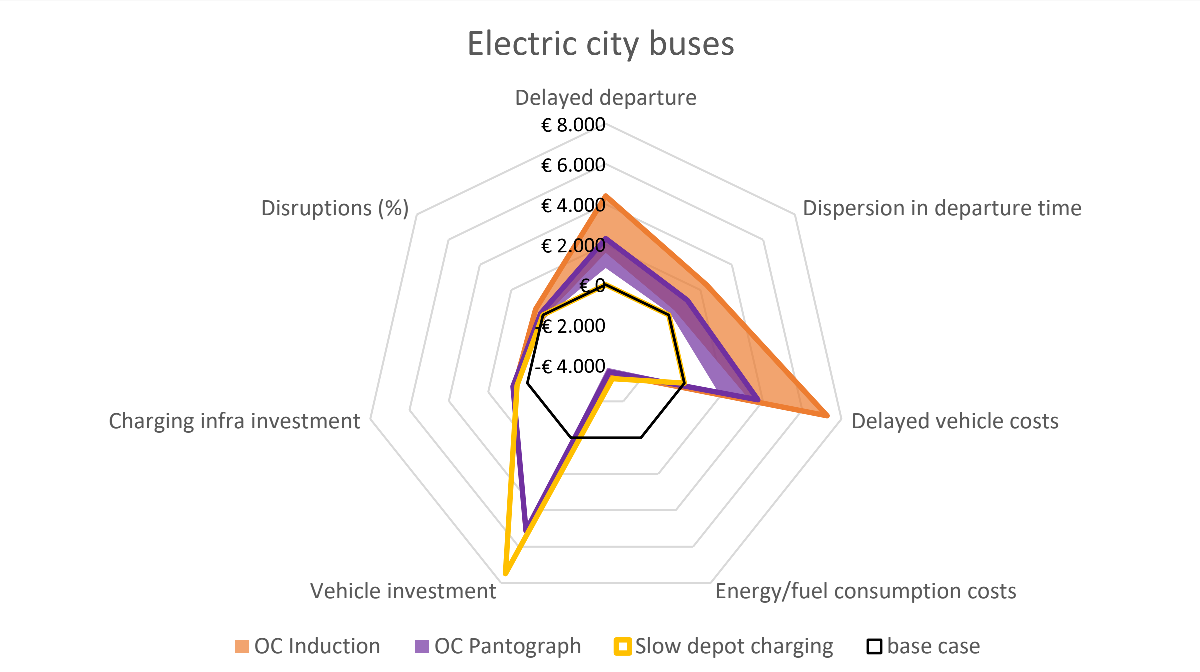


*Figure ii - Assessment results for electric city buses relative to the base case*

For slow depot charging, the vehicle investment costs are the highest, while the delay costs becomes also a substantial cost component for the OC methods, especially for OC by induction. This has to deal with the fact that Schiphol Knooppunt Noord is not a terminal, so short dwell times are considered in the timetables. In reality, however, timetables are adjusted before the electric operations will start. For the OC methods, charging mechanism Max determines the maximum values for the delay related criteria and Min the minimum. The minimum and maximum values for the dispersion in departure time are indicated by Peak and Need, respectively. For all charging methods, an energy/fuel consumption costs reduction, compared to non-electric operations, is visible.

**General research findings**

Based on model results of 33 variants, 7 scenarios and 9 sensitivity checks for application Schiphol, combined with a critical analysis and reflection on the results, the model limitations and existing literature, conclusions are drawn. In general, the shift towards more sustainable and liveable cities, where the Zero-emission agreement is meant for, is involved with higher overall costs. The investment costs increase substantially: Most electric vehicles are around 60 to 80 percent more expensive than conventional diesel engine vehicles and additional charging infrastructure investments are required. Yet, electric operational benefits, including vehicle propulsion cost savings up to 70 percent, are not able to compensate these high investments.

In this research, three main charging methods are distinguished:

1) Slow depot charging
2) Fast/opportunity charging (OC)
3) In-motion charging (IMC)

Besides overnight charging, electric vehicles could also be (re)charged slowly at the depot during the daily operations. The vehicle to be charged is replaced by a fully loaded one, so there is no deterioration in level of service compared to non-electric operations. However, an oversized vehicle fleet should be purchased, especially in cases of electric operations at long routes, like BRT lines and long distance regional lines. A large fleet overcapacity (up to 70%) is required, which result in substantial vehicle investment costs. For short distance (regional or city) lines, the required fleet overcapacity is limited. For these lines, (slow) depot charging could be an opportunity, when the depot is located close to a bus station served by all electric vehicles.

OC could take place at bus stations, preferably combined bus stations and terminals, or at the depot, for instance in cases of unsuitable bus station locations. At bus stations, the dwell time is often extended by the charging process, resulting in charging related delays. These delays are lower when conventional dwell times are higher (at terminals) and/or can be limited by introducing higher power charging systems. In addition, (low variation) charging times can be implemented in timetable planning in order to reduce the level of service impacts. The number of charging systems should be sufficient in order to prevent substantial decreases in operations and level of service. The delays could be prevented completely by constructing multiple OC stations in the network in order to be able to reduce the charging time to the dwell time level. However, these large scale bus station redevelopments result in high charging infrastructure related investments.

In regards of operations and level of service, IMC offers opportunities due to combined charging and operation time. However, IMC is still in its infancy stage yet, so substantial charging infrastructure investments are involved. The charging method choice and decisions concerning the implementation of a charging method, contain trade-offs between level of service (and operations) and (vehicle/charging infrastructure) investment costs, as indicated in Figure iii.

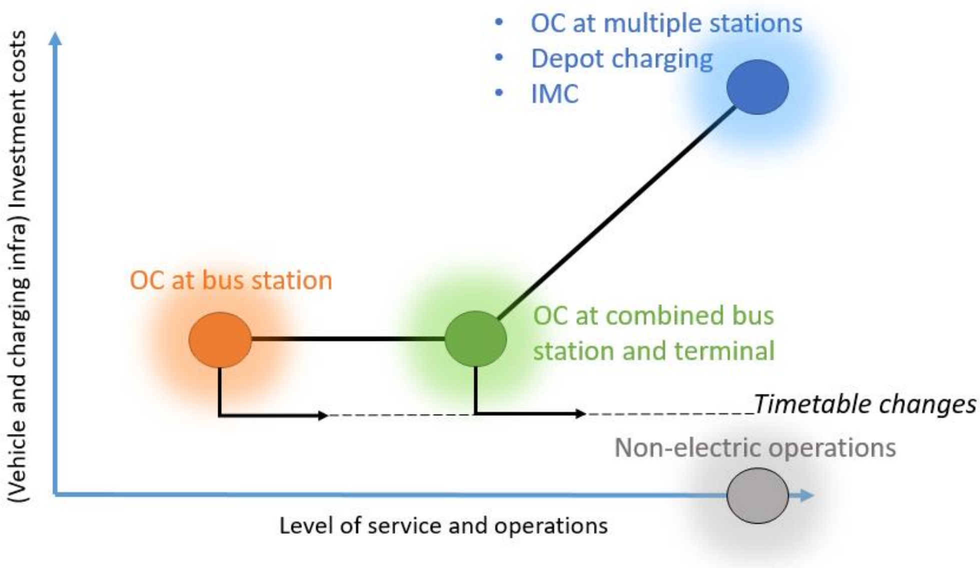


*Figure iii - Relationship between level of service and investment costs for charging electric vehicles*

Finally, based on the assessment results of different charging mechanisms, opportunities for efficient planning of the charging process are provided. For Need, including a minimum number of charging activities and therefore, relatively long charging times, the number of disruptions is minimized. Due to delay reductions, Min offers the best possibilities in regards to level of service. However, for an increasing difference between peak and off-peak passenger loads, Peak could be implemented in order to minimize the level of service impacts in the peak periods. To obtain an efficient charging time planning, it is recommended to vary between different charging mechanisms during operations.

**Recommendations for stakeholders and future work**

First, for operators, it is recommended to limit the delays for passengers, in order to confront the public transport users only with positive effects of electric vehicles, such as travel comfort and more sustainable cities. Based on several location and network dependent characteristics, a charging method decision tree is developed (Figure iv). In order to deal with increasing investment costs for operators, it is recommended for authorities to financially support operators, by providing subsidies or maintain and manage the charging infrastructure.

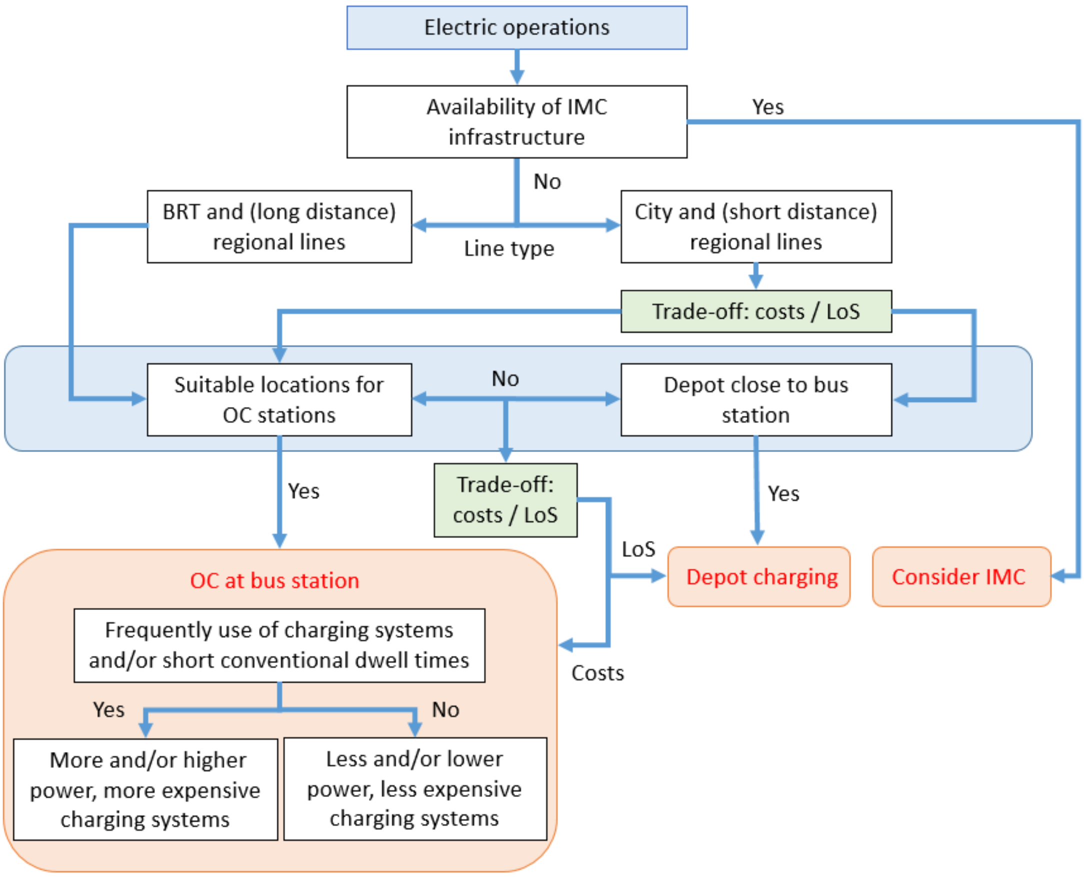


*Figure iv - Charging method decision tree for operators*

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 fast charging limits, are rendered.

For application Schiphol, it is recommended to implement data, obtained after the introduction of the electric vehicles into the model in order to compare alternatives for electric operations with the current plans and validate both, the current plans and the developed model. For more accurate passenger related costs, the implementation of automated passenger counting (APC) data is recommended as well.

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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# 1. Introduction

In this introduction chapter, the reason for doing this research, the primary focus of this research and the research questions are stated. This chapter starts with the context, describing where the interest for zero-emission bus transport came from and why this particular research focusses on electric buses. Secondly, the problem statement will be elaborated, followed by the statement of the research objective, the research goal and its contribution in both practical and scientific context. The scope of this research is determined in section 1.4. The main research question and corresponding sub questions are mentioned in section 1.5, followed by a reading guide for the remainder of the report.

## 1.1 Context

A goal of the Paris climate agreement of 2016 is to limit global warming to 2 degrees Celsius. To achieve this goal, the transportation sector has to contribute significantly (UITP, 2016). Once again, according to Ou et al. (2010), 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 (in 2004). Also public transport can make a difference here. Public bus transport, nowadays mostly performed by diesel engine vehicles (79% in 2013 in Europe (UITP, 2016)), is highly polluting.

The last couple of years, an on-going shift towards more sustainable transport modes is taking place. Striving for more sustainable transport is not something new, however, decades ago, it was not taken that seriously, as indicated by the (1st April) joke in Figure 1-1. The technological developments and the awareness of environmental pollution in combination with ongoing urbanization, resulted in a more active attitude of different parties in the (public) transport stakeholder field in the last couple of years.


18 maart 1992
nr. 3

HTM VERVOERSKRANT
NIEUWS VOOR HTM-PERSONEEL

Uniek HTM-experiment krijgt wereldwijde bekendheid

De HTM heeft een superschone, milieuvriendelijke bus ontworpen: de combibus, een DAF-standaardbus die op de tramrails kan rijden en gebruik maakt van stroom als energiebron.
U leest meer over deze primeur in deze Vervoerskrant.

*Figure 1-1 - Newspaper article/joke from 18 March 1992 about a sustainable bus transport experiment in The Hague*

In order to limit global warming and strive for more liveable and sustainable cities, in the Netherlands from 2025 onwards, all new buses should be zero-emission vehicles (Government of the Netherlands, 2016). Several sustainable, alternative propulsion types exist, such as: compressed natural gas (CNG), liquid propane gas (LPG), methanol, dimethyl ether (DME), hydrogen and electricity (Tzeng, et al., 2005; Ou, et al., 2010). Some of these, especially electricity are on the rise rapidly. Overall, electric vehicles are considered to be the most promising future fuel alternative vehicles (Tzeng, et al., 2005; Topon & Hisashi, 2014; Laizans, et al., 2016).

Due to the ongoing urbanization in the world and its simultaneous need for sustainable mass transit, the interest in electrification in public bus transport is growing worldwide. In several Dutch cities and regions, different electric vehicle pilots are currently running, of which some are followed with great interest by other counties. The number of electric vehicle pilots is growing rapidly, however, scientific literature focused on the operation and charging scheduling of electric vehicles is scarce. Research on this topic lags behind practice. Where some charging methods are compared in literature, an assessment of the operations of different applied charging methods has never been made.

## 1.2 Problem statement

By signing the zero-emission agreement, the Dutch government has set a goal to achieve sustainable bus transport. This provides actions from both transit authorities and public bus transport operators. Their exact roles however are unknown. The question is whether the authorities should be guiding or following in order to achieve sustainable bus transport and what, for both authority roles, will be the responsibilities? Yet, it is unclear which of the two parties should own the charging infrastructure. Both possibilities have advantages and disadvantages.

Another, more technical problem is that the current battery technologies are not sufficient to cover the same distances as a conventional diesel engine vehicle. For electric (or hybrid) vehicles, (on-route) charging time should therefore be taken into account in the timetable planning and/or vehicle scheduling. This charging time depends specifically on the charging method and the amount of charging infrastructure. In this research, with 'charging method', the charging system and corresponding power range is meant. Different charging methods are applied (in pilots) all over the world. There is no standardization of charging infrastructure yet, however, this will be necessary for wide application (EVConsult, 2016). Several local circumstances need to be taken into consideration when it comes to making decisions regarding the charging method. For a transit authority or a bus operator, it is therefore difficult to make this decision. The question for them is: What charging method(s) is/are most cost and time efficient for their specific case? In other words, which charging methods result in the lowest costs for the operators and the best quality of public transport for the passengers? The quality of public transport will be mainly described here by (experienced) travel time and travel time reliability. For some charging methods, the conventional timetables developed for the diesel engine vehicles, could probably not comply anymore. To what extend should those timetables be adjusted?

Another problem has to do with the charging infrastructure usage. First, the number of charging infrastructure systems should be determined carefully. Charging infrastructure is expensive in investment and operation and there should be enough space to install it. Therefore, efficient charging infrastructure usage is required. By setting certain charging regulations and/or installing the right charging power systems, this can be realised. The local electricity grid should be sufficient to deliver the desired amount of power to all charging equipment. At the same time, the charging and waiting time of the vehicles should be kept as low as possible. There will be a trade-off between the use of charging infrastructure and the efficiency of vehicle operation and scheduling. In other words, a balance between operating costs, travel time (experience) and level of service 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 exploitation? 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?

## 1.3 Research objective

The goal of this research is to provide insight in the charging method choice in different situations. Therefore, an assessment of the operations, the level of service and the costs of different charging methods for electric vehicles is obtained. By providing a general model, including important variables as input parameters, a wide range of bus stations could be modelled. This research is provided at and in collaboration with Goudappel coffeng, a consultancy for mobility. For Goudappel Coffeng, the model will be a useful tool to provide advice about the exploitation of electric vehicles in different cases. Variants with different charging methods and different levels and types of electrification can be modelled by this tool. In scientific context, this research provides the first step in the standardisation of charging methods. Furthermore, insights in improving exploitation efficiency by charging process regulations, are provided.

## 1.4 Scope

Electric vehicles are not only the most sustainable alternative for propulsion, as mentioned in the context, but in fact, they are the only zero-emission alternative (Veenendaal & Naber, 2017; Visser, 2017) since other alternatives (CNG, LPG, DME) still emit some polluting particles, other than $CO_2$. Therefore, only electric, battery cell vehicles are included in this research. For the period of improving battery technology, hybrid electric vehicles provide an alternate mode (Tzeng, et al., 2005), while hydrogen (fuel cell) vehicles offer promising possibilities for longer distance, regional bus lines in less dense areas (Veenendaal & Naber, 2017). However, in order to achieve the desired level of detail, this research only focusses on full electric vehicles, relative to the conventional diesel engine vehicles. Besides, the research focus is on the assessment of different charging methods. Therefore, only assessment criteria, based on the differences between charging methods are considered and no criteria based on differences between diesel engine and electric vehicles. The assessment criteria are further discussed in section 3.4.

The research object is a bus station. This could be different stations, however, more frequently serving, often used bus stations, serving multiple lines, are more interesting to install charging infrastructure. But even though those stations are more interesting (and complex) for this research, in the end, all types of bus stations located in different regions are within the scope of this research (Figure 1-2). Bus terminals, besides central stations in large cities and regular bus stops in small villages are all relevant, because zero-emission vehicles should be operating on all conventional bus lines in the near future. All complete lines serving the bus station, are relevant for this research. Those will however 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.


*Figure 1-2 - Bus station types*

Making a timetable is an iterative process, concerning the following four aspects: 1) routing, 2) frequency determination, 3) vehicle scheduling, 4) crew scheduling (Zhu & Chen, 2013). According to van Kooten Niekerk et al. (2017), infeasible vehicle schedules arise when properties of electric vehicles are not taken into account. Therefore, this research focusses on the vehicle scheduling part. However, like iterative processes work, that does not mean that the other aspects stay unchanged. Routing and frequency determination are outside the scope of this research in order to keep this study manageable. Crew scheduling is partly considered by taken the drivers breaks into account in the vehicle scheduling process.

## 1.5 Research questions

Based on the problem statement, the research objective and the demarcation of this research, one main research question and four sub questions are formulated.

| **Main 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? |

| **Sub questions** |
| --- |
| 1. Which charging methods are available right now and are expected in the future and what are their advantages and disadvantages in regards of operations and costs? |
| 2. How could the charging process of electric vehicles at a public bus station be regulated? |
| 3. How are charging methods for electric vehicles affecting the conventional vehicle schedules and timetables and how does that relate to the operational and investment costs? |
| 4. To what extend are different charging mechanisms improving the operations and level of service? |

Answers to the first two sub questions should be provided in order to develop the model and model variants. The third and fourth sub question should be answered based on the model results. Moreover, the first and third sub questions relate to the charging methods (charging infrastructure systems), while the second and fourth sub questions relate to the charging mechanisms (charging regulations), as indicated in Table 1-1. These charging mechanisms have to deal with charging regulations for electric vehicles at the bus station and provide a first step in optimising the charging activities.

*Table 1-1 – Allocation of sub questions*

| | Model development | Model results |
|---|---|---|
| Charging methods | q1 | q3 |
| Charging mechanisms | q2 | q4 |

## 1.6 Report outline

After this introduction chapter, the literature review and state of the art is elaborated in chapter 2. Literature about the past developments, different charging methods, scheduling and operation components are discussed in succession. Then, the methodology, including the research methods, the conceptual model, the assessment framework and the required data and tooling, is elaborated on in chapter 3. Following is the three model modules of the bus station operation model in chapter 4. Also the composition of the model variants are introduced, based on the charging mechanisms and development paths. The model is then used in an application in chapter 5. A bus station at Schiphol airport is considered in this application. Then, in chapter 6, the model and model results are discussed. Finally, in chapter 7, conclusions are drawn and recommendations for stakeholders and for further research on this topic are provided. Appendices are included in the back of the report. In the text is referred to these appendices.

# 2. Literature review & State of the art

This literature review and state of the art chapter has a dual purpose: 1) the current state of development is determined, 2) important model settings and parameters are derived. This chapter starts with an introduction, followed by an elaboration of the past and current developments of electric buses, as well as their batteries, in section 2.2. This is followed by section 2.3, where different types of charging infrastructure are elaborated. In section 2.4 and 2.5, the scheduling and operations of electric vehicles are discussed in succession. Finally, the conclusions of the literature review are drawn in section 2.6.

## 2.1 Introduction

Oil supply uncertainty, growing mobility demand, and increasingly stringent regulations on pollutants and carbon footprint are expediting a paradigm shift towards sustainable transportation (Hu, et al., 2013). According to several researches and experts, electric driving will be the future, both for private driving and in public transport (Cruw-Zambrano, et al., 2013; Sadeghi-Barzani, et al., 2014; Jang, et al., 2016; UITP, 2016). The majority of literature on this topic evolves around electric private vehicles, while the electrification in public transport is in a less progressed stage (EVConsult, 2016). Laizans et al. (2016) mentioned that buses are potentially even a better market for electric applications, because the operational expenses accounts for much higher proportion than for private owned cars. Multiple electric bus charging methods are available, however a comparing study of different charging methods and the usage of them has never been made.

Stimulated by the climate agreement of Paris (2015), several national sustainable transport goals are developed worldwide. To promote wide-spread adoption of electric vehicles, various government organizations are providing support for installation of charging infrastructure in various countries and encouraging the adoption of electric buses for city transportation (Topon & Hisashi, 2014). In the Netherlands, the zero-emission agreement was introduced in 2016. The goal of this agreement is that all new manufactured buses from 2025 and onwards, should be zero-emission vehicles (Government of the Netherlands, 2016). Moreover, all signed parties should strive for 100% emission free bus transport by 2030 (Buitelaar, 2016).

## 2.2 Developments of electric buses

Nowadays, a lot of electric buses are already in operation worldwide and this number is growing fast. In this section, the operational electric buses worldwide, in Europe and in the Netherlands are discussed first, followed by a subdivision in electric vehicle types. After that the battery technology developments are elaborated on.

### 2.2.1 Operations of electric vehicles in public bus transportation

In 2015, approximately 173,000 electric buses were in operation worldwide. 98,3% of this total global electric fleet size operate in China, which makes it the leader in the electric public bus transport market. These developments are strongly endorsed by the Chinese government, which includes an official program for 'new energy buses'. The Asia-Pacific region is therefore home to some of the biggest bus and battery producers in the world (UITP, 2016). The European market is one of the leading regions for electric bus research and development. Also in Europe, multiple cities are providing electric public bus transport services. The systems used in 90 different European cities, are analysed in the E-bus Reports (Figure 2-1). These reports are results of the ZeEUS (Zero Emission Urban bus System) project coordinated by the UITP (Union Internationale des Transports Publics). The ZeEUS partners tested electrification solutions of the urban bus system and facilitated the market of electric buses in Europe.


*Figure 2-1 - Analysed electric urban bus systems in Europe (2016). Source : UITP (2017)*

The Netherlands are very progressive in the electrification of public bus transport. The last few years, the Netherlands has changed into an experimental garden for electric buses (RTL Z, 2017). The share of electric vehicles increased from 1% (61 vehicles) of the total fleet in 2016 to almost 6% (280 vehicles) in 2017 (CROW-KpVV, 2017). So far, China is the only country with faster developments in the electric bus transportation market.

Topon and Hisashi (2014) name the cost of the buses as well as the installation cost of infrastructure as the major hurdle for large-scale adoption of electric bus vehicles. Therefore, they expect that a bus operator may introduce a small number of electric vehicles first before transitioning completely to an electric fleet. In Utrecht, a phased introduction of electric vehicles has taken place. On one busline, half of the operating vehicles were replaced with electric vehicles. After a period of two months the complete line operations, consisting of ten vehicles, were electrified (Scholtes, 2017). In the contrary, in Eindhoven, they directly implemented an electric fleet of 43 vehicles (Stroecken, 2017). In Amstelland Meerlanden, the largest electric fleet of Europe, consisting of 100 electric vehicles will be implemented in April 2018 (de Winter & de Bruijn, 2017). A complete overview of electric vehicle operations in the Netherlands is shown in Figure 2-2.


*Figure 2-2 - Locations of electric vehicles in operation in the Netherlands*

### 2.2.2 Electric vehicle types

Yet, electric buses face challengers including: (1) heavy battery packs, (2) high battery costs, and (3) the inconvenience and time requirements for charging (Bi, et al., 2015). For the period of improving battery technology of electric vehicles, hybrid electric vehicles were seen as good alternative (Tzeng, et al., 2005). A hybrid electric vehicle is defined as a vehicle with the conventional internal combustion engine and an electric motor as its major sources of power. For pure electric vehicles, the following distinction can be made: (1) trolleybuses; (2) fuel cell buses; (3) battery electric buses (Table 2-Table 2-11).

*Table 2-1 - Different types of electric vehicles including some of their basic properties*

| | Hybrid vehicles | Full electric vehicles | | |
|---|---|---|---|---|
| | | **Trolleybuses** | **Fuel cell buses** | **Battery electric buses** |
| **Traction system** | Diesel and electricity | Electricity | Electricity | Electricity |
| **Energy supply** | Combustion engine and electric motor | Overhead wires | Hydrogen for generating electricity on-board | Battery to store electricity on-board |
| **Costs** | Vehicles around €400,000; 2X conventional bus | Expensive infrastructure | Vehicles around €800,000; 4X conventional bus | Vehicles around €400,000; 2X conventional bus |
| **Limitations** | Not complete zero-emission | Bound to certain tracks, visual landscape pollution | Limited hydrogen fuelling stations | Limited range |

*Based on Rogge et al. (2015) and van Gompel (2017)*

In the Netherlands, one trolleybus system is in operation, located in Arnhem. In Eindhoven, Rotterdam, Apeldoorn and in Groningen/Drenthe, some fuel cell/hydrogen vehicles are in operation. The two vehicles operating in Groningen and Drenthe are transported to Helmond on a semi-trailer for refuelling, because there are only two hydrogen fuelling stations in the Netherlands: One in Rotterdam and one in Helmond (van Gompel, 2017). This is an important limitation on fuel cell vehicle usage.

Operational buses have different sizes and passenger capacities. The ZeEUS partners analysed 125 different types of electric buses in 90 cities spread over 22 different European countries. According to this study, the most common vehicle lengths are 10, 12 and 18 (articulated bus) meters or lengths close to those values. The number of bus types in the European E-bus research per vehicle length, including their average total passenger capacity, are shown in Table 2-2.

*Table 2-2 - Vehicle lengths and average total passenger capacity of electric buses in Europe (2017).*

| | 10 meter | 12 meter | 18 meter |
|---|---|---|---|
| **Range** | 9 – 11 m | 11 – 13 m | 17 – 19 m |
| **Number of bus types in research** | 17 (14%) | 90 (72%) | 12 (10%) |
| **Average passenger capacity** | 63 | 77 | 130 |

*Based on UITP (2017)*

### 2.2.3 Battery properties

According to the multi criteria analysis of alternative fuels of Tzeng et al (2005), battery electric vehicles could be the best alternative-fuel option if the cruising distance of the electric bus extends to an acceptable range. What the acceptable range exactly is, depends on local circumstances. Dutch electric bus developer Ebusco, has vehicles operating for a whole day at one single charge in some Scandinavian cities (de Bruijn, 2013). The range of that particular vehicle is already enough to operate there a whole day without recharging during the day. However, this is not the case in Utrecht, were the same vehicle type has to cover 350 kilometres a day in comparison to 230 kilometres in Helsinki (Scholtes, 2017). The maximum range of an electric vehicle is mainly determined by the battery storage power. In practice, different battery storage power is used, varying from a few kWh to more than 350 kWh. The last years, a lot of improvements in battery technology and battery storage power have taken place. On 19 September 2017, Proterra set an all-electric record by traveling 1100 miles (1770 km) with an electric bus, the Proterra Catalyst E2 Max on a single charge (Lambert, 2017). Given the current state of battery development and the growing demand of more efficient batteries, further improvements in battery technology are expected the upcoming years (Adesanya-Aworinde, 2017).

The lithium-ion (Li-ion) battery is the type of battery that is used for most electric vehicles (van Kooten Niekerk, et al., 2017). Homogeneous battery use is relevant, because a charger for one type of battery is usually not capable of charging another type. Besides the high investment costs and charging time requirements suggested by Bi et al. (2015), Lukic and Pantic (2013) also mentioned the charge rate limitations and capacity degradation as main issues of Li-ion batteries. To limit the capacity degradation and extend the duration of the battery's life, most battery manufacturers recommended to avoid full charging and deep discharging the battery pack (Topon & Hisashi, 2014). Therefore, it is recommended to define a maximum charging rate and a maximum Depth of Discharge (DoD) rate for the battery. Especially the DoD is a relevant factor, because discharging a battery fully, time after time will dramatically reduce its lifetime (van Kooten Niekerk, et al., 2017). This battery lifetime is mostly described in number of full charging cycles. According to van Kooten Niekerk et al. and Rogge et al. (2015), the end of life of a Li-ion battery is usually when a remaining capacity of 80% of the original capacity is reached. When the internal resistance doubled first, this will bottleneck the end of life of the battery. The battery lifespan is typically much shorter than the lifespan of the vehicle, according to Zeng et al. (2014), around 5 years.

Furthermore, the charging task itself is not a complete linear process. When a battery is completely empty, it takes half of the charging time to reach a battery load of 80%, while the other half is needed to charge the remaining 20%. This has to do with charging power, which should be reduced at a battery load of 80% in order to not overheat the battery (van Kooten Niekerk, et al., 2017). If the battery temperature becomes too high, the battery management system (BMS) stops the charging activity automatically (Veenendaal & Naber, 2017). In practice, fast charging is often limited to 80% of the battery capacity. Based on this and the minimum DoD rate, Figure 2-3 shows the battery capacities for both slow and fast charging cases.

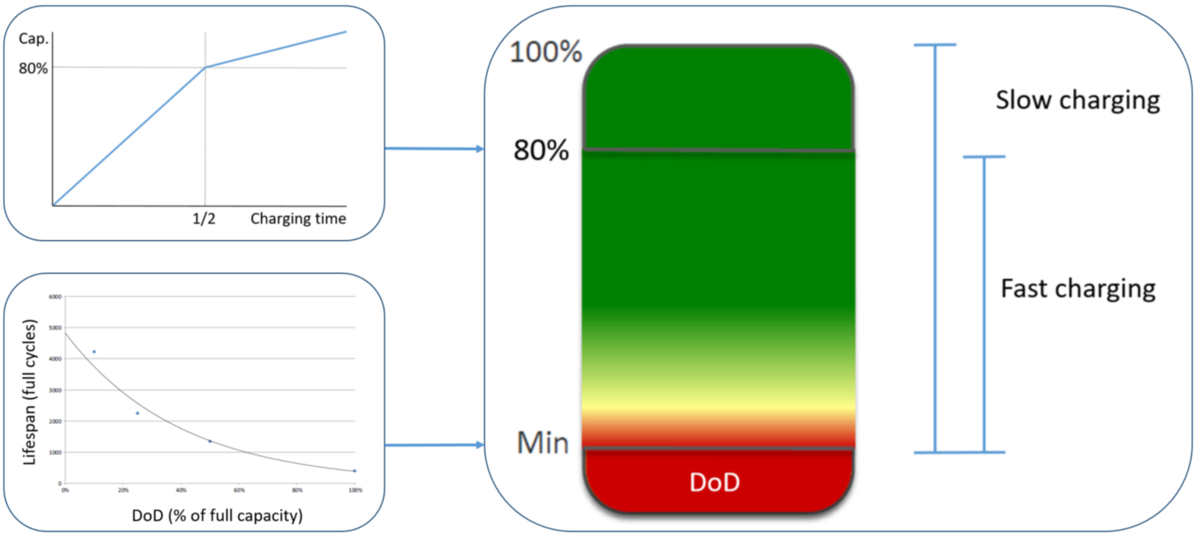



*Figure 2-3 - Practical useable battery capacity for slow and fast charging. Based on van Kooten Niekerk et al. (2017), Battery university (2017) and Touzin (2017)*

Another relevant variable affecting the battery capacity is the temperature. When the temperature of the battery is either low or very high, the capacity can be reduced drastically, by tens of percents (van Kooten Niekerk, et al., 2017). In that case, the battery should be cooled or heated.

### 2.2.4 Battery downsizing

As mentioned before, heavy battery packs and high battery cost are two of the main challenges electric buses have to deal with. 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 (Bi, et al., 2015). Both percentages decrease when smaller batteries are used, or in other words, when the batteries are downsized. Hu et al. (2013) names the following advantages of battery downsizing: vehicle light weighting, fuel economy improvement, reduced energy consumption and emissions in battery production and potential reduction in use-phase electricity consumption for a pure electric vehicle. A lighter bus will consume less energy to cover daily travel distance, which results in secondary downsizing of the battery. According to Hu et al., 10% vehicle mass reduction results in about 5% energy reduction for a conventional bus. Moreover, less space for the battery pack means more space for passengers. However, battery downsizing results in shorter covering distances on one full battery pack. Extra charging time should therefore be taken into account. Moreover, Hu et al. (2013) found that battery downsizing has an apparent negative effect on the recuperation and fuel-to-traction efficiency of the vehicle (Figure 2-4). Therefore, the so-called C-rate of the battery should be low. The C-rate indicates the time at which a battery is discharged, relative to its maximum capacity. If the battery is too small, the C-rate will be high and the battery will degrade faster (Bi, et al., 2015). This trade-off between battery downsizing and energy efficiencies could also be described as a trade-off between purchase cost and operating cost, considering the total ownership cost (TCO) (Hu, et al., 2013). Another reason to limit the battery downsizing is to make sure that there is enough storage capacity for the battery as a precaution for unexpected situations.

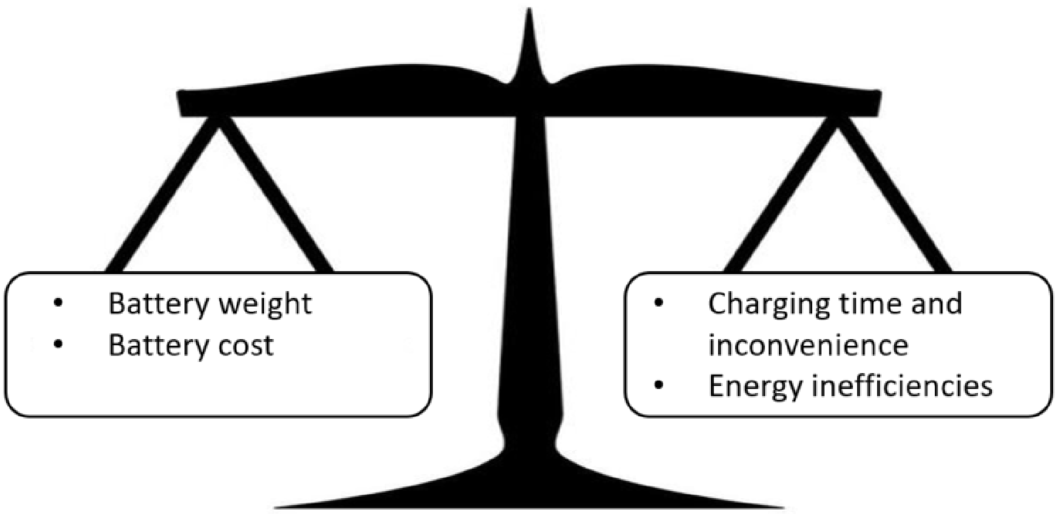
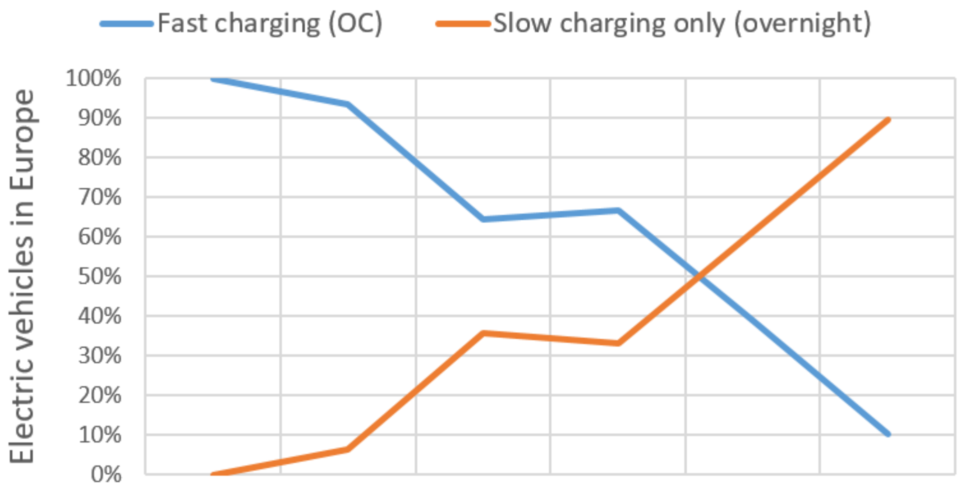



*Figure 2-4 - Trade-off for battery downsizing. Based on Bi, et al. (2015)*

Battery downsizing results in lower battery storage power. Therefore, the batteries should be charged more often during the day. When the charging process takes place within a relatively short amount of time, it is called fast charging. The distribution of battery storage power of the researched European electric buses in the ZeEUS E-bus Reports, is shown in Figure 2-5, including the shares of slow charging during the night only and fast charging, per storage power range. For fast charging (mostly combined with overnight charging), relatively low storage power batteries are used often, while the use of higher storage power batteries increase when the batteries are only charged by night.




| | < 50 | 50-100 | 100-150 | 150-200 | 200-250 | > 250 | Total |
|---|---|---|---|---|---|---|---|
| # electric vehicle types | 19 | 31 | 14 | 12 | 18 | 29 | 123 |
| Percentage | 15,4% | 25,2% | 11,4% | 9,8% | 14,6% | 23,6% | 100,0% |

Battery storage power (kWh)

*Figure 2-5 - Battery storage power in relation to slow and fast charging of electric buses in Europe (2017). Based on UITP (2017)*

## 2.3 Charging methods for battery electric buses

For bus transport, there is a trend that vehicles are developed in such a way that charging infrastructure can be adapted to specific customer needs (APPM management consultants, 2014), which depend 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. Just in the Netherlands, there are large variations: In Schiermonnikoog and Rotterdam, they charge slow at the depot; in ‘s Hertogenbosch and Schiphol, they charge fast at selected bus stops and slow at the depot; In Utrecht, they charge fast at the terminal and slow at the depot and in Eindhoven, they charge both fast and slow at the depot (Figure 2-8) (UITP, 2016). For fast and slow charging, different charging methods and corresponding charging infrastructure/technologies exist, which are globally classified in Figure 2-6 and further explained in the remainder of this section. First, a subdivision in battery swapping (2.3.1) and in-vehicle battery charging is made. Then, slow (2.3.2) and fast (2.3.3) in-vehicle battery charging is distinguished. Fast charging is further subdivided into static (2.3.3.1) and dynamic (2.3.3.2) charging.

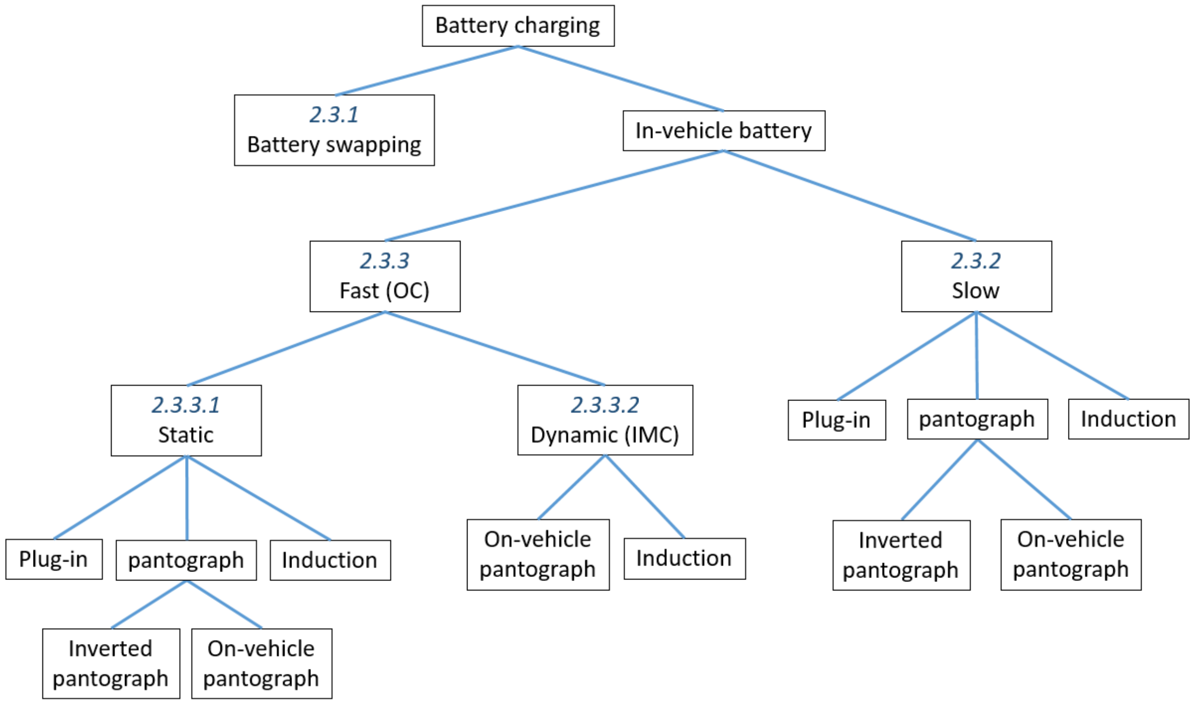



*Figure 2-6 - Subdivision of charging methods*

## 2.3.1 Battery swapping

The first division is made between battery swapping and battery in-vehicle charging. Battery swapping means that drained batteries are replaced with freshly charged ones. The advantage is that the vehicle does not have to wait at place till the battery is recharged. This makes the charging duration basically irrelevant (Phoenix Contact, 2013). Zheng et al. (2014) did a comparing study of electric vehicle battery charging and swap stations in distribution systems. They mention the following additional advantages of battery swapping: (1) The charging of batteries is centralized during off-peak periods (in the night) when the charging cost is low; (2) The provision of grid-support service in a centralized charging and discharging manner; (3) The charging of batteries in slow-charging mode to extend their lifetime; (4) The savings in cost of electric vehicles by providing batteries by operators. Zheng et al., concluded that battery swapping is more suitable for public transport in distribution systems than battery charging. They also provided an optimal planning for battery swapping. As counter argument on the fourth advantage, it should be mentioned that the battery is often the most expensive part of the vehicle, as mentioned in section 2.2.2 and 2.2.4. Therefore, Lukic and Pantic (2013) considered the costs for additional battery packs for swapping as one of the issues that battery swapping brings forth. Furthermore, they mention battery ownership and standardization issues and significant swapping infrastructure costs, like a battery swap station (Figure 2-7) as limitations.

Reuer et al. (2015) developed a solution approach for the electric vehicle scheduling problem, where they considered both battery charging and swapping. They considered 10 minutes as the breakeven point. For charging times longer than 10 minutes, they chose to swap the battery, instead of recharge the battery inside the vehicle. In Qingdao, an eastern Chinese city with 8 million inhabitants where the swapping technology is successively applied, it takes seven minutes for all the battery units of a vehicle to be swapped (Phoenix Contact, 2013).

*Figure 2-7 - Beijing's battery swapping station and quick battery exchange robot. Sources: Busworld (2013), Chao & Xiaohong (2013)*

## 2.3.2 Slow charging

Slow charging often takes place at the depot during the night by using a plug-in cable or a pantograph. In literature, different terminology is used, like slow, standard or overnight charging, however, they all indicate charging with a moderate charging power (Rogge, et al., 2015). Therefore, the time to fully charge the battery is relatively long, especially when the battery storage power gets high. At first sight, overnight charging seems to be the best option, because it simply enables vehicles to perform the trips according to the conventional timetable. Just the polluting diesel engine vehicles are replaced by sustainable zero-emission electric vehicles, which should be charged by night. However, some problems are involved. First, the battery technology is most of the time not sufficient to operate a vehicle a whole day without recharging. If the vehicle is able to do that, a high battery capacity and a high weight of the system is required. This is relatively expensive, both in investment and operation (Rogge, et al., 2015). Secondly, when all vehicles are plugged-in at night and should be recharged completely after a full day of operation, a huge load on the electricity grid arises. To deal with the first problem, an oversized fleet can be purchased or overnight charging can be combined with fast charging. From the 125 electric bus types researched by UITP (2017), 59 types make use of both charging methods, while 48 types only charge by night.[1] In order to reduce the pressure on the electricity grid, overnight charging can be performed with relatively low energy levels. (On-vehicle) Pantograph and induction charging are theoretically also possibilities for slow charging, however they are more valuable for fast charging.

***Case: Eindhoven, the Netherlands***

In Eindhoven, an oversized fleet was purchased. The fleet consists of 43 electric vehicles, of which a maximum of 33 vehicles are in operation at the same time (Stroecken, 2017). 36 inverted charging pantographs are inside the depot to recharge the vehicles in five to seven hours during the night. This time is used in order to reduce the load on the electricity grid. There are also 6 charging points in front of the depot, which are used during the day to recharge vehicles in 10 to 20 minutes with much higher power (Figure 2-8). When the maximum number of vehicles are in operation, seven vehicles will be out of rotation for charging.

[1] The remaining 18 vehicle types only use opportunity charging.

*Figure 2-8 - (Charging) depot in Eindhoven. Photo (Wiercx)*

### 2.3.3 Opportunity charging

Opportunity charging (OC) is the fast charging process of an electric vehicle along the route. In contradiction to overnight charging, the use of the conventional timetables could already be possible with the current battery technology. Opportunity chargers use mainly the regular dwell time at the stops. Therefore, a strong linkage between the vehicle scheduling and the infrastructure planning is necessary (Rogge, et al., 2015). Furthermore, batteries could be downsized and in general, the overall pressure appealed on the electricity grid is lower, due to more dispersion of charging activities over the day (Jacobs, 2016). In contradiction to the positioning of charging stations for passenger cars, where consumer behaviour is predicted in order to get information on demand, the positioning of those stations for public bus transport is much easier, because the operating conditions of the energy consumers are well known. The vehicles have a fixed route and the dwell time can be estimated based on the timetable and an expected delay. The longest dwell time is usually located at the terminal stops (a bus stop located at the end of a line). Here, delays can be compensated and the bus driver can have a break according to the regulations of driving time. When the vehicles next trip is at the same line, theoretically, there are no passengers inside the vehicle during its waiting time. Furthermore, the terminal stops are often located outside the city centre, where it is easier and cheaper to construct charging infrastructure. Therefore, the terminal stops are highly suitable locations for fast charging stations (Rogge, et al., 2015). Fast charging can also take place at bus stops on the track and in the depot.

#### *2.3.3.1 Static opportunity charging*

**SOC1: Pantograph**

A pantograph is a power purchaser which can be implemented in the vehicle (on-board) or in the form of a pole bending over the vehicle (inverted) (Schunk, 2015). This roof charging system provides power transmission through four contacts between the energy supplier and collector. Furthermore, underbody pantograph charging systems exist (Bouhuijs, 2014). Pantograph charging is also named as conductive charging in literature. In Eindhoven, inverted pantographs are used for slow and fast charging. An on-vehicle pantograph is especially interesting for an operator when there are already wires available, for instance in cities where trams are operating. In The Hague and Utrecht, in 2017, a pilot took place where a pantograph on the electric vehicle was coupled to the wires of the tram system for energy transmission. The full battery range of those vehicles is 50 kilometres and considering the average speed of the vehicles in an urban environment, the vehicle will be charged completely within 15 minutes. The vehicles use the surplus of braking energy generated by trams (Jacobs, 2017). Besides this efficient use of energy, another advantage is that the power supply is in own management, so there will be one stakeholder less in the complex stakeholder field.

***Case: Vienna, Austria***

The two electric vehicles operating in The Hague and Utrecht came from Vienna where the ElectriCitybusse (Figure 2-9) was introduced on two inner-city bus lines in 2012. Twelve electric vehicles are in operation in Vienna. Due to difficulties in obtaining a planning and building permits for new power lines or charging stations in the historic centre, Vienna decided to use the extensive existing network of overhead tram power lines to recharge the vehicles at their end stations by using an extendable pantograph. Maximum 30% of the batteries' power is used for each trip, so each charging process only lasts five to eight minutes. The quick recharging allows the use of relative smaller batteries, which make them less expensive (Wiesinger, 2014). The costs per pantograph construction were €90,000, while the charging points at the bus depot, used for overnight charging, cost €320,000 altogether.


*Figure 2-9 - ElectriCitybusse in Vienna. Source: rail.cc (2017)*

**SOC2: Induction**

Inductive or wireless charging uses a charging point with a source coil embedded in the road, for example at a bus stop. In the bottom of the vehicle, a receiver is implemented. When the bus stand still at the stop, the charging infrastructure in the road and the receiver in the vehicle make a wireless connection used for power transfer. The whole dwell time at the stop can be used to charge the vehicle (Bi, et al., 2015).

Lukic and Pantic (2013) mentioned that induction charging is safer than plug-in charging, because it takes place automatically without the user having to plug-in and remove cords and cables. This also speeds up the charging process. Moreover, the inductive charger has low maintenance requirements and inductive charging provides Dutch companies an opportunity to stay on top of charging infrastructure development (APPM management consultants, 2014). However, the electromagnetic emissions of the charger must be considered in the system design. The induction charging power and distance at which energy can be transferred are limited by the well-established standards on magnetic emissions. A practical advantage of induction charging infrastructure is that it can be applied everywhere in the city without having a license, because the charging infrastructure will be close to the ground surface (EVConsult, 2016), in contradiction to pantographs. For this charging method, it is possible, as far as local circumstances make it possible, to obtain electricity from a metro network. This possibility also exist for (underbody) pantograph charging. In Mannheim, Germany, there is an inductive charging system using energy from the tram supply network, like in Vienna, to completely recharge the two electric vehicles at the depot in 14 minutes (UITP, 2016).

Bi et al. (2015) compared the life cycle energy and greenhouse gas emissions for an electric bus system of wireless and plug-in charging. A case study in Michigan was performed. They concluded that the life cycle greenhouse gas emissions of wireless charging could be 6.3% less compared to plug-in charging considering the same efficiency rates. Also, the wireless charged battery pack can be downsized to 27–44% of a plug-in charged battery pack. This results in lower prices for electric vehicles. However, the charging efficiency of inductive charging (85%) is lower than for plug-in charging (90%). Furthermore, they also mentioned that wireless charging may pose challenges for the electric grid. Besides, the inductively charged battery may degrade faster, so battery replacement may be more frequent.

***Case: Torino, Italy***

In Torino, wireless charging points along bus routes on two of its lines have been used for more than 10 years (Figure 2-10). The battery is fully charged overnight and topped up during the day by about 10 – 15 percent along the route. With two charging points on the route, recharging takes place in 10 – 12 minutes. The inductive charging (under)ground system (primary coil) costs about €120,000, while the inductive recharging system (secondary coil) inside the vehicle costs about €16,000. In total, 15 electric vehicles are in operation for 13 hours a day (Salucci, 2015).


*Figure 2-10 - Inductive electric vehicle charging at a bus stop in Torino. Source: Salucci (2015)*

**SOC3: Plug-in**

Plug-in charging is mostly used for slow charging. For fast charging it is also an option, however it is not as efficient since someone has to plug-in and -out the electricity cable and high charging power (higher than 150 kW) through a cable is technically not possible (Veenendaal & Naber, 2017). Therefore, opportunity plug-in charging often takes place for a relatively long time, around one and a half to three hours and with relatively low (in terms of OC) charging power.

#### *2.3.3.2 In-motion charging*

An answer to the charging time problems of electric vehicles, is the use of dynamic (in-motion) charging. In-motion charging (IMC) is a concept that is still in its infancy stage (Lukic & Pantic, 2013), but is nonetheless a very promising option for the future.

**IMC1: In-vehicle pantograph**

A vehicle using a wire in a dynamic way is better known as a trolleybus. However, there are new innovations, making it possible to "transform" a wireless electric vehicle for a certain distance in a trolleybus. In other words, an electric vehicle is charged over a certain distance by a roof charging system, while driving. Therefore, it is needed to implement the charging technology on the vehicle. For this form of IMC, a catenary wire is needed on 30 to 35% of the bus route (van Kerkhof & Joanknecht, 2017). This expensive infrastructure costs about €700,000 per kilometre, varying between €440,000 and €870,000 per kilometre (Centrum Vernieuwing Openbaar Vervoer, 2005). For Arnhem this is an option worth considering, because they already have the catenary wire network in the city. At the end of the lines, buses will drive wireless into the region (Stroecken, 2017). Nowadays, two dual-mode vehicles, operated both in trolleybus mode and in battery mode are tested in Arnhem till 2020 (Euregio Rijn-Waal, 2016). This IMC method is also an option worth considering for Amsterdam. There, they can use the energy from electricity stations of the tram to feed the vehicles. It is not possible to feed an electric vehicle by the catenary wire of the tram system in a dynamic way, because the energy remittance of a tram system takes place via the rail. Therefore, the infrastructure investments will be substantial for Amsterdam.

**IMC2: Induction**

Inductive charging can also be applied in a dynamic way. A lot of research is done on this topic, because it is an interesting option for electric cars as well as buses. However, currently, wireless charging has been mostly demonstrated on vehicles with fixed routes, such as public transit buses (Suh & Gu, 2011). Theoretically, mixed usage is an opportunity, since a large number of vehicles and different vehicle types use the same road segments that can be dynamic-charge enabled. Already three commercial bus applications of wireless IMC are introduced, all applied for shuttle bus services in China (Jang, et al., 2016) (Figure 2-11).

For inductive dynamic charging, the vehicle battery can be further downsized, which result in lower prices for the vehicles (Bi, et al., 2015). Moreover, the hindrance in public spaces is limited, because all charging equipment is embedded in the road and no charging infrastructure at bus stops or terminals is needed. On the other hand, wireless dynamic infrastructure is relatively expensive (yet). According to research conducted at the TU Delft, inductive charging infrastructure costs 300,000 – 500,000 euro per kilometre (APPM management consultants, 2014). The system efficiency of dynamic induction charging is 70%, while it is 90% for static induction charging (Lukic & Pantic, 2013), which means that there is still substantial room for improvement.


*Figure 2-11 - Wireless in motion charged campus shuttle on the KAIST campus, China. Source: Jang et al. (2016)*

Instead of serving as a consumer only, buses can also function as inductive energy supplier for other electric vehicles. Maglaras et al. (2015), presented this new concept: Inter-Vehicle Communications (IVC) for Mobile Energy Disseminators (MEDs). Buses can play the role of MEDs since they follow predefined scheduled routes and their paths cover a major part of a city (Figure 2-12). To realise this concept, more charging locations along the bus route are necessary, because the vehicles should charge enough to perform their own operations and their energy supplier function. For the bus operator, a certain margin of profit should be on the supplied energy in order to see IVC for MED as interesting option.

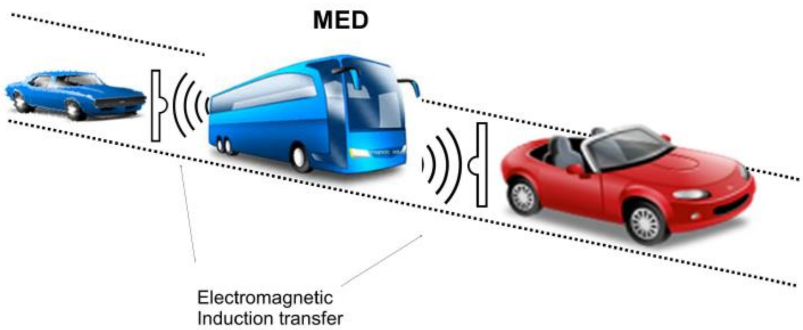



*Figure 2-12 - The use of an electric bus for the IVC for MED concept of Maglaras et al. (2015)*

## 2.4 Scheduling electric vehicles

The characteristics of different charging methods lead to differences in (charging) scheduling of electric vehicles. First, general vehicle scheduling is introduced, followed by some uncertainties in the operation, which should be considered in the electric vehicle scheduling process. Finally, the electric vehicle scheduling principles are elaborated on.

### 2.4.1 Vehicle scheduling

Scheduling vehicles is an important task for public bus transport operators, usually carried out by transport planners. Vehicles should be assigned to a given set of timetabled trips, considering practical requirements like depot locations and different types of vehicles. An optimal vehicle schedule is characterized by minimal fleet size and minimal operational costs (Bunte & Kliewer, 2009). Bunte and Kliewer presented different model approaches for different kinds of vehicle scheduling problems (VSP). They start with a basic model, the minimal decomposition model, based on covering all trips with a minimum number of vehicles. Then, they introduce extensions of the basic model, by also considering operational costs, deadheading times and multiple depots, which result in new, more complex models. However, those models result in more realistic model results for a larger variety of cases.

In practice, at the end of a trip, vehicles will often continue operations at another line than the line they served before. Sometimes this is regulated by the authority and sometimes done in order to eliminate a common transfer (Veenendaal & Naber, 2017). According to Visser (2017), RET always chose the option with the lowest waiting times for the vehicles in order to minimize the operational costs. If that means that a vehicle continues operation at another line, vehicles will be scheduled in that way. The only exceptions are: 1) lines where often (sizeable) delays occur in order to prevent spillback of delays towards other lines and 2) lines where specific vehicle types operate, like the lines towards Rotterdam-The Hague airport, where more luggage capacity is included in the vehicles.

### 2.4.2 Operation uncertainties affecting vehicle schedules

The battery load of an arriving vehicle at a charging station can be estimated, based on several line characteristics. This expected battery load is used for charging scheduling of electric vehicles. However, there are several sources of uncertainty affecting the expected battery load. The energy consumption rate (and arrival time) of an electric vehicle depends on multiple factors, like number of passengers, weather conditions and traffic conditions (Topon & Hisashi, 2014). For instance, a vehicle may be delayed due to bad weather conditions, while at the same time the energy consumption increased in order to heat the cabin. Also the driving style of the driver has a contribution to the energy consumption rate. Therefore, it is suggested to train drivers in driving an electric vehicle in a sustainable way (EBSF, 2017).

### 2.4.3 Electric vehicle scheduling principles

If an electric vehicle makes delay to arrive at a charging station or arrives with the remaining energy being lower than the estimated value, there is a possibility that the planned charging amount cannot be charged to the electric vehicle, and a judgment of rescheduling is needed (Topon & Hisashi, 2014). Van Kooten Niekerk et al. (2017) researched the scheduling of electric vehicles. They propose two models and solution methods: one basic model and one model that resembles practice much better, including every type of charging processes, actual electricity prices and depreciation cost of the battery. They conclude that properties of electric vehicles should be taken into account in order to not end up with an infeasible vehicle schedule. Often, extra vehicles are needed for a feasible vehicle schedule, especially when the operational hours increase. In the end, they recommended to do future work on integrating the properties of charging infrastructure in the model. This research will then focus on different charging infrastructure types, including different properties.

Rogge et al. (2015) did a feasibility study focusing on OC infrastructure and energy storage requirements. They conclude that a strong linkage between the vehicle scheduling and the infrastructure planning is needed in order to mainly use the regular dwell times at stops. Therefore, it is necessary to focus on entire vehicle schedules instead of focussing on individual trips. According to Topon & Hisashi (2014), the task of creating charging schedules of an electric vehicle consists of determining the appropriate charging locations and charging amounts for each electric vehicle. According to Reuer et al (2015), the positioning and the amount of charging infrastructure can be considered as stand-alone problem or integrated in the scheduling process using multi-criteria optimization. In the end, they found no significant correlation between the number of charging stations and the percentage of electric vehicles or the problem size. Rogge et al. (2015) mentioned that the difficulties are in the amount of charging infrastructure. In contradiction to the positioning of charging infrastructure for electric cars, the location choice for (fast) charging infrastructure for electric buses is more straightforward, since the operating conditions are well known.

## 2.5 Operations of electric vehicles

Both, the charging method choice and adapted vehicle (charging) schedules affect the operations of the public bus transport service. The main restrictions in optimizing the operations are created by the investment and operation costs and the energy supply. Those aspects are both elaborated in this section and the obtained, relevant values are summarized in respectively Table 2-4 and Table 2-6. Before that, a short introduction of public transport operations and bus station operations and modelling is provided in respectively section 2.5.1 and 2.5.2.

### 2.5.1 Public (bus) transport operations

According to van Oort (2011), public transport is able to ensure accessibility and liveability of our cities for future generations, even concerning the growing population and urbanization. Therefore, high quality of public transport should be provided in order to get a modal shift from car traffic towards public transport. Quality factors in public transport are described by the pyramid of Maslow (Figure 2-13), where the dissatisfiers must be sufficient in order to not discourage travellers for using public transport, while the satisfiers concern additional quality aspects. In the European Bus System of the Future (EBSF) project, it is stated that the bus service must be reliable, efficient, accessible (for everybody), easy to understand and user-friendly in order to satisfy the high service quality (EBSF, 2017). Improvements in dissatisfiers and satisfiers are included in order to improve the trip experience for the passengers, but result in higher costs for the public bus transport operator and/or authority.

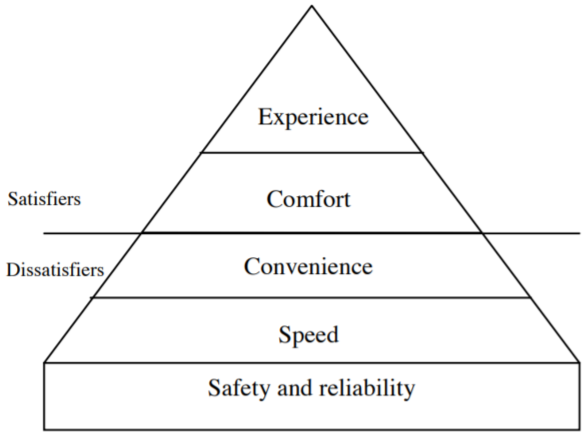



*Figure 2-13 - Pyramid of Maslow. Source: Van Oort (2011)*

### 2.5.2 Bus station operations and modelling

A bus station is normally used to refer to an off-road bus stop with at least basic facilities for passengers, such as shops or eateries. Especially in cities, the majority of passengers start and/or end their trip at bus stations. Bus drivers often take their breaks at bus stations, because in the Dutch general collective labour agreement for public transport, it is mentioned that at least some basic facilities should be available at break locations. Also minimum break duration is mentioned in this collective labour agreement (FNV, 2016) (Table 2-3). 'Bus terminal' is also used a lot in literature, which refer to the point where bus routes start and end (PPIAF, 2006). This can be a bus station, but it can also be merely a point in the road. At terminals, vehicles often wait a certain time before the next trip start. This buffer time tries to prevent delay continuation towards the next trip and is as well as the break durations, different per operator. HTM for example use a buffer time of five to six minutes (FNV, 2012), while the buffer time at RET vary between zero and five minutes (Visser, 2017).

*Table 2-3 - Minimum break duration in the Netherlands*

| Working time | 4 hours | 5.5 hours | 9 hours |
|---|---|---|---|
| **Minimum break** | 15 min | 30 min | 45 min |

*Source: FNV (2016)*

Bus stations are important aspects in the network. More information about bus station layout is included in Appendix B. According to Widanapathiranage et al. (2014), bus stations often control the line capacity, because they act as bottlenecks, at least in case of BRT (Bus Rapid Transit). The most important characteristics defining BRT are their high frequencies, relatively high operational speed and relatively long stop spacing and line lengths. Congestion may occur when buses manoeuvring into and out of the platform lane (especially in a DIRO case [see Appendix B]), hinder other buses or when a queue of buses forms upstream of the station, is blocking inflow. Hence, optimizing bus station operations could increase line capacities. For these optimization processes, bus station operation modelling tools are developed.

Basic bus station modelling aspects are discussed in Appendix B. Here, the Simbus simulation tool is discussed. Simbus is a bus station simulation tool, developed and used at Goudappel Coffeng. Originally, the simulation tool is developed in 2001 for a project concerning a new dynamic bus station at Leiden Central Station. Simbus has already been used for multiple bus station simulations in the Netherlands. Simbus generates trips according to the timetables and given dispersion. These trips are performed and Simbus determines the inter station vehicle route. To do so, Simbus assigns all vehicles to specific boarding and/or alighting platforms and possibly to long or short term buffer places. In general, the input for a Simbus simulation consist of the following components:

- Simulation variables
- Information about geometry of the bus station
- Information about timetables and its variations
- Information about desired line-platform combinations
- Information about transfer connexions
- Information about combined and conflicting lines

All input components are arranged in a 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. The exact arrival time, dwell time and buffer time per trip is shown in this file, as well as the occupation rates, the number of trips and the number of disruptions at each station component. For the output data, numbers, averages, standard deviations and minimum and maximum values are represented (Jägers, 2001).

### 2.5.3 Investment and operational costs

Laizans et al. (2016) compared initial investment costs and operational costs of a diesel engine vehicle and an electric vehicle, both serving urban public transportation systems. The comparison results show that large initial investments are involved when electric energy is being added/used. Purchasing an electric vehicle, cost about twice as much as a comparable diesel vehicle (Wiesinger, 2014). Also charging infrastructure is a substantial cost component. At the same time, operational costs, including energy costs, show an opposite picture. Especially with large annual distances covered, electrical energy is substantially cheaper. Laizans et al. also performed a case study in Latvia, where the initial investments of changing public transportation fleet to electric buses and the costs of battery replacement still outweighed the monetary advantages gained from lower operational costs and additional environmental benefits.

The purchase cost of an electric vehicle will probably decrease in the coming years, because it is expected that the costs of the relatively expensive battery packs will decrease in the near future. The Electric Power Research Institute (EPRI) identified three key cost dependencies: (1) cell size; (2) cell production volume; (3) standardization of battery components. The first dependency is already discussed in section 2.2.4: battery downsizing. The other two aspects are directly connected to the progress in the battery technology development. Since a large progress in the technology development is expected in the near future, the costs of the batteries, and therefore the electric vehicle cost in general, will decrease fast (Figure 2-14) (California Air Resource Board, 2016).

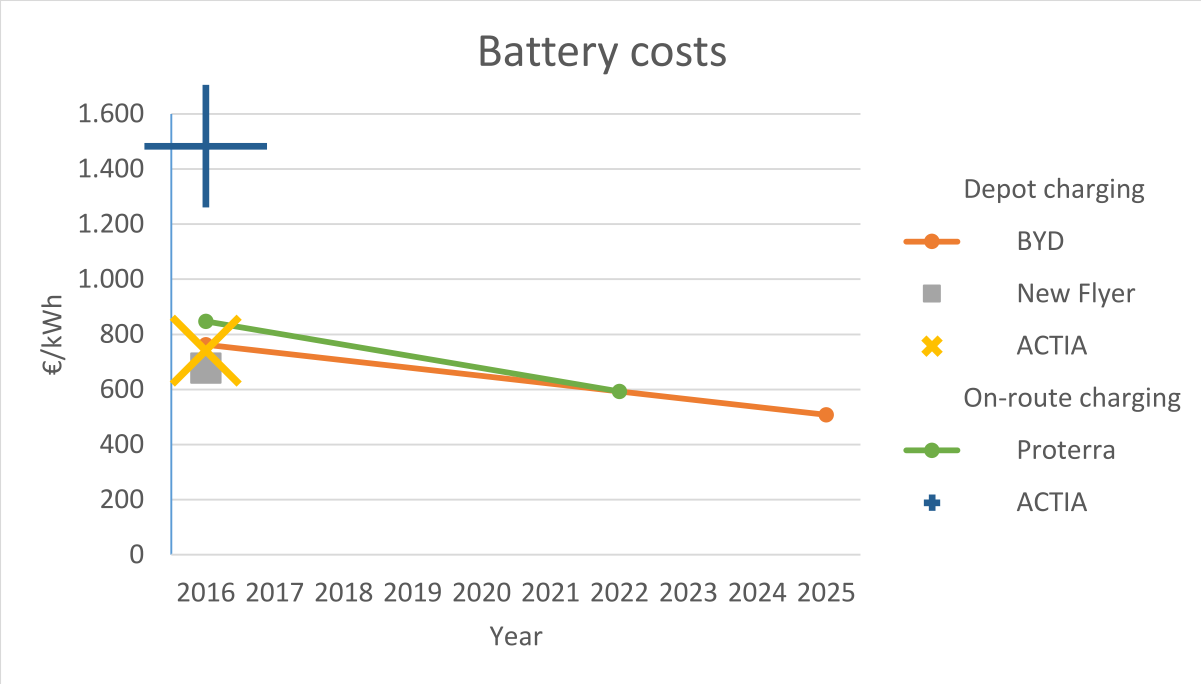



*Figure 2-14 - Battery cost estimates and projections and their ranges from different sources.* Exchange rate: $1.00 = €0,8472. *Based on California Air Resource Board (2016).*

Reuer et al. (2015) mentioned a trade-off between the number of electric vehicles and the number of necessary charging stations, both fixed costs for public transport companies. The main aspects determining the costs for a charging station, according to van Kooten Niekerk et al. (2017) 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. Values for those variables obtained from literature are summarized in Table 2-4.

*Table 2-4 - Literature based values for important cost variables*

| Cost aspect | Range | Main dependencies |
|---|---|---|
| Vehicle | €400,000 - €450,000 | Vehicle length, producer |
| Battery | €635 - €1,694 / kWh | Manufacturer |
| **Charging station** | | |
| Ground prices (the Netherlands) | €20 – €3,600 / $m^2$ | Location |
| Charging equipment | €25,000 - €150,000 | Charging method |
| Energy | €0.05 – €0,43 / kWh | Time of day, VAT |

*Sources: de Groot, et al. (2010), Wiesinger (2014), Zheng, et al. (2014), California Air Resource Board (2016),* Gudde (2016), *Heliox (2017) and Stravens (2017)*

## 2.5.4 Energy consumption

According to Cooney et al. (2013), improvements in battery technology reduce the life cycle impacts from the electric bus, but the electricity grid makeup is the dominant variable. The electricity grid sets certain limitations for the charging power. In the feasibility study for OC by Rogge et al. (2015), charging powers from 100 kW to 500 kW in steps of 100 kW are taken into account. This subdivision reflected the available systems in the market at that time. Nowadays, fast charging systems with charging power up to 600 kW (Heliox, 2017) and even 1000 kW (UITP, 2017) are available. Beuchat Beroiza did research in order to prepare a zero-emission fleet at RET in Rotterdam. He stated 150 kW as lower boundary for charging power, because for lower power, vehicles are not able to charge during the night and may begin the next day without full charge. 300 kW was his upper boundary, because for higher power, almost no improvement is observed in the number of feasible blocks. In practice, very low charging power, like 30 kW is often used for overnight charging, for instance in Eindhoven (Heliox, 2016). Regular charging power, sufficient for most trips, is around 200 kW. Higher power will be more expensive and result in higher pressure on the electricity grid. Especially when multiple vehicles charge at the same time, for instance by night, charging with relatively high power will cause problems (EVConsult, 2016). The energy efficiency for charging a battery depends on the charging method. This efficiency can vary from 70% for dynamic induction charging to 99% for off-vehicle battery charging (battery swapping) or some types of pantograph charging.

According to Cooney et al. (2013), policy makers must consider regional variations in the electricity grid for the use of battery electric vehicles. Based on practical experiences, it is mentioned that an efficient time planning for charging and power use, could result in 15% lower electricity costs (Jacobs, 2017). Zheng et al. (2014) mentioned that optimal control of charging and discharging processes can help balance the supply and demand of the grid. Therefore, in Utrecht, they will start a pilot where the remaining battery load is returned to the electricity grid at the end of the day. In this way, the electricity grid gets extra electricity at the end of the evening, when the electricity demand is high. During the night, when the electricity demand becomes lower, the vehicles can be charged, so that the vehicle is fully charged when it has to start its operations the next day (RTL Z, 2017).

The energy consumption of an electric vehicle is another important aspect. Electric vehicles in the E-bus Reports have a varying energy consumption from 0.25 to 2.9 kWh per kilometre, with an average of 1.23 kWh per kilometre (UITP, 2017). The Brno Public Transport Company tested the energy consumption of some electric vehicle types in real operation in Brno, Czech Republic (Cerny, 2015). Their results are shown in Table 2-5. In comparison to the theoretical energy consumption, the practical energy consumption is affected by different network characteristics, influencing the amount of acceleration and deceleration. According to Veenendaal & Naber (2017), the energy consumption of urban bus transport is higher than the energy consumption of regional bus transport. However, this difference is smaller compared to the fuel consumption differences between urban and regional diesel engine vehicles, because an electric vehicle recovers some of its braking energy, which is more beneficial in an urban environment.

*Table 2-5 - Average energy consumption of four different electric buses*

| Electric vehicle type | Length | Passenger capacity | Average consumption |
|---|---|---|---|
| **SOR EBN 10.5** | 10.5 m | 85 | 0.9 kWh/km |
| **AMZ CitySmile 10E** | 10 m | 85 | 1.1 kWh/km |
| **Siemens Rampini (Vienna)** | 7.7 m | 46 | 1.3 kWh/km |
| **Skoda Perun** | 12 m | 82 | 1.3 kWh/km |

*Source: Cerny (2015)*

Concerning the average consumption in Table 2-5, it should be mentioned that the electric energy for the SOR EBN 10.5 is only used for driving, while diesel is used for heating. For pure electric vehicles, heating and cooling the vehicle require extra energy. According to Beuchat Beroiza (2017), the unit for cooling the cabin is the second largest on-board energy consumer under conditions of very high ambient temperatures and high solar radiation. When the automatic cooling unit was turned on, the battery consumed between 10% and 17% more energy (Zhou, et al., 2016). Suh et al. (2014) 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. The different energy aspects described here, are summarized in Table 2-6.

*Table 2-6 – Literature based values for important energy related variables*

| Energy aspect | Range | Main dependencies |
|---|---|---|
| **Charging power** | 30 - 1000 kW | Charging method (slow / fast) |
| **Energy efficiency** | 70 – 99% | Charging method |
| **Energy consumption** | 0.25 – 2.9 kWh/km | Vehicle weight, route characteristics |
| **Heating & cooling (% of battery capacity)** | Heating: 10 – 21,4%<br>Cooling: 18.8% | Temperature of the environment |

*Sources: Lukic & Pantic (2013), Suh et al. (2014), Zhou et al. (2016) Battery university (2017) and Heliox (2017)*

## 2.6 Conclusions

In this chapter, scientific and practical literature about electric buses and their charging methods, scheduling principles and operations are elaborated on in order to understand the operations and derive model variables for modelling bus station charging activities. Till now, a comparison study of different charging methods has never been made, but this will be an important first step in the standardization of charging infrastructure, needed for wide application of electric vehicles.

Worldwide, electric vehicles are in operation in (urban) public bus transportation systems, of which, the largest part in China. The share of electric vehicles is growing rapidly, caused by politic pressure on more sustainable (public) transport and improvements in battery technology, which results in longer ranges of electric vehicles. On the other hand, especially in Europe, the use of OC is also growing, which makes battery downsizing possible. Therefore, ranges become shorter, but batteries - and therefore also electric vehicles - become lighter and cheaper. Opportunity (fast) charging can be performed in a static way by using a pantograph, induction or a plug-in charger or in a dynamic way by partly using catenary wires or induction. A plug-in cable or a pantograph is also used for slow charging in the depot during the night. Another possibility is to charge the battery outside the vehicle and swap an empty battery for a fully loaded one.

Different uncertainties in operating electric vehicles exist and determine the actual battery load, so they should be considered in vehicle (charging) scheduling. The charging method as well as the amount of charging infrastructure are important variables in the charging scheduling process. Also charging locations are important, however, they are more straightforward. Combined bus stations and bus terminals are well-established locations for OC infrastructure, because multiple vehicles arrive there, the buses have to wait there for a certain time and the vehicles are often empty during this waiting time. Realising a charging station at those locations could be expensive, however, battery and vehicle cost savings (partly) compensate those costs. Moreover, the battery price is expected to decrease the upcoming years due to economies of scale and technological developments. Besides the (investment) costs, the energy capacity is also an important practical challenge for operating electric vehicles. Charging infrastructure providing high charging power (up to 600 kW) is already available, but this is relatively expensive and results in high pressure on the electricity grid. In Table 2-7, ranges of relevant aspects affecting the operations, are summarized per charging infrastructure type. In respectively, green and red colours, important advantages and disadvantages are indicated.

Based on Table 2-7, battery swap stations and dynamic charging infrastructure are relatively expensive, however, vehicles are able to continue operations during the IMC process, while a vehicle has to wait a certain time for performing the battery swap. Also for OC, the vehicle has to wait a certain time, however, this time is relatively short, especially when the charging power becomes higher. Nowadays, both static and dynamic induction charging have to deal with low energy transmission efficiencies. For overnight charging, longer charging times are available, so lower charging power can be used. Current battery technologies are in most cases not sufficient to operate vehicles a whole day, so overnight charging is often combined with OC at bus stations in order to limit the overcapacity of the fleet size.

In the remainder of this report, information from this literature review is used to support model assumptions, dependencies and calculations, to deliver model input and to generate charging mechanisms.

*Table 2-7 - Relevant cost and energy aspects for different types of charging infrastructure.* Exchange rate: $1.00 = €0.8472

| | Battery swapping | Overnight charging | | OC | | | | IMC | |
|---|---|---|---|---|---|---|---|---|---|
| | | Plug-in | Pantograph | Inverted pantograph | On-vehicle pantograph | Induction | Plug-in | On-vehicle pantograph | Induction |
| Charging location | Swap station | Depot | Depot | Terminals / depot / selected bus stops | Terminals / depot / selected bus stops | Terminals / selected bus stops | Terminals / depot | Along the route | Along the route |
| Charging time *swapping time | 1 – 2 hours 7-10 min* | 1.5 – 8 hour | 5-7 hour | 0.5 - 40 min | 20 sec - 1 hour | 0.5 - 12 min | 1.5 – 3 hour | Basically irrelevant | Basically irrelevant |
| **Costs** | | | | | | | | | |
| Charging infrastructure | €546,000[2] Whole station | €25,000 – 50,000 | €35,000 – 50,000 | €35,000 – €150,000 | €35,000 – €150,000 | €35,000 – €120,000 | €15,000 – 50,000 | €450,000 - 700,000 /km | €300,000 – €500,000/km |
| Vehicle | €400,000 – €450,000 | €400,000 – €450,000 | €415,000 – €480,000 | €415,000 – €480,000 | €415,000 – €480,000 | €416,000 - €466,000 | €400,000 – €450,000 | €415,000 – €480,000 | €416,000 - €466,000 |
| Battery | Up to €850 /kWh, €120,000-260,000 | €635 – 850 / kWh | €635 – 850 / kWh | €850 – 1,200 / kWh | €850 – 1,200 / kWh | €850 – 1,200 / kWh, €20,000 | €850 – 1,200 / kWh | €850 – 1,200 / kWh | €850 – 1,200 / kWh |
| **Energy** | | | | | | | | | |
| Storage system power | No information | 72 - 352 kWh | 123 kWh | 20 - 100 kWh | 23 - 172 kWh | 36.4 - 230 kWh | 85 – 208 kWh | 13.6 – 38 kWh | No information |
| Charging power | 280, Up to 300 kW | 30 - 150 kW | 150 kW | 150 – 600 kW | 60 – 500 kW | 50 - 200 kW | 150 - 300 kW | 160 - 240 kW | 100 kW |
| Energy efficiency | 99% | 90 - 97% | 97% | 97% | 97% | 80 - 95% | 90 - 97% | 97 – 99% | 70 – 80% |

*Sources:* Centrum Vernieuwing Openbaar Vervoer (2005), Hanzhuo Wu, et al. (2011), Lukic & Pantic (2013), Phoenix Contact (2013), APPM management consultants (2014), Wiesinger (2014), Zheng, et al. (2014), California Air Resource Board (2016), Gudde (2016), Jang, et al. (2016), UITP (2016), Battery university (2017), Fang, et al. (2017), Heliox (2017), Knorr-bremse (2017) and Stroecken (2017)

[2] Exchange rate: NT$1.00 (Taiwanese Dollar) = €0,0281

# 3. Methodology

In this chapter, the research activities, conceptual model and assessment framework are elaborated on, after a short introduction. Thereafter, the required data and tools are described, as well as the way the data is provided and applied.

## 3.1 Introduction

In order to quantify the effects of the charging infrastructure choice on the operations, the level of service and costs, a quantitative research is performed. This research is conducted from September 2017 till April 2018. The research activities, the relevant intermediate products and the relations with the research questions are schematically represented in Figure 3-1.

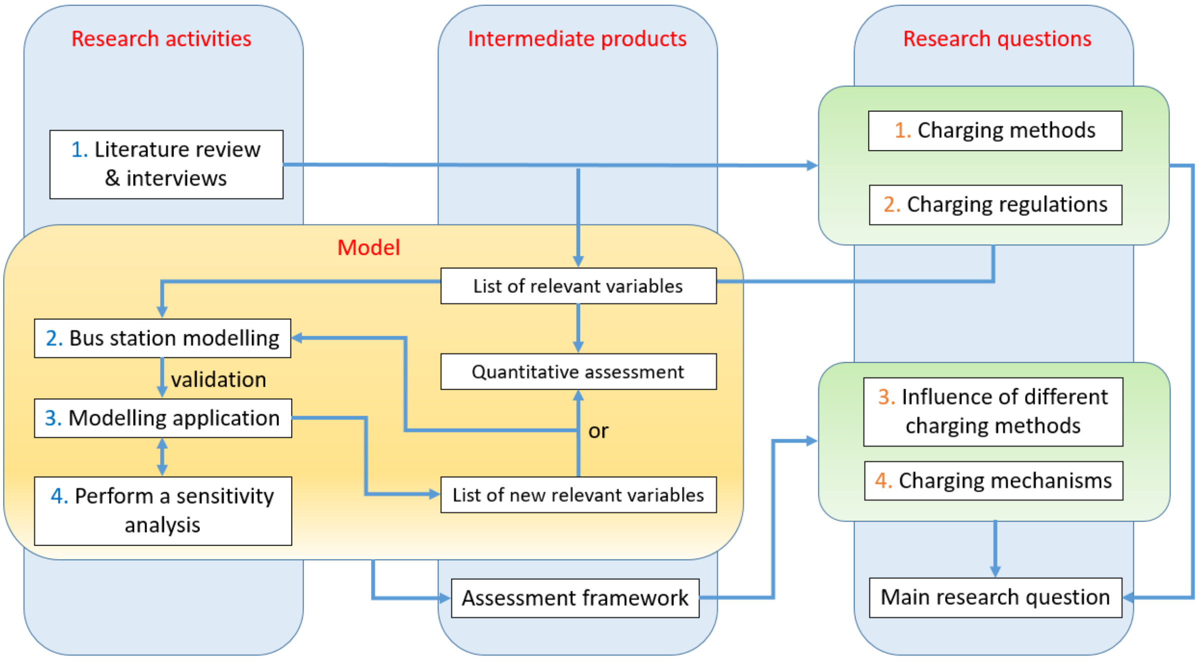



*Figure 3-1 – Methodology; connections between the research activities, intermediate products and research questions*

## 3.2 Research activities

On the basis of the methodology scheme from Figure 3-1, the research activities are described in this section. First, theoretical and practical literature are analysed and some important stakeholders in the (zero-emission) bus transport field are interviewed in order to find 1) Current problems/limitations of electric vehicles and electric vehicle (charging) scheduling; 2) Different types of charging infrastructure including their specifications (like charging power and costs) and limitations; 3) Values for certain relevant model variables; 4) Information for the application at Schiphol airport. After a deepening in especially scientific literature, transport planners of RET and Arriva are interviewed in order to find answers on points 1 and 2 and to determine and/or confirm values for point 3. At Arriva, besides a transport planner, also the Zero-emission project manager was present during the interview. Furthermore, a product manager of Schiphol Group, responsible for the public bus transport on behalf of Schiphol's employers, is interviewed in order to obtain information concerning point 4.

Secondly, a bus station is modelled. Answers on the first two research questions and the list of relevant variables obtained from the literature review and interviews are used to build the model. The model simulates a part of the real system as realistic as possible. It is impossible to reproduce the real world, so some important variables determining the preference for a certain charging method, are not modelled, but are described quantitatively. The model development is further explained in section 3.3.

During the model development, a model application was conducted in order to validate the model variables and determine other important model parameters, which could be implemented in the model. In this way, the model developed in an iterative way. If certain variables could not be implemented in the model, those variables and their influence on the operations, level of service and costs are described quantitatively. Based on the literature review conclusions, an interesting case and bus station for the application, is determined. After that, the obtained data is imported and the dependent model variables are adjusted to the specific case. Also this is further elaborated on in section 3.3. For the application, a sensitivity analysis is performed by changing the most relevant or uncertain model variables and evaluate the new model results.

The model results are implemented in an assessment framework, which is further specified in section 3.4. Based on the assessment framework results, the third and fourth sub-questions, concerning the influence of different charging methods and the effect of several charging mechanisms respectively, are answered. All sub-questions together are used to provide an answer on the main research question.

## 3.3 Conceptual model

The research object for this study is a bus station (section 1.4). In order to assess the charging methods and mechanisms, a (Z)E-bus station operations model that simulates the charging operations at a bus station, is developed. In this model, (Z)E stands for ‘Zero-Emission’ and ‘Electric’ as well. The conceptual model is shown in Figure 3-2. The Input and Output boxes consist of several dependent and independent variables, which are shown in Appendix C.

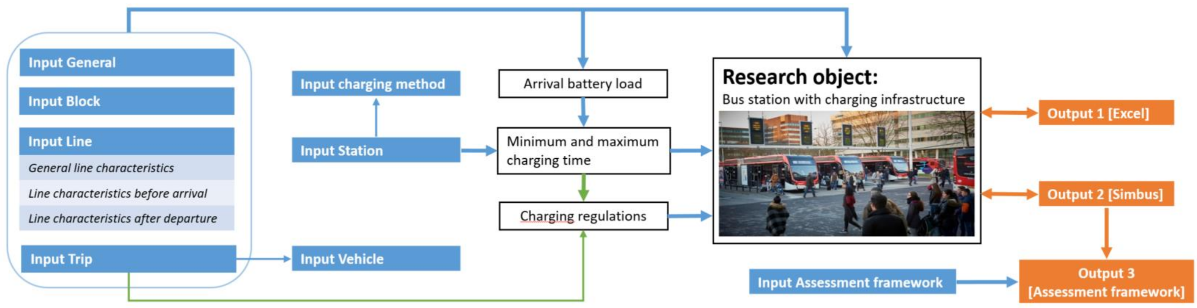



*Figure 3-2 - Conceptual model framework*

Although the research object is a bus station, the charging time per vehicle depends on multiple time, network, station and vehicle characteristics. Therefore, all variables affecting the charging time are described exogenously in a detailed way and are used as input parameters. The network characteristics are case dependent. Those variables are set in the Input Block, Line, Trip and Station boxes. The Input Line variables are subdivided into general line characteristics, line characteristics before arriving at the station and line characteristics after departing the station. The vehicle variable in the Input Trip box refers to the Input Vehicle box, where several electric vehicles available in the market are listed including some of their specifications. In the Input General box, the season of the year is specified, which results in energy consumption factors for the heating and cooling system.

Based on several variables set in those Input boxes, the battery load of a vehicle arriving at the charging station is calculated. This arrival battery load in combination with several Station input variables, like charging method and number of charging points, are used for the calculation of the minimum and maximum charging time. Besides the charging times, the model also determines the number of electric and diesel vehicles, the average departure battery load and average vehicle battery storage power, the required amount of diesel and the required number of extra vehicles in case of slow charging at the depot only. The last output variable is an answer on the so-called “Hermes-problem”, which will be further explained in chapter 5. Finally, an indication for the number of necessary charging points is determined, which could be helpful in setting the number of charging points for the simulation.

In the model different charging mechanisms can be implemented, which determine whether the minimum or the maximum charging time should be considered for each trip. Subsequently, the charging times are processed in an input file of Simbus, a bus station simulation tool, in order to take the charging activities into account. Simbus was previously described shortly in section 2.5.2, but will be elaborated on in more detail in section 3.5. As simulation results of Output 2, the new departure times and number of disrupted vehicles are given. Based on those results and some additional variables in order to translate the results into costs, Output 3 results are generated. Output 3 represents the assessment framework, which is further explained in the next section.

## 3.4 Assessment framework

The model is used to assess different variants and scenarios, in a consistent way, in order to draw valuable conclusions. Therefore, an assessment framework is developed (Table 3-1). This assessment framework is an indicative societal cost benefit analysis framework, including 1) three important public transport criteria: operations, level of service and costs and 2) the distribution of different positive and negative effects of the most important stakeholders in this field: passengers, public bus transport operators and public transport authorities. A short description of these three stakeholders and their interests is included in Appendix D. The assessment framework and their seven criteria, are shown in Table 3-1 and further discussed in the remainder of this section.

*Table 3-1 - Assessment framework of the (Z)E-bus station operations model*

| Criterion | Variable | Unit | Expression / Calculation | Affected stakeholder(s) |
|---|---|---|---|---|
| **Operations** | Disruptions | % | Percentage of vehicles that have to wait on other vehicles at boarding, alighting and buffer places, per day | Operator, Passengers |
| **Level of service** | Delayed departure | € | Δ departure time * # passengers * Value of Time, per day | Passengers, Authority |
| | Dispersion in departure times | € | Dispersion * # passengers * Value of Reliability, per day | Passengers |
| **Costs** | Delayed vehicle costs | € | Extra inefficient hours * costs per vehicle hour, per day | Operator |
| | Energy/fuel consumption costs | € | Charging time * charging power * costs per kWh green energy + diesel price * diesel required, per day | Operator |
| | Vehicle investment | € | NPV per vehicle * # vehicles | Operator |
| | Charging infrastructure investment | € | NPV per charging infra system * # charging systems | Authority |

First, it should be mentioned that the criteria are determined based on differences between charging methods, derived from the literature review. Other important aspects in favour of electric vehicles, but without a distinction between charging methods, are therefore not included in the assessment framework.

To start, the operations are assessed by providing disruption percentages, which indicate how many vehicles have to wait on other vehicles before boarding, alighting and/or charging activities can take place. These values are directly imported from the Simbus output files and are relevant for both the operator and the passengers. The level of service is described by 1) the change in departure time, relative to non-electric operations, which expresses the waiting time of passengers inside the vehicle during charging, in costs, and 2) the dispersion in departure times, which indicate the societal costs of reliability of departure times from passengers perspective. Finally the cost components are assessed by: 1) Operational costs, which described the extra vehicle hours per scenario and expressed it into cost. The extra loss time at the station due to charging, which is the main aspect in the change in departure time, is included here from an operators perspective. 2) Energy/fuel consumption costs, which represents the daily vehicle propulsion costs for both electric and diesel engine vehicles. 3) Vehicle investment, which depend on the net present value (NPV) per vehicle and the fleet size. Here the minimum required fleet size is considered and is calculated based on the charging method(s) and the charging times. 4) Charging infrastructure investment, which is also expressed in its NPV. Also the required space for the charging infrastructure is included here. In the end, the assessment framework results are graphically represented in spider graphs.

## 3.5 Data and tooling

In order to obtain different variables that are needed for the model and assessment framework, data is indispensable. Different tools are required to obtain valuable results, based on the data. First, the used data sources and developed data files are discussed in section 3.5.1, followed by an elaboration of the used tools for this research.

### 3.5.1 Data sources and data files

For providing all relevant variables for the input variables mentioned in section 3.2 and elaborated in Appendix C, multiple sources are used. The data-sources for deriving values for or getting insight into different variables are shown in Table 3-2.

*Table 3-2 - Data sources for the model variables*

| Required input | Variables | Data sources |
|---|---|---|
| Input General | Season factors | Literature review |
| Input Block | Deadheading distances and times | Google maps |
| | Roundup percentage | Interviews |
| | Start and ending times line operations | AVL data |
| Input Line | Operator, dwell times, travel / dwell time variations | AVL data |
| | Authority, minimum waiting times, driver breaks, vehicle composition, battery buffer, line type factors | Literature review |
| | Travel distances | Google maps |
| Input Trip | Timetables, trip continuation | AVL data |
| | Vehicle type | Literature review |
| | Passenger loads | Passenger counts |
| Input Station | Number of charging points, driving time to charging location, platform lengths, number of platforms, entrances and exits | Google maps, visiting station |

| | | |
|---|---|---|
| Input charging method | Charging methods, charging system power, charging efficiencies, max OC rate, max charging time, charging infra costs, lifetime and discount rate | Literature review |
| Input Vehicle | Fuel consumption and fuel consumption factor, battery buffer, vehicle (propulsion) costs, vehicle lifetime and discount rate | Literature review |
| | Vehicle model and length, passenger capacity, energy consumption, battery storage capacity | ZeEUS E-bus Reports |
| | Vehicle model (non-electric vehicles) | AVL data |
| Input Assessment framework | Cost per vehicle hour, Value of Time (VoT) and Value of Reliability (VoR) | Literature review |

Most variables are directly determined from the literature review. Some location dependent variables are determined by using Google maps. Thereafter, determinations of station variables are checked by visiting that station physically. Passenger loads, are obtained from passenger counts, preferably provided by APC (automated passenger counting) data, such as check-in and check-out OV-chipcard data in the Netherlands. However, this data should be processed and delivered by the operator(s). According to experts at Goudappel Coffeng, an operator would probably not provide this data if the project is not commissioned by the operator itself. In addition, for the model application of this research, performed at Schiphol airport, two different operators were involved. Therefore, in consultation, it is decided to waive the APC data and base the passenger loads on real life passenger counts. Vehicle occupancy rates were observed on Tuesday 9 January 2018 in order to estimate the passenger loads.

AVL (automated vehicle location) data is provided by CROW-NDOV, with permission of the client (Vervoerregio Amsterdam) and the operators (Connexxion and GVB). CROW-NDOV is a collaboration of 15 Dutch public transport authorities (CROW-NDOV, 2018). For the model application at Schiphol, bus station Schiphol Knooppunt Noord is chosen (see section 6.1), so AVL data of all bus lines serving this station at the moment of the data request[3]: lines 69, 193, 194, 196, 197, 199, 245, 246, 247, 300, 310, 356, N30 and N97, is provided. Per delivered data file, trip data of one line, including all stops, vehicle numbers, target and realised arrival and departure times, concerning a whole month are obtained. All data is put together in one Trip data file, which is processed to four different data files, according to Figure 3-3.

[3] At 10 December 2017, the timetables and line numbers were changed significantly.

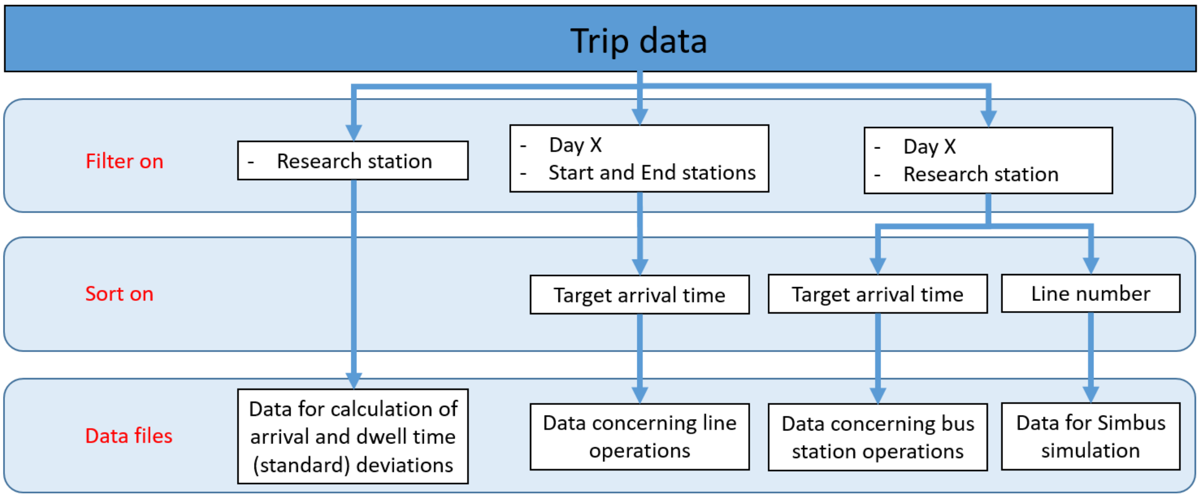



*Figure 3-3 - Processing steps from trip data towards required data files*

The purpose of the data files from Figure 3-3, are described from left to right here. The first data file concerning trip data at the subject station concerning a whole month, is used to calculate the average deviation of the arrival times and average dwell times, as well as the standard deviations of those times, which are used in the reliability determination for the Simbus simulation. These values are determined for each line for the morning peak, evening peak and off-peak periods. The second obtained data file is used to determine the deadheading distances of vehicles coming from or going to the depot. The third data file is referred to in the charging time calculations. At last, the same data, ordered on line number is used to construct the Simbus input sheet.

Besides the AVL data, also an electric vehicle database, based on two E-bus reports, is developed. In the vehicle database, 60 different vehicle models of 27 different manufacturers are specified. This database consist of all electric vehicles from the ZeEUS Ebus Reports with information about their energy consumption and battery capacity. A comparable database for charging infrastructure, based on available charging power per charging method in the market, is also developed. This database is based on the second ZeEUS Ebus Report, where an extra chapter about system suppliers is added.

### 3.5.2 Research tools

For this research, two tools are used: Excel and Simbus. The AVL data is delivered in CVS format, so it is easy to implement in Excel. The data files, described in section 3.5.1 are included in the same Excel file. In this file, also the battery dynamics are modelled and the charging times are calculated. The Simbus input sheet is also developed in Excel.

The Simbus input sheet is developed in order to perform simulations in Simbus. Simbus is a bus station simulation tool that determines the optimal distribution of vehicles over the available platforms in order to optimize the bus station operations. Further in this section, Simbus is described in more detail. Before this research, electric vehicles have never been simulated in Simbus. The charging times are derived earlier, as shown in section 3.2 and are used as input variables in the Simbus simulation. Charging takes place at buffer spaces, so the charging times are embedded in the buffer times. Also the allocation of vehicle type (electric or diesel) per trip is obtained from Output box 1. The Excel input file should be saved as text file in order to import it into Simbus. After the simulation, a detailed output (text)file, with a lot of information about vehicle arrival and departure times, vehicle waiting/charging times, disruptions, etc. is provided. Interesting information from those files is exported to Excel, in order to translate the results to criteria of the assessment scheme. The tooling scheme including the required and obtained data for/by the Simbus simulation is shown in Figure 3-4.

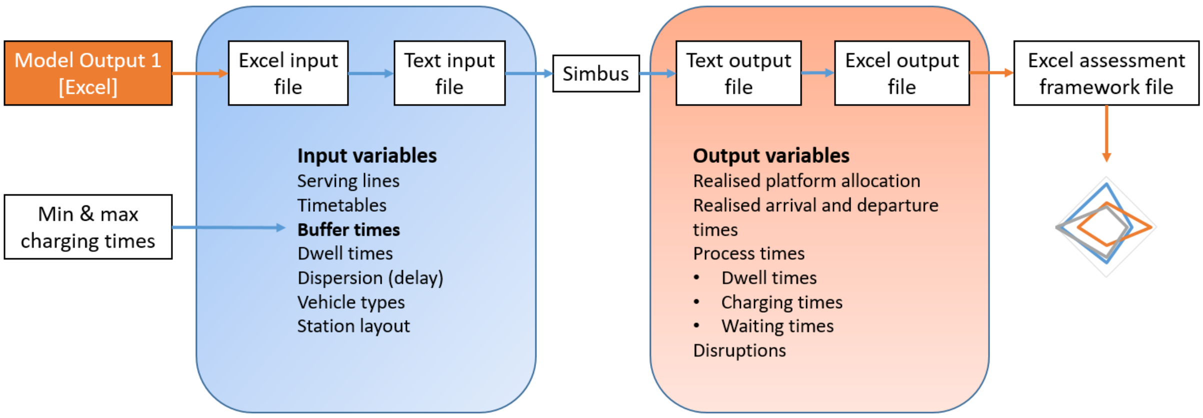



*Figure 3-4 - Tooling and data scheme for the (Z)E-bus station operations model*

## Simbus

In this paragraph, the general Simbus workings are explained. The processing of input variables related to the developed model and the introduction of charging activities for electric vehicles is therefore not included here. This is further elaborated on in section 4.3.

The Simbus input file strongly depends on the case, because multiple case dependent variables are included, as indicated in Figure 3-4. Based on four supporting sheets, concerning 1) General input data, 2) Distances between station components, 3) Reliability of arrival and dwell times, and 4) Trip data, a final input sheet is developed. For bus station simulations, the trip data file is set manually, based on timetables and AVL data. Each separate sheet is discussed in more detail in section 4.3.2. In the final input sheet, each trip arriving at the station is sorted on time. For each trip, the arrival time, alighting time, buffer time and dwell time, including their standard deviations are shown, as well as the vehicle length, the type of line: through going, starting or ending and the used station entrance and exit.

Finally, some specific characteristics can be set, like certain line combinations or conflicts according to the timetable. Also combined platforms can be defined here. In Simbus, only separate platforms, represented next to each other, can be modelled. When two platforms are in a row, this can still be modelled in a realistic way by defining those platforms as combined platform. The Simbus input sheet text file is imported in Prosim, the simulation application of Simbus. In the simulation, Simbus picks the deviation of the arrival and dwell times for each trip from the normal distribution. During the simulation, each vehicle representing each defined trip is visible (Figure 3-5).

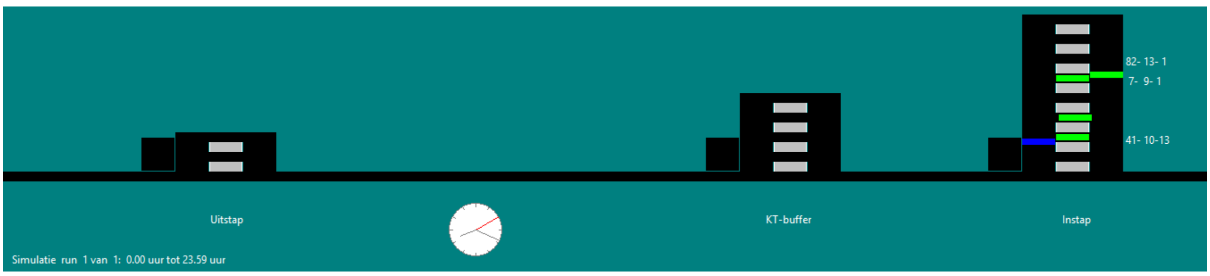



*Figure 3-5 – Screenshot of Simbus simulation*

During the simulation, the results are written to an output text file. The exact arrival time, dwell time and buffer time per trip is shown in this file, as well as the occupation rates and the number of disruptions at each station component. In order to analyse the results, the output text file is imported into Excel again.

**Platform allocation**

Simbus' purpose is to distribute all vehicles over the available platforms in an optimal way in order to optimize the bus station operations. Therefore, the essential part of Simbus is the platform allocation. The driving process of the vehicles are direct results of this allocation. In Simbus, two optimization principles for the platform allocation are available: 1) Linear optimisation, and 2) Cyclic optimization. For the linear optimization of the platform allocation, a fixed order of procedures is performed in order to find the optimum allocation for each vehicle. For the cyclic optimization of the platform allocation, a system optimum is provided. The system optimum consist of weighed scores of seven different aspects (included in confidential Appendix L). The optimization of the total score determines the platform allocation. However, for each case, research for determining the weights of each aspect is required. Therefore, the linear optimisation for platform allocation is considered for general use of the model and discussed in more detail here.

For each line serving the bus station, a preferred platform could be selected as input. Besides, a range of other platforms, in case of unavailability of the preferred platform, can be predefined. Based on the predefined preferred platform and platform range per line, the linear optimization of platform allocation per trip is represented roughly in Figure 3-6.

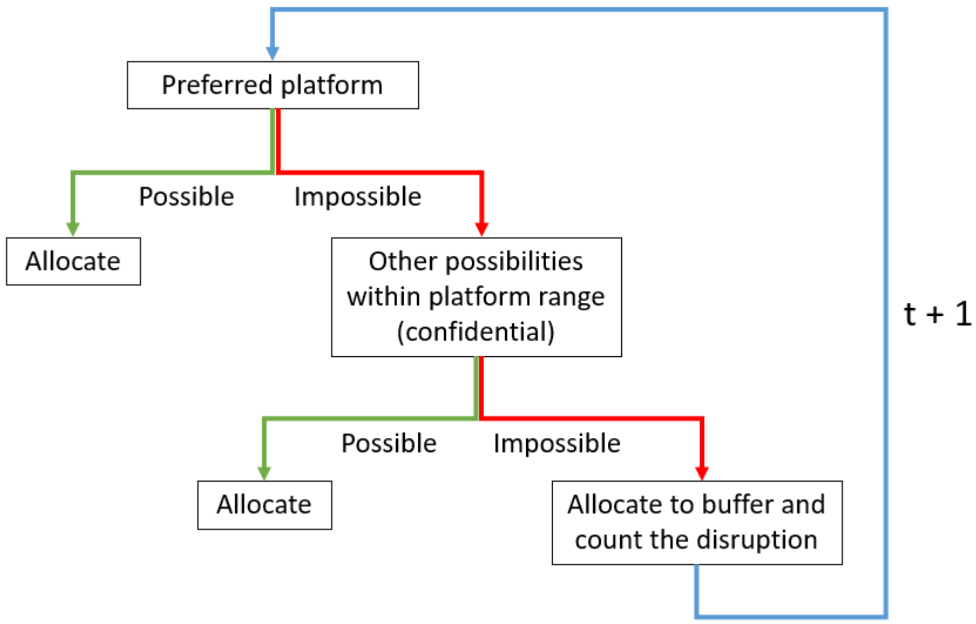



*Figure 3-6 - Linear optimization of platform allocation algorithm*

Simbus always tries to allocate a vehicle to its preferred platform, as long as this is predefined by the user. If nothing is specified, Simbus could select all platforms to assign each vehicle to, which result in quite unclear bus station operations for passengers. If the preferred platform of a vehicle is already occupied, Simbus allocate the vehicle to another platform, if a platform range is specified and one of the platforms within that range, is available. If none of the platforms is available, the vehicle is allocated to a buffer place. Then, Simbus calls it a disrupted trip. The loop starts again and in the second linear optimization for platform allocation, the vehicle from the buffer can be allocated to a platform again (Jägers, 2001). Technical modelling steps, describing the selection of a platform from the platform range, is based on ideas of Goudappel Coffeng and consists of confidential information. Therefore, a more detailed explanation of this, is included in confidential Appendix L.

## 3.6 Conclusions

In this chapter, the research methodology is elaborated on. This research consists of four main research activities: 1) Doing a literature review and interviews, 2) Modelling bus station operations, 3) Applicate the model, simultaneously with the model development, 4) Performing a sensitivity analysis. The literature study and interviews with public transport planners of different operators and a manager of Schiphol Group, responsible for public transport, are performed in order to chart the main problems of the exploitation of electric vehicles and obtain and validate model variables. In the conceptual model, the bus station modelling is described roughly. A lot of important network, vehicle, bus station and charging method variables are described exogenously in order to determine the minimum and maximum charging times. These variables are derived from multiple data sources. The case dependent variables are included in the AVL data. This data is used to develop four different trip data files in order to 1) Calculate the deviations and standard deviations of the arrival and dwell times 2) Calculate the charging times per arrival, 3) Determine which trips came from or go to the depot, and 4) Realise the Simbus simulation. Simbus is a bus station simulation tool that determines the optimal distribution of vehicles over the available platforms in order to optimize the bus station operations. Also the derived charging times are used for the Simbus simulation, in order to take the charging processes at the bus station into account. Finally, the Simbus output results are processed to criteria results indicated in the developed assessment framework. These criteria are:

1) Disruptions
2) Delayed departure time
3) Dispersion in departure time
4) Operational delayed vehicle costs
5) Operational energy/fuel consumption costs
6) Vehicle investment
7) Charging infrastructure investment

These criteria are allocated to three important public transport criteria explicitly mentioned in the research question: operations (1), level of service (2, 3) and costs (4, 5, 6, 7) and to the main stakeholders in the public bus transport field: passengers (1, 2, 3), public transport operators (1, 4, 5, 6) and public transport authorities (2, 7).

# 4. Modelling bus station operations for electric vehicles

In this chapter, different model modules are discussed in sequence (section 4.2, 4.3 and 4.4), followed by the model variant identification (section 4.5). First, a short introduction of the model is given in section 4.1.

## 4.1 Introduction

A bus station operations model is developed in order to assess different charging methods (at a bus station), compared to each other and the current situation. The model, as well as this chapter, is subdivided into three parts: 1) The charging time calculation model; 2) The bus station operation model, and 3) The cost/benefit calculation model. For all three parts, the model input variables are subdivided and elaborated first. Then, the main model algorithms are discussed, followed by a summary of all model assumptions (Figure 4-1). As indicated by the orange output boxes and the black arrows in Figure 4-1, some output variables of specific model parts are used as input in another model part.

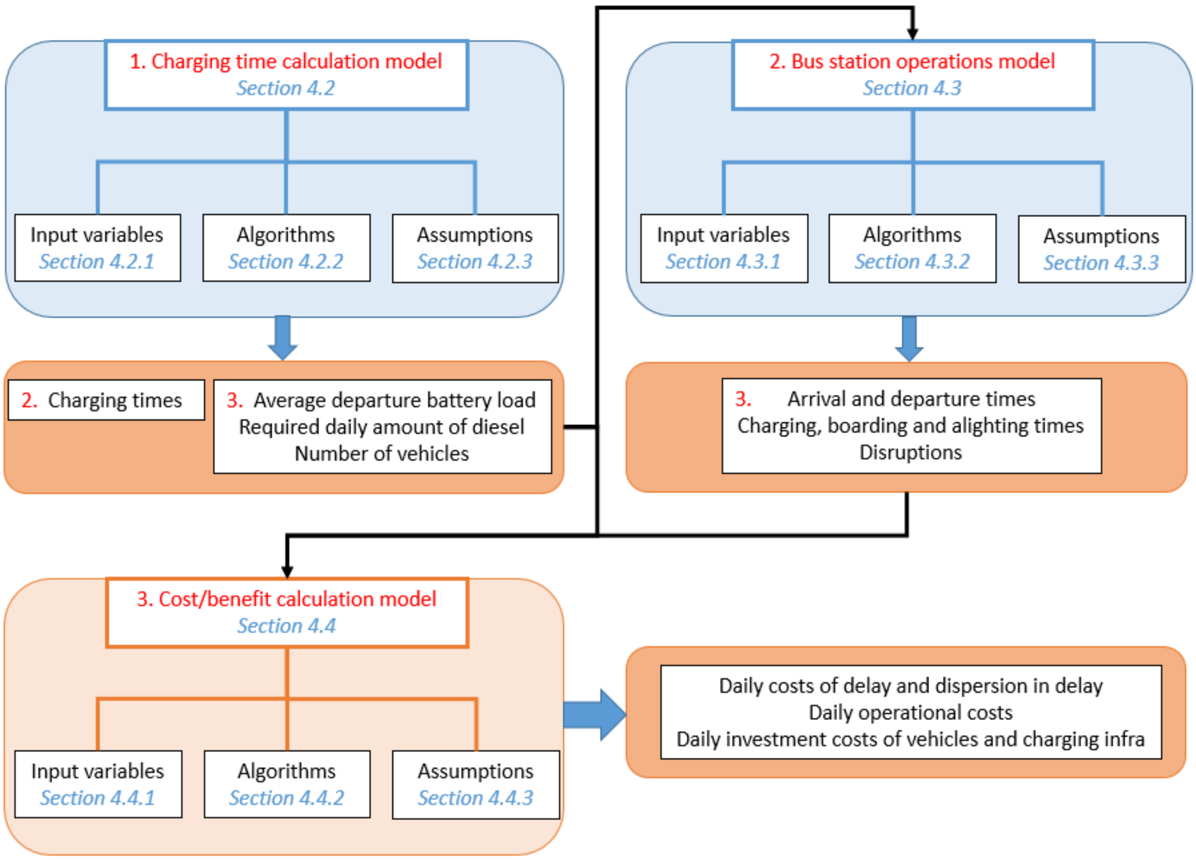



*Figure 4-1 - Bus station operations modelling components*

After a detailed elaboration how the model works, the model variant identification, based on charging mechanisms and development paths, is discussed. Here, the question is: What will be modelled? The first question to answer is: How does the model work?

## 4.2 Charging time calculation model

In the first part of the model (Figure 4-2), the charging times at the research station are calculated. In order to calculate those times, some input variables are necessary and certain assumptions need to be made. Throughout the text of section 4.2.1 and 4.2.2, the model assumptions are already stated. At the end, all model assumptions are summarized in section 4.2.3.

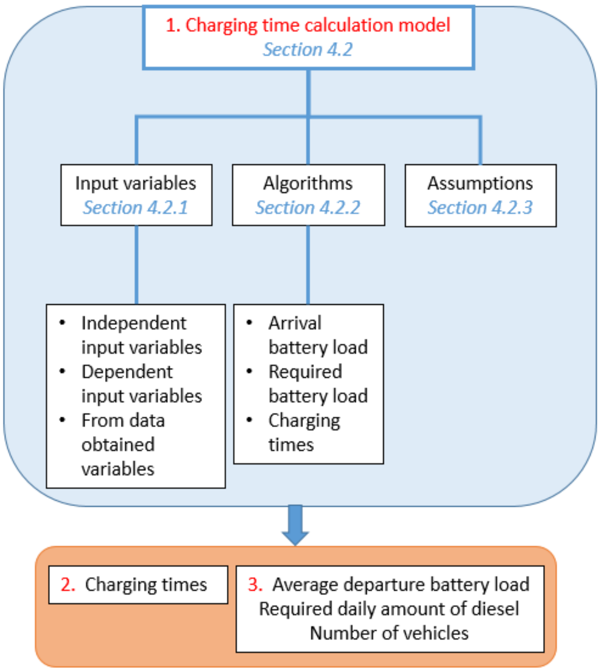



*Figure 4-2 - Charging time calculation model; input variables, model explanation and main output*

### 4.2.1 Input variables

In section 3.2 Conceptual model, all input variables for modelling charging activities at a bus station are already mentioned. In this section, the variables needed to calculate the charging times are ranked and values are derived. As shown in Figure 4-2, input variables are subdivided in three different categories: independent input variables, dependent input variables and input variables derived from the AVL data. According to this categories, all input variables for the charging time calculation model are discussed.

#### *4.2.1.1 Independent input variables*

The blue boxes in Figure 4-3 represent the independent input variables which are shown in a general input sheet and easy to change while using the model. Based on the figure, the different boxes are explained in more detail.

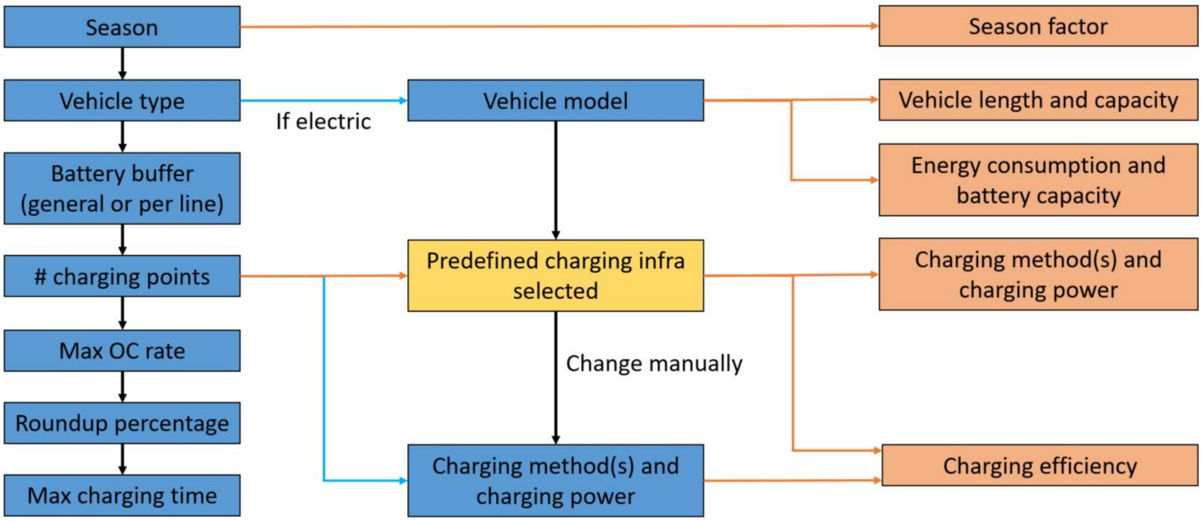



*Figure 4-3 – Independent input variables (blue boxes) and their relationships with other variables (orange boxes)*

*Season:* In this input box, the season is specified. In section 2.4.4, is mentioned that, according to test results, 21.4% of the total energy consumption of an electric bus is used for heating, while 18.8% is used for cooling the cabin. Based on this research of Suh, et al. (2014), the energy consumption rate per vehicle is multiplied by the season factor of the corresponding season. Those factors are shown in Table 4-1.

*Table 4-1 - Season factors for energy consumption*

| Season | Percentages of energy consumption for heating or cooling | Season factor | |
|---|---|---|---|
| | | **Calculation** | **Factor** |
| **Summer** | 18.8% | 100/(100-18.8) = 123% | 1.23 |
| **Spring/autumn** | - | - | 1.00 |
| **Winter** | 21.4% | 100/(100-21.4) = 127% | 1.27 |

*Based on* Suh et al. (2014)

*Vehicle type:* The vehicle type: Electric or diesel is set here per line. Vehicles can operate on multiple lines during a day. The vehicle settings per line are based on the line where the vehicle starts its operations. In the vehicle input sheet, vehicle settings can be changed manually on trip level. In this way, it is also possible to implement a few electric vehicles on a line.

*Vehicle model:* For electric vehicles, the vehicle manufacturer and model should be selected. In a scroll down menu, all available electric vehicle models at the European market, sorted on battery range, are shown. This scroll down menu is linked to the electric vehicle database, consisting of electric vehicles researched in the ZeEUS Ebus Reports, as mentioned in section 3.5.1. An electric vehicle model can be selected per line, however, the vehicle model can be changed on trip level manually. In this way, very specific (electric) vehicle allocation can be applied. As indicated in Figure 4-3, a specific type of charging infrastructure is already given per chosen vehicle model. This includes in Europe applied charging methods and charging power (according to ZeEUS Ebus Reports) per vehicle model. That does not mean that the model can only simulate already applied combinations of vehicle models and charging infrastructure types, because the infrastructure choice can be adapted.

*Battery buffer:* The battery buffer, based on uncertainty in operations and on battery properties should be set here. Considering the available risk in operations and a limitation of battery life time reduction by too much discharging the battery, a battery buffer of 20% is considered as default. However, based on the amount of risk an operator will take and the battery life time reduction effects of discharging the battery, this value can be changed. Not only a general battery buffer can be set, also a line dependent battery buffer can be assigned to specific lines. In this way, a reliability difference between city and regional transport or between city buses and BRTs, can be made.

*Number of charging points:* The number of charging points at the bus station should also be specified. This is an interesting variable to change in different scenarios, because charging requires space and space is often scarce at many bus stations.

*Charging method and charging power:* The charging method and charging power is already determined automatically by selecting the vehicle model. However, this can be adapted manually. First, a charging method can be selected. Secondly, a scroll down menu with the available charging power for the selected charging method, pops up. These scroll down menus are connected to a charging infrastructure database. Besides applied charging power, available charging power predefined by electric system suppliers, also indicated in the ZeEUS Ebus Reports, is also included in this database. The database consist of 46 different charging method/charging power combinations. The ranges and averages of the available charging power per charging method are shown in Figure 4-4. IMC induction is not mentioned here, because it has never been applied and/or launched in Europe (yet). Hence, it is not included in the database.

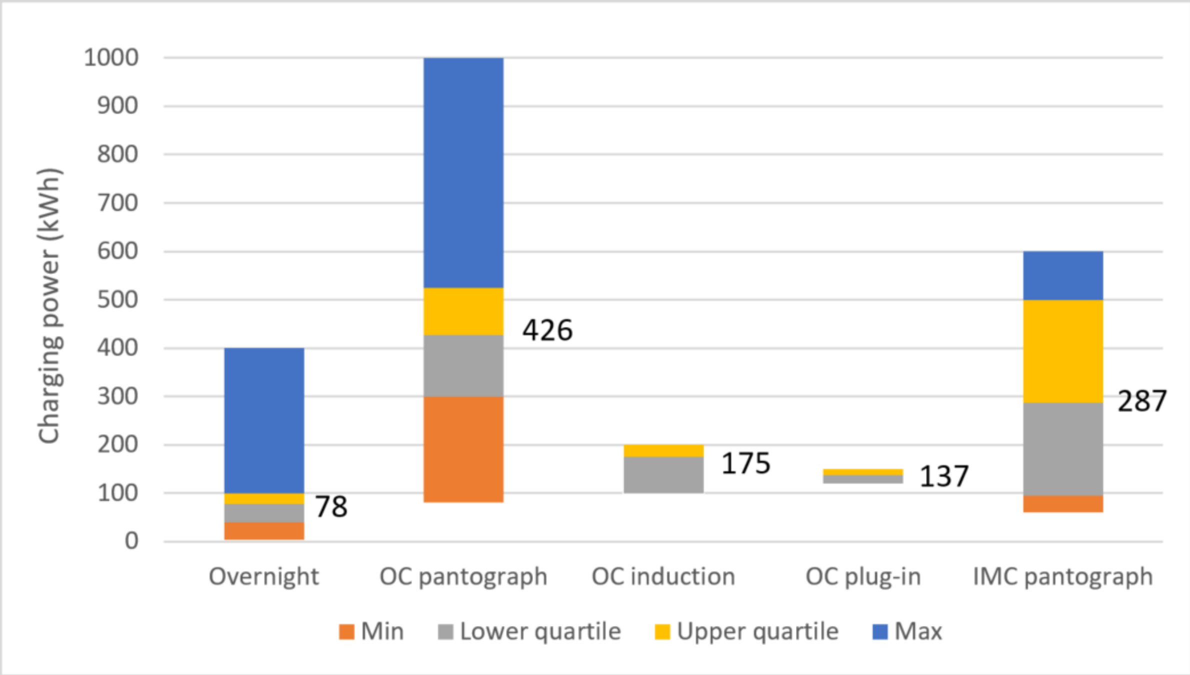



*Figure 4-4 - Available charging power per charging method in charging infrastructure database. Based on UITP (2016 & 2017)*

*Maximum OC rate:* Based on the non-linearity of charging a Li-ion battery, a battery load of 80% is considered as maximum for OC. After this level, the probability that the battery management system (BMS) stops the charging activity in order to not overheat the battery, becomes higher (Veenendaal & Naber, 2017). In addition, the charging process slows down after reaching a battery level of 80%. If the maximum OC rate is not considered or is set to a higher value than 80%, a failure rate for the charger is considered. This rate set a random value between 80% and 100% at which the BMS stops the charging process.

*Roundup percentage:* This percentage determines when the charging time should be expanded in order to combine charging times and driver break times. The operators and concession names are found in the database directly. The break times per operator (further discussed in section 4.2.1.2) is referred to by the model. If the roundup percentage is set to x and the charging time is less than x smaller than the break time of the corresponding operator, the charging time is rounded up to that break time. The standard value of x is 10%. This means that a charging time of 13.5 minutes is expanded to 15 minutes, if the duration of a short break is equal to 15 minutes. Every percentage can be selected here.

*Maximum charging times:* Here, a maximum value can be set for the OC times. As default, a maximum of 30 minutes is selected, but any random value can be set here. It is also possible to consider no maximum at all.

#### 4.2.1.2 Dependent input variables

Besides the independent input variables, (discussed in section 4.2.1.1) which should be set in order to use the model, there are also some dependent input variables. All dependent input variables of the charging time calculation model depend on other dependent input variables or the independent input variables.

*Vehicle length, capacity and energy/fuel consumption:* The values for these variables depend on the vehicle model and are included in the vehicle database. The energy consumption rates are expressed per kilometre and are based on real life test results in urban environments. The energy consumption especially depends on the weight of the vehicle. In Figure 4-5, the relation between energy consumption, passenger capacity and vehicle length of the vehicles included in the vehicle database are shown. In general, larger vehicles are heavier and consume more energy, but note that there is quite some variety.

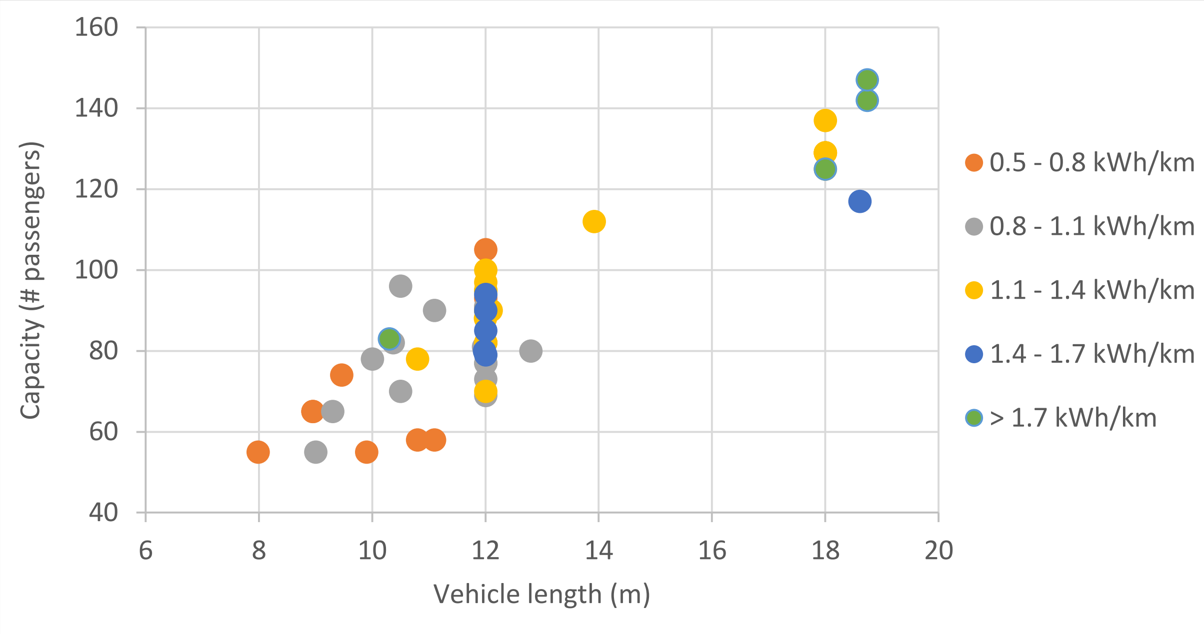



*Figure 4-5 - Energy consumption rates as function of vehicle length and passenger capacity in the vehicle database. Based on UITP (2016 & 2017)*

For non-electric vehicles, vehicle lengths are also known, however, they are involved in a separate sheet of the second model. These non-electric vehicle types and lengths are derived from an earlier performed study by Goudappel Coffeng at Schiphol Plaza. For the fuel consumption a distinction is made: 1) Rigid city buses are modelled to drive three kilometres on one litre of diesel, 2) Rigid BRT buses are modelled to drive four kilometres on one litre of diesel. Thereby, a fuel consumption factor of 1.25 is added if a articulated bus is considered. The fuel consumption rates can be adapted per line in order to consider different line characteristics, influencing the required amount of diesel.

*Battery storage capacity:* The battery type is determined by the vehicle model choice. Therefore, the battery storage capacity is also determined by the choice of the vehicle model.

*Charging efficiencies:* The charging efficiency depends on the chosen type of charging equipment. Different charging equipment, including their predefined charging efficiencies based on section 2.4.4, are included in the model and shown in Table 4-2.

*Table 4-2 - Charging efficiencies of different charging equipment*

| Charging equipment | Charging efficiency |
|---|---|
| Pantograph | 97% |
| Induction | 90% |
| Plug-in | 97% |
| IMC pantograph | 98% |
| IMC induction | 75% |

*Sources: Hu, et al. (2013), Lukic & Pantic (2013) and APPM management consultants (2014)*

#### 4.2.1.3 Input variables obtained from AVL data

The last category consist of variables (partly) obtained from the AVL data. Four variables are included and discussed here.

*Public transport operator(s) including break times:* The operator per trip is directly obtained from the trip data. For most Dutch operators, their drivers break times are specified in Table 4-3. If another operator is included in the data, their break times should be set manually. The break times are used in rounding up the charging times in order to match the charging and break times, where possible.

Table 4-3 - Break times per operator

| Operator | Operator code in trip data | Short breaks | Long breaks |
|---|---|---|---|
| **GVB** | GVB | 15 min | 30 min |
| **HTM** | HTM | 17 min | 32 min |
| **RET** | RET | 17 min | 32 min |
| **Connexxion** | CXX | 15 min | 30 min |
| **Arriva** | ARR | 15 min | 30 min |

*Sources: FNV (2012 & 2016), Veenendaal & Naber (2017), Visser (2017), Expert judgement*

*Arriving and departure times:* These times per trip are directly derived from the AVL data.

*Line distances:* The line distances are derived from the trip data. Based on specific bus station and bus stop numbers included in the AVL data, the distances from one stop to another are derived by using the distance sheet of the GOVI-tool, developed and used at Goudappel Coffeng. Different stop and station numbers in a row represent a bus line. By adding the corresponding distances included in this GOVI-tool, the line length, subdivided in line length from terminal A (start of the line) to the charging station and line length from the charging station to terminal B (end of the line), is derived for each line serving the research station.

*Start and ending times of line operations:* This information is derived from the AVL data and is checked by the online timetables per line. In case of night buses for instance, it is more difficult to retrieve the information from the data directly.

### 4.2.2 Charging times

Based on the input variables discussed above, the minimum and maximum charging times per trip will be calculated. In this section, multiple formulas are included. The meaning of all symbols in the formulas are represented in Appendix E. The minimum and maximum charging times are derived in the following three steps:

1. Calculation of the battery load when the vehicle arrive at the station;
2. Calculation of the required battery load for performing the next trip;
3. Calculation of the maximum charging time based on 1 and calculation of the minimum charging time based on 2.

First, the arriving battery load is determined by the following formula:

$$Batt\_load_{ar} = Batt\_load_{last} - \frac{EC * d_{covered} * F_{season}}{BSP} * 100\% \qquad \text{Eq. 1}$$

The last calculated/derived battery load ($Batt\_load_{last}$) is equal to the battery load of that vehicle when it departs at the charging station. Therefore, the number of arrivals ($\#A$) of a specific vehicle(number) at the station is counted by the model. If the number of arrivals is larger than one, the last battery load can simply be found by looking up the same vehicle number in the past and pick its departure battery load. If the number of arrivals equals one, the assumed battery load is 100% when the vehicle came from the depot or is equal to the maximum OC rate when the vehicle was already in operation.

The distance covered ($d_{covered}$) is equal to the distance to cover ($d_{to\ cover}$) of one arrival earlier of the same vehicle. The determination of the distance to cover is elaborated in the explanation of equation 2. This equality only holds when the number of arrivals ($\#A$) is larger than one and when the research station is the only fast charging station in the network. If a vehicle enters the station for the first time, the vehicle could be departed from the depot, as indicated (with a) in Figure 4-6. In that case, the distance covered is equal to the distance from the depot to the terminal plus the distance from the terminal to the charging station of research. In some cases, a vehicle arrives at the station for the first time, though it did not come directly from the depot. In that case, the assumed distance covered is equal to two times the distance from the terminal to the charging station (b1).

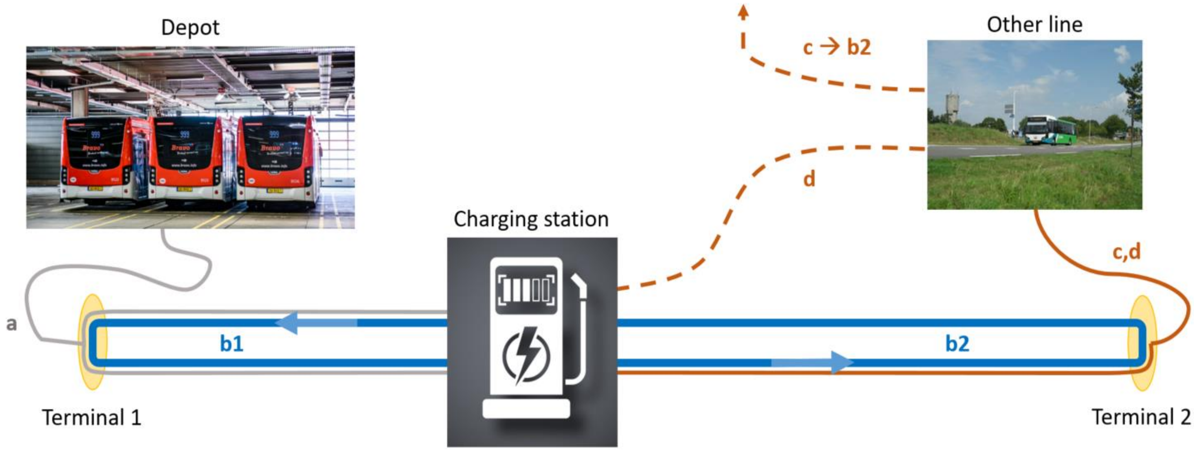



*Figure 4-6 - Possible distances to consider for the calculation of the battery dynamics*

The energy consumption ($EC$) rate, as well as the battery storage power ($BSP$) is directly connected to the electric vehicle type choice, while the season factor ($F_{season}$) depends on the set season, as discussed in section 4.1.1.1.

Secondly, the minimum required battery load to perform the next trip is derived:

$$Batt\_load_{req} = \frac{EC * d_{to\ cover} * F_{season}}{BSP} * 100\% \qquad \textit{Eq. 2}$$

This equation looks like equation 1, however, in this formula, the distance to the next charging location ($d_{to\ cover}$) after departure is considered, instead of the distance covered to reach the charging station. First, when a vehicle goes to the depot, the distance from the charging station to the last serving station (often the terminal) is added to the distance from the last serving station to the depot (a in Figure 4-6). If the vehicles operation continues, the model determines the distance to the next terminal first. Then, the model looks forward in time to derive what the vehicle will do: return to the station in opposite direction (b2) or continue operations on another line (c). When the vehicle returns to the station, the distance from the terminal to the station is added. When the vehicle returns to the station while operating on another line, the distance from the terminal to the station of that specific line is added (d). If a vehicle is not returning to the station anymore, twice the distance from the station to the terminal (b2) is assumed for the calculation of the minimum required battery load.

Based on the arrival battery load and the minimum required battery load, the model determines whether it is necessary to charge a vehicle or not. Charging is necessary if:

$$Batt\_load_{ar} < Batt\_load_{req} + BB \qquad \text{Eq. 3}$$

Based on this inequality, the minimum battery recharging percentage is determined. This percentage of the battery load is restricted by the battery buffer and the max OC rate. The minimum battery charging load is equal to:

$$Batt\_load_{charge,min} = MIN\,(-\,Batt_{load_{ar}} + Batt_{load_{req}} + BB\,;\; -\,Batt\_load_{ar} + Max\;OC\;;\;0\,) \qquad \text{Eq. 4}$$

When the minimum charging load is determined by the maximum OC rate, the minimum and maximum charging time will be equal, because the maximum charging load is always determined by reloading the battery to the maximum OC rate. Based on the minimum and maximum battery charging load, the minimum and maximum charging times are derived by:

$$t_{charge,min} = \frac{Batt\_load_{charge,min} * BSP * \; Max\;OC * Eff}{CP} * 60 \qquad \text{Eq. 5}$$

$$t_{charge,max} = \frac{(Max\;OC - \; Batt\_load_{ar}) * BSP * \; Max\;OC * Eff}{CP} * 60 \qquad \text{Eq. 6}$$

Finally, based on the minimum and maximum charging time, the minimum and maximum departure battery loads are derived. The minimum departure battery load is equal to the arrival battery load plus the minimum charging load, while the maximum departure battery load is the arrival battery load plus the maximum charging load. Therefore, the maximum departure battery load is often equal to the maximum OC rate. Those departure battery loads are used to set the last calculated/derived battery load when the same vehicle arrives at the/a charging station again. For clarification, model results of one vehicle are shown in Table 4-4. In this example, the minimum charging time is considered. Hence, the minimum departure battery load is equal to the battery start load of the next arrival. The covered distance is equal to the distance to cover of the previous arrival. That means that the vehicle is operating at the same line during the whole simulation.

*Table 4-4 - Charging time calculation model results for one vehicle*

| #A | Battery start % | Covered distance (km) | Distance to cover (km) | Arriving battery % | Min req. battery % | Min charging time (min) | Max charging time (min) | Min dep. battery % |
|---|---|---|---|---|---|---|---|---|
| 1 | 80,00% | 21,18 | 21,18 | 68,53% | 11,47% | 0,00 | 3,03 | 68,53% |
| 2 | 68,53% | 21,18 | 10,04 | 57,06% | 5,44% | 0,00 | 6,06 | 57,06% |
| 3 | 57,06% | 10,04 | 21,18 | 51,62% | 11,47% | 0,00 | 7,49 | 51,62% |
| 4 | 51,62% | 21,18 | 10,04 | 40,14% | 5,44% | 0,00 | 10,52 | 40,14% |
| 5 | 40,14% | 10,04 | 21,18 | 34,71% | 11,47% | 0,00 | 11,95 | 34,71% |
| 6 | 34,71% | 21,18 | 10,04 | 23,23% | 5,44% | 0,58 | 15,00 | 25,44% |
| 7 | 25,44% | 10,04 | 21,18 | 20,00% | 11,47% | 3,03 | 15,84 | 31,47% |
| 8 | 31,47% | 21,18 | 10,04 | 20,00% | 5,44% | 1,44 | 15,84 | 25,44% |

The model is also able to calculate the charging times for charging activities at the depot only. In practice, this problem is better known as the Hermes problem. Hermes is the public transport operator in Eindhoven where the first large scale electric fleet was implemented, as discussed in section 2.3.2. In Eindhoven, all charging activities, both fast and slow, take place at the depot. In the model, the loss time due to charging, concerning two times the driving time to the depot (and back) and the charging time, is captured by the deployment of extra vehicles. The number of charging activities is counted. At the same time, when the loss time of a vehicle is over, one vehicle will be subtracted again. The highest number arose in this charging counting column, represents the number of extra vehicles required to charge at the depot without causing extra delays.

### 4.2.3 Model assumptions

Some characteristics of the operations are unknown or outside the modelling scope. Therefore, some assumptions are made in order to be able to calculate the charging times. A subdivision is made here: the filled dots represent assumptions used in the determination of the input variables (section 4.1.1), while the empty dots represent assumptions used for the calculation of the charging times (section 4.1.2).

- A random failure rate is considered for OC equipment with a higher maximum OC rate than 80%. The non-linearity of the charging process for higher rates than 80% is therefore not modelled.
- For the determination of the distances between different charging locations and terminals, the research station is considered as the only fast charging location in the network. When multiple fast charging locations in the network should be modelled, the distances per trip should be adapted manually.
- The use of only one depot per operator is considered. All vehicles of the operator go to that depot if they are not in operation. This is considered, because all distances from the depot to the end and start stops of all bus lines should be determined by forehand. It always contains the closest depot to the research station.

○ It is considered that all vehicles are completely charged at the depot. Therefore, the assumed last battery load is 100% when the vehicle originates from the depot. Here is no charging time dependent component included.

○ When a vehicle arrives at the charging station for the first time and it is not coming from the depot, it is considered that the battery load at the start of its trip is equal to the maximum OC rate. In such situations, vehicles performed operations on another line, not serving the charging station. The route lengths covered on these lines is unknown.

○ When a vehicles trip starts at the operations starting time or if the previous arrival of the vehicle at the terminal is more than four hours ago, it is considered that the vehicle came from the depot.

○ When a vehicle trip ends at the operations ending time or if a vehicle is not signalised at a terminal for more than four hours, it is considered that the vehicle went back to the depot.

○ When the distance covered or the distance to cover of a vehicle is unknown, the distance from the terminal to the charging station or the distance from the charging station to the terminal respectively, is multiplied by two to get the assumed driving distance. This happens for instance when a vehicle continuous operations on another line, which is not serving the charging station. This considered distance is equal to the distance when the vehicle continues operations at the same line.

## 4.3 Bus station operations model

The second part of the model, the bus station operations model (Figure 4-7), consists of the Simbus input Excel-sheet and six underlying sheets. Those underlying sheets are supported data in order to develop the Simbus input sheet. All sheets are explained in detail in section 4.2.2, but first, all input variables for the bus station operations simulation are discussed in section 4.2.1. At last, the model assumptions for this part, are summarized in section 4.2.3.

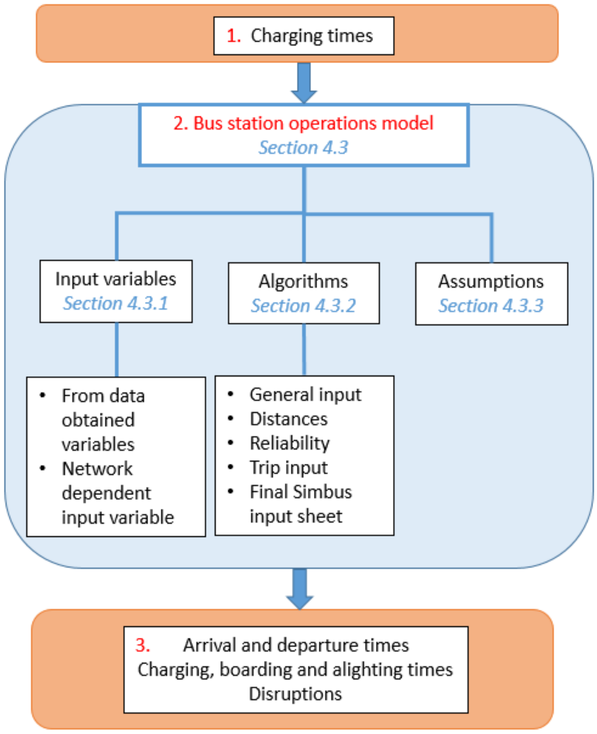



*Figure 4-7 - Bus station operations model; input, model explanation and main output*

### 4.3.1 Input variables

Some important input variables for the bus station operations simulation are also used in the calculation of the charging times. Hence, those variables are already discussed. Only additional input variables, which contain only dependent input variables, are discussed here. A new group of dependencies, DIV depend on network specific characteristics, is also introduced here.

#### *4.3.1.1 Input variables obtained from AVL data*

*Dispersion:* Based on the target and recorded arrival and departure times, included in the AVL data, the dispersion in arrival and dwell times can be derived for different periods of the day, as discussed In section 3.5.1. The results are imported in a reliability data sheet. Based on these values, the average deviation and standard deviation of the arrival and dwell times are assigned to each trip.

#### *4.3.2.1 Network dependent input variables*

*Deadheading distances:* The deadheading distances represent the distance from the charging station to the depot and depends on the location(s) of the depot(s), which is/are case dependent and not traceable from the AVL data. Therefore, the distance from the last stop to the depot and from the depot to the first stop should be derived. In combination with the line distances (discussed in section 4.2.1.2), the deadheading distances can be derived. It should be considered here that the first and the last bus stop not always corresponds with the terminals.

*Number of platforms and platform lengths:* These variables depend on the station layout. The number of platforms is an important constraint in the vehicle allocation problem, where Simbus is developed for. The platform lengths determines which restrictions are involved in the platform allocation for buses with different lengths.

*Number of entrances, exits and long and short term buffer places:* These variables depend on the station layout and are relevant Simbus input variables.

*Driving time between station components:* Those components are entrance(s), exit(s), boarding and/or alighting platform(s) and buffer place(s). The driving times depend on the station layout and are derived by dividing the distances by the average driving speed of the vehicles inside the station. All distances are set in a distance matrix, included in Appendix F. The average driving speed between station components is set to 30 km/h.

### 4.3.2 Bus station operation simulation

The second part of the model consist of seven sheets: one final Simbus input sheet, four supporting sheets in order to develop the final sheet and two data sheets. One data sheet consist of the trip data, this time ordered per line. The other data sheet consist of the calculation results of the monthly average deviations and standard deviations of the arrival times and dwell times. The other five sheets are discussed in the remainder of this section.

**Sheet 1: General input**

As discussed in section 4.3.1, the station layout input variables are set in the input sheet. The number of platforms for boarding and alighting and the number of buffer places, entrances and exits are set. Also the platform allocation per line is determined. Per line, serving the station, the preference platform is set. For each line it is also possible to select other platforms to move to when their preference platform is already occupied. Also a small database of non-electric vehicles including their lengths are included in this sheet. This information is obtained from an earlier performed research by Goudappel Coffeng at Schiphol Plaza.

**Sheet 2: Distances**

In this sheet, the geometry of the bus station, including platform types (boarding, alighting) and lengths are set. Also the distances between all station components, described in sheet 1, are set in a distance matrix. Those distances, expressed in meters, are measured using Google maps.

**Sheet 3: Reliability**

In a reliability sheet, the results of the averages and standard deviation calculations of arrival and dwell times per line for the two peak hours and the rest of the day, are assigned to each trip. When there is no deviation or standard deviation assigned to a trip, for instance if only one trip is performed in one period, the average deviation or standard deviation of the whole month, is assigned to that trip.

**Sheet 4: Trip input**

In this sheet, the trip data is ordered per line and direction and sorted on arrival time. For each trip, the line number, driving direction and vehicle number for both arrival and departure, including the corresponding times, are shown. Here, it is also indicated when a vehicle came from the depot or goes to the depot. The resulting charging times from the first part of the model are assigned to each trip. The short-term buffer is used for charging the vehicles. Therefore, the number of short-term buffer places should be equal to the number of available charging points. Based on this information, a number is assigned to each trip, describing the route of a vehicle inside the station. All relevant numbers are indicated in Table 4-5.

*Table 4-5 - Numbering classification of the bus route at the station*

| Station route nr | Meaning | When to use? |
|---|---|---|
| **1** | Alighting – Charging – Boarding | Charging during operations |
| **2** | Alighting – Boarding | When there are different platforms for those activities |
| **3** | Charging – Boarding | Charging when the vehicle is empty while arriving at the station. For example when the vehicle came from depot |
| **4** | Boarding | When those activities take place at the same platform |
| **5** | Alighting – Charging | Charging when a vehicle will be empty while departing at the station. For example when the vehicle will go to the depot |
| **6** | Alighting | When the vehicle stops for the last time before it goes to the depot |

*Based on Jägers (2001)*

The deviations and standard deviations of the arrival and dwell times, retrieved from the reliability input sheet are assigned to each line and direction. Dependent on the bus route at the station, the deviation and standard deviation at the alighting platforms and buffer places are also represented. Finally, the vehicle lengths and the used entrance and exit per vehicle are represented.

**Simbus input sheet**

The calculation results, based on the input parameters or some input parameters itself, are linked to the input sheet for Simbus. First, some general simulation settings, partly obtained from sheet 1, are shown in this sheet. In Appendix G, a complete overview of all components of the general settings (for the application) is presented. Secondly, station layout characteristics, retrieved from sheet 1 and 2, are presented. The number of entrances, exits, short-term and long-term buffer places, boarding and alighting platforms is copied to this file, as well as the distance matrix. Then, all trips, including their arrival, dwell and (possibly) charging times and the standard deviations are shown. Each Excel row represents one trip arriving at the station. In other words, each trip is generated individually. For each (peak/off-peak) period of the day, an extra Excel row needs to be added manually, in order to distinguish different groups. This distinction is made according to line number, driving direction and time of the day, as represented in Figure 4-8.

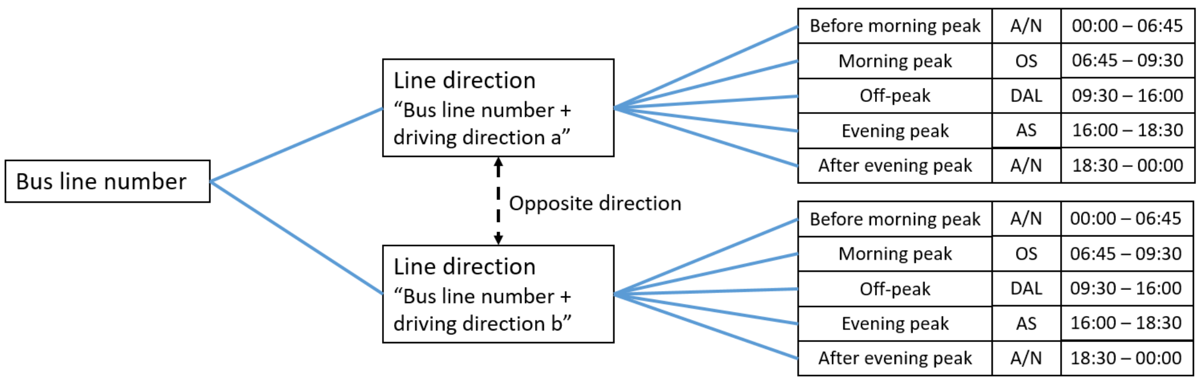



*Figure 4-8 – Distinction in different groups where trips should be assigned to*

Each group needs to have a unique number, and the number of trips inside each group should be counted. The maximum allowable number of trips per group is 50. Per group, the buffer place and platform allocation, as set in the input sheet, is shown. Per trip, the target arrival time is shown, followed by its average deviation and standard deviation. Those values are calculated per morning peak, evening peak and off-peak period, so the (standard) deviations are equal for the different trips inside each group. In the simulation, Simbus picks the deviation from the normal distribution for each trip.

The output text file is imported into Excel again. In this Excel file, Simbus output variables: arrival, departure, alighting, charging and boarding times and disruptions, are translated into values for the assessment criteria. In order to do that, the third part of the model: cost/benefit calculation model (section 4.4) is developed.

### 4.3.3 Model assumptions

For realising the simulation, certain assumptions need to be made. Again, the bold dots represent assumptions used in the determination of the input variables (section 4.3.1), while the empty dots represent simulation based assumptions.

- It is assumed that all inter station trips are executed with a vehicle speed of 30 km/h.
- ○ When there is no deviation and/or standard deviation assigned to arrival and dwell times of a specific trip, the average (standard) deviation of all calculated values is assigned to that trip.
- ○ The standard deviation of charging a vehicle is considered to be 10%. In literature, no concrete value is mentioned for that, but there is always some deviation considered. Based on expert judgement, a 10% standard deviation is reasonable (Veenendaal & Naber, 2017).
- ○ The arrival times are fixed in such a way that the arrival time of a vehicle does not depend on the departure time of the same vehicle earlier that day. In other words, a delay caused by charging a vehicle does not result in a delay for the next trip. This assumption is made in order to not change the timetables too much. This research does not focus on timetable planning of electric vehicles, but focuses on the impacts of charging at a station. The conventional timetables used for this, are often not developed for electric vehicle operations.
- ○ The boarding and alighting platforms are considered to be independent. In reality, those individual activities can take place at the same platform (see chapter 6), which implicate dependencies between those platforms. How large these dependencies are depends on the station layout. In case of DIRO, this dependency is larger compared to a DIDO situation.

## 4.4 Cost/benefit calculation model

In the last part of the model (Figure 4-9), the Simbus simulation results are translated to a quantification of the assessment criteria. Therefore some additional input is necessary (section 4.4.1). Then, the required formulas for calculating the costs and benefits of a simulated daily operation pattern, are explained (section 4.4.2), followed by an summary of the assumptions made (section 4.4.3).

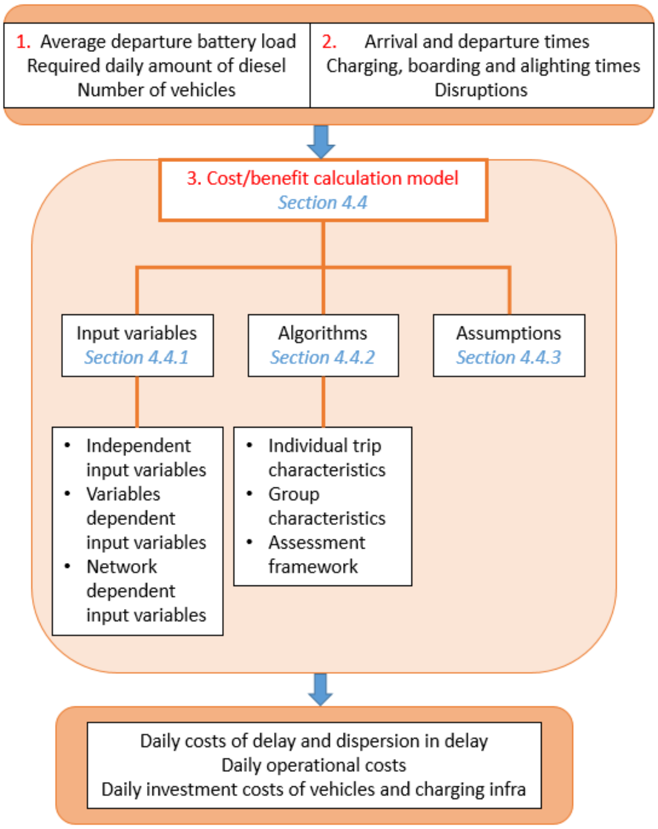



*Figure 4-9 - Cost/benefit calculation model; input, model explanation and main output*

### 4.4.1 Input variables

Also for this model part, some additional input variables are necessary in order to calculate values for the assessment criteria. Both, independent and dependent input variables are involved.

#### *4.4.1.1 Independent input variables*

*Vehicle costs:* The considered costs per vehicle are shown in Table 4-6. Based on literature (Section 2.2.2), a standard price for a conventional diesel bus is around €200,000, while the price of an electric bus is around two times more. However, the investment of a standard bus including ICT is around €250,000 (CROW, 2015), so an additional price of €50,000 is considered for each vehicle. A price factor of 1.5 is mentioned for an articulated bus (CROW, 2015), which corresponds with an additional price of €100,000.

*Table 4-6 - Vehicle investment costs per vehicle type*

| | Rigid/standard bus | Articulated bus |
|---|---|---|
| **Non-electric vehicle** | €250,000 | €350,000 |
| **Electric vehicle** | €450,000 | €550,000 |

*Source: CROW (2015)*

*Vehicle propulsion costs:* Here, once again, a distinction is made between electric and diesel engine vehicles. The assumed vehicle propulsion costs for an electric vehicle is €0.088/kWh and the propulsion costs for an diesel engine vehicle is €1.093/litre. These values are based on the average Dutch green energy price excluded VAT of €0.05 - €0.07 per kWh (Milieu centraal, 2018) and the actual Dutch diesel price of €1.384 per litre (price of 8 January 2018), excluded VAT, respectively. However, for electricity, more cost components are involved in the price. An average tax of €0.018 is added. This value is based on an annual use of 5 million kWh, which correspond with a low energy use variant (section 5.2). In practice, for more energy use, this value decreases, so the price per kWh decreases as well (Belastingdienst, 2018).

*Fuel consumption diesel buses:* It is considered that the average consumption of BRT vehicles is one litre diesel at four kilometres driven. The average consumption of city and regional vehicles is set to one litre diesel at three kilometres driven (CROW, 2015).

*Costs per vehicle hour:* In order to express the operators loss time in costs, the costs per vehicle hour is considered. Per vehicle hour, this contains €110 (CROW, 2015).

*Value of time and value of reliability:* These two variables, the VoT and VoR, are used for quantifying the delay and dispersion in delay experiences by travellers into costs. Therefore, those values are multiplied with the number of affected passengers. For both values, the average for category bus/tram/metro is taken, which gives a VoT of €6.75 and a VoR of €3.75 (Warffemius, 2013).

*Charging infrastructure and vehicle lifetime and discount rate:* The discount rate of vehicles is 6% (CROW, 2015), as well as the discount rate of the charging infrastructure. The lifetime of all vehicles and charging infrastructure types is considered to be 12 years, however, in practice, this will be highly influenced by the duration of the concession. For the charging infrastructure costs, not only the charging equipment is considered, but also the required surface for the charging activities. This consist of an average of 60 square meters for each charging point (depend on maximum vehicle length) plus an additional 150 square meters for the marshalling yard. This surface is multiplied by the case specific local ground price.

#### 4.4.1.2 Input variables depend on independent input variables

*Charging equipment costs:* Different charging equipment, including their predefined costs (section 2.4.3) are included in the model and shown in Table 4-7. In order to use certain charging equipment, some adjustments to the vehicles need to be made. Those additional vehicle costs, based on section 2.4.3) are included in Table 4-7 either.

*Table 4-7 - Charging equipment and investment costs*

| Charging method | Charging equipment | Charging infrastructure costs | Additional costs per vehicle |
|---|---|---|---|
| **Overnight** | Pantograph | €35,000 | €15,000 |
| | Plug-in | €25,000 | €0 |
| **Opportunity** | Pantograph | €150,000 | €15,000 |
| | Induction | €100,000 | €16,000 |
| | Plug-in | €25,000 | €0 |
| | IMC pantograph | €500,000/km | €15,000 |
| | IMC induction | €400,000/km | €16,000 |

*Sources: Centrum Vernieuwing Openbaar Vervoer (2005), Wiesinger (2014) and Gudde (2016)*

#### 4.4.1.2 Network dependent input variables

*Passenger load:* The passenger load per trip is (unfortunately) not involved in the AVL data, however, the passenger load during the trip is an important variable. First, the passenger load at the charging station is important in order to quantify the effects of the charging time. Secondly, the passenger load over the line section after the charging station is important in order to quantify the effects of unreliability of charging times. For this research, the difficult to obtain APC data is excluded. In vehicle passenger loads can be obtained by more basic and simple, but less accurate data collection methods, such as on-location passenger counts.

*Passenger factor:* According to van Oort (2011), basic occupancy patterns at public transport lines can be described using the graphs in Figure 4-10. The network characteristics and location of the charging station in the network determine which occupancy pattern and which location on the line are relevant for each charging station. In A, all passengers board at the start terminal and alight at the end terminal. This could be an example of a basic representation of a long distance bus connecting two cores. In B, every stop, people get into the vehicle, till a certain stop at the line, where after, every stop, people alight. An example of such an occupancy pattern could be a vehicle connecting outlying areas with a city, especially during peak periods. In C, the pattern is comparable with B, however, there is one hotspot in the area where a lot of people board the vehicle.

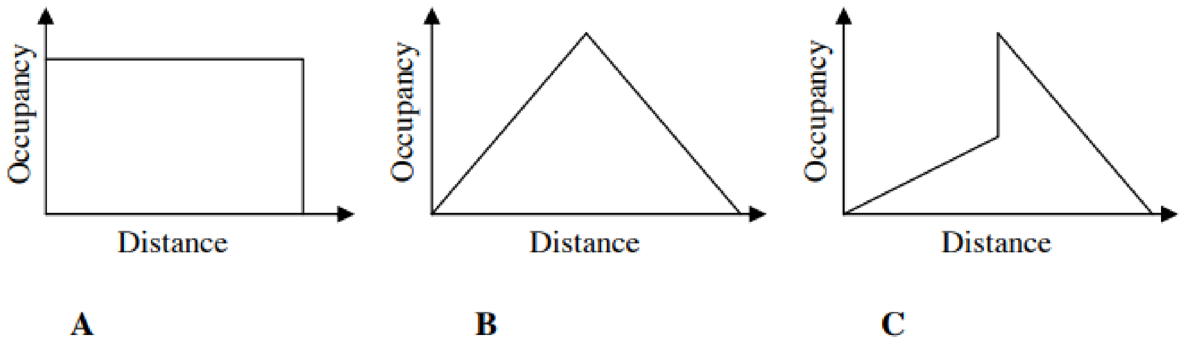



*Figure 4-10 - Basic occupancy patterns at public transport lines. Source: Van Oort (2011)*

Based on the corresponding pattern and location of the charging station for each line, a passenger factor is determined per case. The number of passengers inside the vehicle is multiplied with the passenger factor in order to get the number of passengers encountered delay. This is relevant information for the calculation of reliability aspects.

### 4.4.2 Costs and benefits

The Simbus simulation results in an output text file including certain meaningful pieces of information concerning actual arrival, dwell, charging and departure times as well as numbers of disruptions. Each output file is opened in Excel in order to analyse the results. In order to calculate values for the assessment criteria, two sheets are developed as intermediate step. In the first sheet, individual trip characteristics are calculated and in the second sheet, characteristics per group defined in section 5.2.2, are determined. First, those two sheets are described shortly, followed by an elaboration of the final sheet, where the assessment criteria are quantified.

**Sheet 1: Individual trip characteristics**

In the individual trip characteristics sheet, the delay in arrival and departure is calculated based on the target and recorded arrival and departure times. Moreover, the delayed departure times are assigned to the corresponding time of the day. The passenger loads are allocated to the time of the day. Based on the delayed departure times and passenger loads per trip and a fixed value of time, the cost of delayed departure is calculated. Finally the standard deviations of all trips per group (line, direction and time of the day) are derived in this sheet.

**Sheet 2: Group characteristics**

Other relevant data obtained from the Simbus simulation output, are process times ordered per group. The simulated boarding, alighting and charging times, including the dispersion per group, are represented here. In sheet 2, this data is ordered and processed towards six relevant variables per group: 1) total number of departures, 2) number of disrupted departures, 3) total loss time due to disruptions, 4) number of charged vehicles, 5) average charging time, and 6) standard deviation of the charging time. Moreover, the number of passengers from sheet 1 are summed up per group and also the determined passenger factors per line are set here.

**Sheet 3: Final cost and benefit calculation**

In this sheet the assessment criteria are quantified in costs and benefits. Per assessment criteria, the calculation of the costs and benefits are elaborated on.

*Disruptions:* The first assessment criterion is the number of disruptions. The number of disruptions is expressed as percentage of the total number of trips arriving at the station. Both, the number of disrupted trips and the total number of trips per group, are derived from sheet 2. In this sheet, the percentages are calculated for each line and direction. Finally, the overall disruption percentage is calculated. In order to verify the calculations, the final disruption percentage is compared to the disruption percentage in the Simbus output file.

*Delay in departure time:* The first level of service criterion is the delay in departure time, which is derived by sum up the costs of delayed departure for each trip from sheet 1. The daily costs of delayed departure is calculated according to the following formula:

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

*Dispersion in departure time:* Except the delay in departure times, the dispersion in departure times is also considered in the assessment of the level of service. Therefore, the standard deviations and number of affected passengers is obtained from sheet 1 and sheet 2 and are ordered per line number and direction and period of day. Thereafter, those values are multiplied by the VoR and summed up:

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

Based on the delays and dispersion in delays, more information can be obtained. Hence, the delays of all trips per group are averaged and compared to the dispersion of other groups. For groups with a relatively low dispersion, it is easier to reduce the costs of delayed departure by adjusting the timetable slightly, even when the delays are quite large. Therefore, a distinction is made in delays with high variation and delays with low variation. A group is categorised in the low variation category when the average delay is at least twice as large as its standard deviation.

*Operational delayed vehicle costs:* The costs per vehicle hour is multiplied by the extra inefficient hours caused by delayed departures in order to obtain the operational vehicle costs.

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

In equation 7, the delays are expressed in costs to express passengers inconveniences, while the delays in equation 9 are expressed in vehicle hours. Those costs are for the operator. The delays are involved in two criteria, but for each criterion, the costs of delays are assigned to another stakeholder.

*Operational charging/fuelling costs:* this cost component is subdivided in costs for OC (green), costs for slow charging (blue) and costs for fuelling (red), according to equation 10.

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

The total charging time ($\sum_{i=m}^{n} t_{charge_i}$) is derived from sheet 2 and the average departure battery load ($Av\ Batt\ load_{departure}$) is calculated in the static charging time calculation model. This value is used to calculate the average amount of power per vehicle to completely recharge all vehicles during the night. It is assumed that the average battery load at departure is a good estimate for the average battery load for arrivals at the depot. Therefore, it should be mentioned that the results of the overnight charging costs calculation are rough estimates. At last, the required amount of diesel ($\sum_{k=m}^{d}(d_{covered} * FC)$) for the diesel engine vehicles is calculated in the static charging time calculation model. The distance covered by a non-electric vehicle is multiplied by its fuel consumption rate. The results of all diesel engine vehicles are summed up and multiplied by the diesel price in order to get the daily operational fuelling costs for all non-electric vehicles.

*Vehicle investment costs:* For the vehicle investment costs criterion, a distinction is made in electric and non-electric vehicles, but also in rigid/standard and articulated vehicles. For those vehicle categories, different prices are considered, as previously discussed in section 5.3.1. In the charging time calculation model the number of vehicles is derived for each category. The net present value of the vehicles is determined, which is finally expressed in daily costs:

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

*Charging infrastructure investment costs:* For this criterion, the fast charging infrastructure systems are distinguished from the depot charging infrastructure systems. For the fast charging systems, the use of space is considered, because this arise as an important limitation in urban environments. For slow charging at the depot, the number of charging points is equal to the number of electric vehicles in order to recharge all electric vehicles overnight. The total charging infrastructure costs are calculated as follow:

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

### 4.4.3 Model assumptions

As for the last model part, assumptions are mentioned throughout the text, they are summarized in this section.

- It is considered that operators do not pay any VAT for diesel and electricity at all. Only a fixed tax for electricity of €0.018 per kWh is considered. For the determination, tariffs from two boxes are considered according to a ratio corresponding to an annual energy use of 5 million kWh.

- For the determination of the VoT and VoR, no distinction is made between types of travellers, because the travel motives are unknown. Therefore, the average VoT and VoR for category bus/tram/metro is taken.
- Although the lifetime and discount rate of charging equipment and vehicles highly depend on the concession duration, fixed values for those variables are considered. The lifetime and discount rate of charging equipment and vehicles are considered to be 12 years and 6%.
- Passenger loads are based on random values between a minimum and maximum occupancy rate per line for a peak-period and an off-peak period. Thus, per line direction, four values between zero and one are given, representing the minimum and maximum share of the total capacity in a peak-period and in an off-peak period. Those values are assumed based on a total daily number of passengers (expert judgement) and an on-location based passenger distribution over the lines (passenger counts).
- The derivation of the number of passengers affected by delays is based on three basic passenger occupation patterns and an assumed location of the charging station in such a distance/occupancy graph. This location is based on the ratio of the distance between terminal A and the charging station and the distance between the charging station and terminal B, followed from section 4.2.1.
  - For depot charging, it is assumed that the average battery load of the vehicles arriving at the depot can be estimated by considering the average battery load of the vehicles departing at the charging station.
  - For slow charging at the depot, the number of charging points is equal to the number of electric vehicles in order to recharge all electric vehicles during the night.

## 4.5 Bus station model variants

The first sections have explained the models workings. Based on three model modules, it is explained how the model works. The modules together form the (Z)E-bus stations operations model. In this section is discusses what will be modelled by the (Z)E-bus station operations model. The model variants are obtained by discussing the charging mechanisms and the development paths in sequence.

### 4.5.1 Charging mechanisms

The (Z)E-bus operations model calculates the minimum and maximum charging time per trip and translates this, including all other input variables, into a Simbus simulation input sheet. 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 are developed from different points of view. Those charging mechanisms are shown in Table 4-8 and further explained in the remainder of this section.

*Table 4-8 - 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 |

The calculation of the minimum and maximum charging time per trip is already explained in section 4.2.2. The minimum charging times are only larger than zero when charging is necessary to perform the next trip, without ending up with a battery load below set the battery buffer rate. The minimum charging time is exactly enough to perform the next trip and arrive at the/a charging station again with a battery load equal to set the battery buffer rate. According to the maximum charging time mechanism, a vehicle is always recharged to the maximum OC rate when the battery load is lower than that value. The minimum and maximum charging times determine the ranges of the charging times per trip arriving at the charging station. The three following charging mechanisms assign the maximum or the minimum charging time to each trip, according to specific rules, represented in the 'Charging principle' column in Table 4-8.

For Peak, the calculation of the maximum charging times are used, except for peak periods. Then, the minimum charging times are used, in order to use the vehicles as optimal as possible during the busiest hours of the day. Not only minimum charging times are considered during peak hours, but all vehicles already have a relatively full battery pack at the start of the peak periods. For cases with delay related problems during peak periods and an obvious difference in number of passenger movements and/or line frequencies between peak and off-peak periods, this charging mechanism could offer a valuable solution. According to this mechanism, a relatively high amount of vehicles is charged, so the distances between the boarding and alighting platforms and the charging locations should be minimized, as well as the time to start the charging process, in order to limit the loss time.

In Place, vehicles are recharged to a maximum if there a is place to charge. The vehicle that enters the last available charging point, is minimally recharged. In this way, the waiting time before charging is limited compared to the maximum charging time mechanism. This charging mechanism could offer a solution when there are space limitations at charging locations and it is not possible to add more charging points. However, this mechanism often has the same problems with high loss times as the previous one.

Need assigns vehicles to charging places only if charging is necessary. This is the same as the minimum charging time mechanism, however, in this mechanism, the vehicles are recharged to a maximum level instead of to a minimum level. This results in a minimum amount of charging location usage. This mechanism could also offer possibilities for cases with space restrictions. However, in cases of homogeneous operational and network characteristics, this charging mechanism could result in an overload of empty batteries at a certain moment of the daily operations.

### 4.5.2 Development paths

The goal of the Zero-emission agreement is to have zero-emission buses in operation by 2030. In the transition period, from now till 2030, multiple decisions should be made by operators and/or public transport authorities in order to realise the replacement of conventional diesel buses by sustainable zero-emission vehicles. Different development paths are possible to reach the goal. These paths, including some important decisions to make during the transition period, are shown in Figure 4-11.

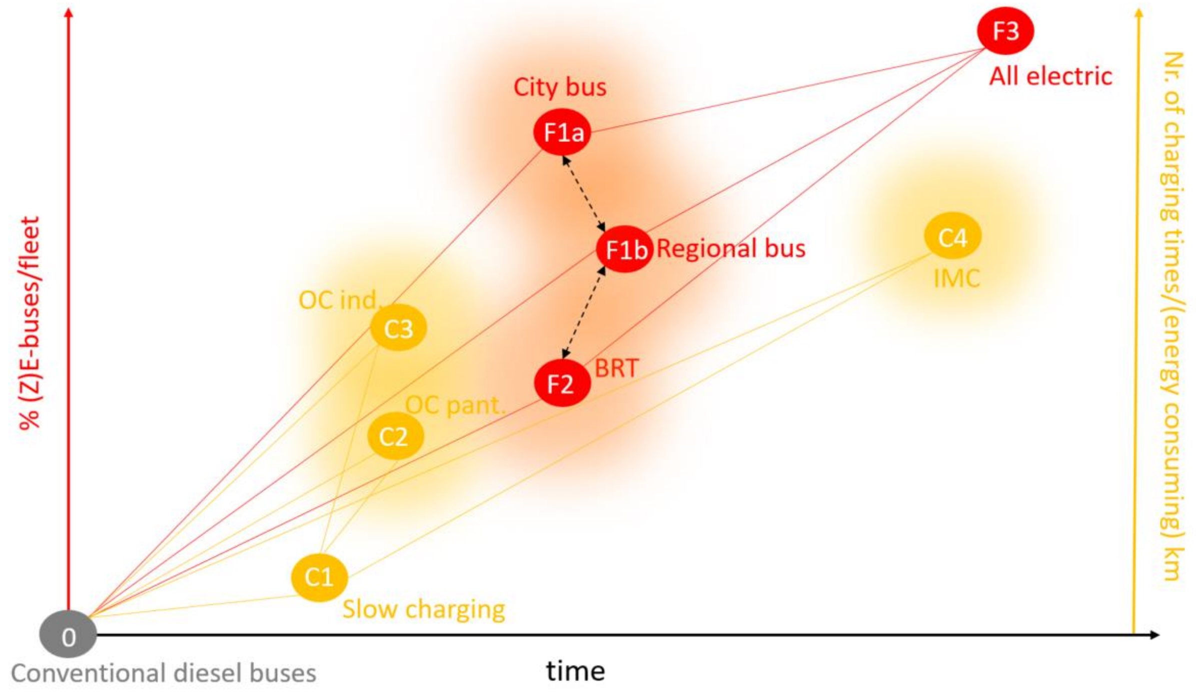



*Figure 4-11 - Development paths for electric operations*

In red, the transition period from only conventional diesel buses towards full electric operation is shown. An important decision (for an operator) to make is which vehicle types should be electrified first. A distinction is made here between BRT, city buses and regional buses. The introduction of electric regional vehicles has shifted more forwards in time, because their long distances and low frequencies makes them more problematic for electrification, especially in case of OC. Hydrogen vehicles may offer good solutions for this vehicle category (Veenendaal & Naber, 2017). The distinction between city and regional vehicles could therefore be made, but they can also be considered as one group. This will be case dependent. An operator can choose to electrify the general city buses (F1a) and/or regional transport vehicles (F1b) first or to give priority to purchasing an electric fleet for the BRT lines (F2). Also, all variations in F1a, F1b and F2 and between F1a, F1b and F2 are possible. For example, vehicles can be electrified per line or some BRT lines and some city and/or regional transport lines could be electrified at the same time or in a certain time frame, like a couple of years. Because of the possible variations, a red glow around F1a, F1b and F2 is visible in Figure 4-11.

In yellow, the development path of the charging method choice is shown. On the secondary (yellow) vertical axis, the number of charging times relative to the total distance covered is displayed. For slow charging (C1), a vehicle should be charged slowly in a couple of hours, while for OC (C2 and C3), vehicles are charged faster and more often between the trips. In practice, mostly, OC is combined with overnight charging, however, it can also be used as the sole charging method. As discussed in chapter 2, different OC infrastructure equipment, including different charging power and charging efficiencies exist. Therefore, a distinction between pantograph (C2) and induction (C3) charging is made here. The number of charging times vary, depended on the (downsized) battery size, the energy consumption rate and the operational distances. The same yields for IMC (C4). The number of charging times per (energy using) kilometre driven is higher compared to OC, because the battery is recharged while driving. IMC is a very promising option for the future, but is still in its infancy yet. Only the trolleybus is a concept of IMC, which is already applied in practice. However, a lot of resistance to trolleybus systems exist due to landscape pollution reasons and in addition, high investments are required to realise a whole trolleybus infrastructure system. Therefore, only innovative IMC systems, like induction or pantographs are suggested by C4[4].

### 4.5.3 Model variant identification

Based on the charging mechanisms and the development paths, 64 variants, plus the base case, can be made, as indicated in Table 4-9. The base case is developed to compare the model results of the other variants with. Slow charging by a plug-in cable or a pantograph, takes place at the depot and the vehicles that should be charged are replaced by other vehicles. Therefore, the most important question for this charging method is: how many extra vehicles are required to perform the operations (Hermes problem)? 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 charging at the depot.

*Table 4-9 - Model variant identification based on charging mechanisms and two development paths*

| **0** | Base case: all diesel and no charging necessary | | |
|---|---|---|---|
| **C1** | Slow charging | **F1a** | City buses |
| **C2** | OC pantograph | **F1b** | Regional buses |
| **C3** | OC induction | **F2** | Only BRT |
| **C4** | IMC | **F3** | All electric |

| | **C1 F1a** | **C1 F1b** | **C1 F2** | **C1 F3** | **C2 F1a** | **C2 F1b** | **C2 F2** | **C2 F3** | **C3 F1a** | **C3 F1b** | **C3 F2** | **C3 F3** | **C4 F1a** | **C4 F1b** | **C4 F2** | **C4 F3** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Min** | - | - | - | - | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 |
| **Max** | - | - | - | - | 6 | 11 | 16 | 21 | 26 | 31 | 36 | 41 | 46 | 51 | 56 | 61 |
| **Peak** | - | - | - | - | 7 | 12 | 17 | 22 | 27 | 32 | 37 | 42 | 47 | 52 | 57 | 62 |
| **Place** | - | - | - | - | 8 | 13 | 18 | 23 | 28 | 33 | 38 | 43 | 48 | 53 | 58 | 63 |
| **Need** | 1 | 2 | 3 | 4 | 9 | 14 | 19 | 24 | 29 | 34 | 39 | 44 | 49 | 54 | 59 | 64 |

In order to obtain more and better insights in both the model dynamics and model capabilities (and limitations), and in order to perform a reality check for the model results, some extreme scenarios are simulated. In these extreme scenarios, multiple variables are slightly changed in order to assess the operations, level of service and costs under specific and/or extreme conditions. Per scenario, the mutation of the variables should reinforce each other in a certain way. Valuable scenarios are highly case dependent, so they are further explained in chapter 5.

[4] If the trolleybus system was considered, it should be placed in the upper left corner of Figure 4-11.

## 4.6 Conclusion

In this chapter, the three different model modules are elaborated: 1) Charging time calculation model, 2) Bus station operations model, and 3) Cost/benefit calculation model. In the first model part, the minimum and maximum charging times are calculated based on 1) A list of independent input variables, which should be selected by the model user, 2) Dependent input variables, depend on the independent input variables or on each other, and 3) Input variables, directly or indirectly obtained from the AVL data. For the charging time derivation, as well as the number of extra required vehicles in case of depot charging, basic calculations are performed for each trip. The charging times are restricted by pre-determined input variables, like battery buffer and max OC rate.

In the second model part, a translation from the trip data, as well as the calculated charging times and different reliability values, towards an input sheet for Simbus, is provided. Besides the reliability values (dispersion), some network dependent input variables are derived. The bus station operations model consist of different sheets: 1) Two input data sheets, 2) General input sheet, 3) Distances sheet, 4) Reliability sheet, 5) Trip input sheet, and 6) Final Simbus input sheet. Sheets 1 till 5 are supported sheets in order to develop the final Simbus input sheet, required to perform the bus station operations simulation in Simbus.

The last model part is the Cost/benefit calculation model, required to translate the Simbus simulation output into values for the assessment framework criteria. Also output variables of the first module are used, like the number of electric and diesel engine vehicles, the required amount of diesel and the average departure battery load. Furthermore, some extra input variables are needed: 1) Independent input variables, in order to translate different units into costs, 2) Input variables depend on independent input variables, including the charging equipment costs, and 3) Network dependent input variables, concerning number of passengers. Using two supporting sheets, including individual trip characteristics and group characteristics, values for the assessment criteria are obtained in the final cost/benefit calculation sheet.

Finally, the model variant identification is discussed. Based on five charging mechanisms: 1) Min, 2) Max, 3) Peak, 4) Place, and 5) Need and different development paths, concerning four charging methods: 1) Slow charging at the depot, 2) OC by pantograph, 3) OC by induction, and 4) IMC and four electrification distributions: 1) Only electric city buses, 2) Only electric regional buses, 3) Only electric BRT vehicles, and 4) All vehicles electric, 64 model variants are obtained. The Min and Max charging mechanisms represent the allocation of the calculated minimum and maximum charging times respectively, to each trip. The other charging mechanisms vary between Min and Max based on a charging mechanism dependent rule: For Peak, Min is considered in peak periods and Max in off-peak periods; for Place, Max is considered in general and Min when the last available charging point should be used; and for Need, Max is considered, but only when charging is necessary (according to Min). Besides, the final model variants, also a base case, considering only diesel engine vehicles is provided, in order to use as a reference.

# 5. Model application: Schiphol airport

In order to validate and test the model, the model is applied for a specific case, which is introduced in section 5.1. In section 5.2, the current plans and corresponding model settings are discussed. Then the model variants, model scenarios and a sensitivity analysis are elaborated on and the results are shown. An improvement measure is suggested in section 5.6, followed by the conclusions in section 5.7.

## 5.1 Introduction

After considerations of different candidate locations, Schiphol airport was chosen as application. Schiphol is the third largest airport in Europe (considering number of passengers in 2017), located in the Netherlands, southwest of Amsterdam (Vliegveldinfo.nl, 2018). Schiphol is interesting for this research, because multiple lines of different operators are operated here at different bus stations. Also BRT lines are serving the stations at Schiphol. These R-net lines are connecting relatively large surrounded cores with each other and Schiphol. These lines have high operational frequencies, just like the Schiphol Sternet lines, connecting the airport with multiple parking lots around the airport. This results in a high number of vehicle movements at the bus stations at Schiphol, especially at Schiphol Plaza, the bus station at the terminals of Schiphol airport. Besides, a new concession of Amstelland Meerlanden, has started in December 2017. The new concession in Amstelland Meerlanden from December 2017 to (at least) 2027, is granted to Connexxion. According to Connexxion's plans, 18 double decker and 100 electric vehicles are introduced, which makes it Europe's largest electric fleet size in one concession. However, the introduction of the electric vehicles is postponed until April 2018 due to practical problems (OV-Magazine, 2017). Goudappel Coffeng is involved in multiple projects at Schiphol and different colleagues mentioned: "when something works at Schiphol, it works everywhere."

## 5.2 Current plans and model settings

In this section, the current plans of Connexxion are described first. Secondly, these plans are translated to model input variables and model settings.

### 5.2.1 Electric exploitation plans for concession Amstelland Meerlanden

According to Connexxion's plans, two fast charging locations are considered: one at Knooppunt Schiphol Noord and one at P30 (Figure 5-2), in order to charge the electric vehicles. A new timetable is developed in order to optimize the planning including the facilitation of charging. Their concrete plans are summarized in Figure 5-1. Besides the two fast charging locations along the route, multiple fast charging points are located at the two depots, together with multiple slow chargers inside the depot. All electric buses are 18 meters, articulated buses, however, also 21 meter buses will be introduced in a further stage of the concession.

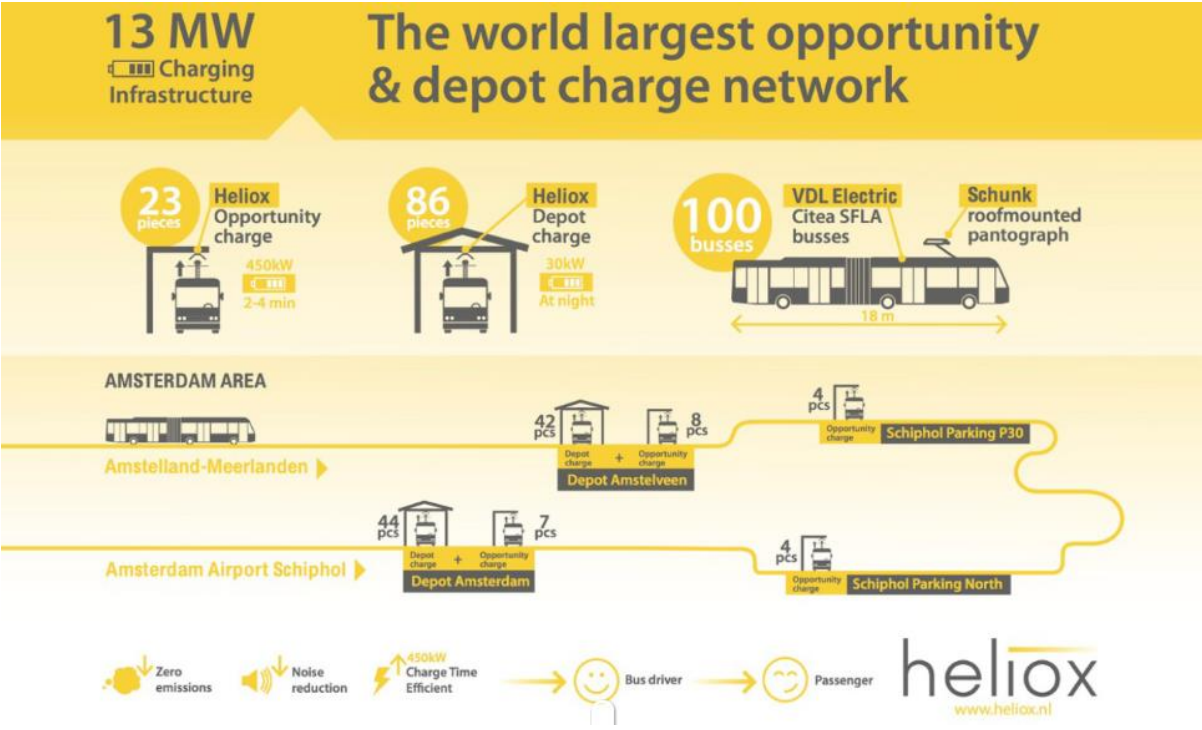



Figure 5-1 - Connexxion's electric operation plans in concession Amstelland Meerlanden

## 5.2.2 Model settings for Schiphol

In this paragraph, the model settings concerning the bus station, vehicle type, simulation day, battery (charging) limits and passenger loads, are discussed in sequence.

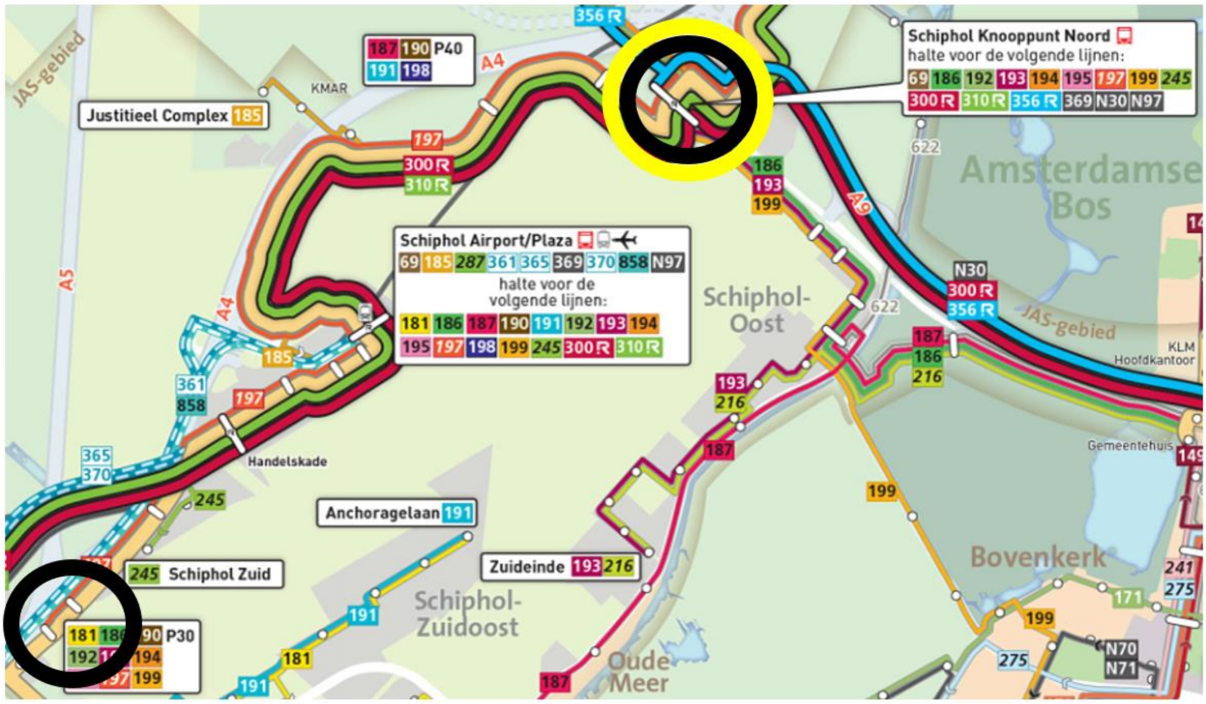



Figure 5-2 - Bus line map around Schiphol

**Bus station**

The model is developed to research one fast charging station in the network. In that way, the battery dynamics can be simulated in detail. Therefore, one fast charging station of the existing plans, is chosen for this research: Schiphol Knooppunt Noord (Figures 5-2 and 5-3). This station is serving more daily trips and more dispersion in different bus line types is present: R-net and Sternet lines of Connexxion and a city line of GVB are serving this station. Instead of four fast charging points at two bus stations, eight fast charging points at Schiphol Knooppunt Noord are considered. At Schiphol Knooppunt Noord, eight boarding and alighting platforms are available, whereof six platforms are designed according to the DIRO principle and two according to the DIDO principle (see Appendix B).

*Figure 5-3 - Schiphol Knooppunt Noord bus station. Photo (Wiercx)*

**Vehicle type**

The electric vehicles are also slightly different compared to the existing plans. The 100 electric VDL buses included in the plans, are 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 vehicle length, charging method and charging power according to Connexxion's plans, one vehicle, the Solaris Urbino 18 electric PA, appears, so this vehicle is chosen to resemble in this case. The specifications of this vehicle are summarized in Table 5-1.

*Table 5-1 - Selected electric vehicle specifications*

| Electric vehicle | |
|---|---|
| Company | Solaris |
| Vehicle model | Urbino 18 electric PA |
| Length | 18 meters |
| Passenger capacity | 129 |
| Energy consumption | 1.3 kWh/km |
| Battery storage Power | 240 kWh |

**Simulation day and battery (charging) limits**

The simulation day is Thursday 5 October 2017. This is a randomly chosen regular week Thursday outside a holiday period. In general, Thursdays (and also Tuesdays) are considered as busiest travelling days, especially in peak periods. 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. No maximum charging time is considered.

**Passenger loads**

Due to absence of APC data, the number of passengers inside the vehicles at the charging station and after departing at the charging station were estimated based on passenger counts and assumed occupation patterns per line direction. The number of passengers inside the vehicles at Schiphol Knooppunt Noord were counted the 9th of January, between 8 and 12 o'clock in the morning. Another timetable is executed compared to the data included in the model. Therefore, passenger counts of vehicles operating on new line numbers, are assigned to out-dated line numbers in the same direction. The occupation rates for the peak periods were based on the first hour, while the last two hours were used for off-peak occupation estimation. Based on the counts, a minimum and maximum percentage of the vehicle seat capacity of all vehicle types per line, is set for peak and off-peak periods. For each vehicle arriving at the station, a random value between those minimum and maximum percentage per line is multiplied by the vehicle capacity in order to estimate the total number of passengers. Twenty passenger determination runs are performed. The results are shown in Table 5-2 and validated by two Schiphol experts: Hendrik Bouwknegt and Erik Oerlemans, both counsellors in public transport at Goudappel Coffeng. The average percentage of daily number of passengers per peak hour of 12%, is a bit more than the 10% for the busiest peak hour mentioned by CROW (ASVV, 2012), however, considering slight variations due to unique daily travel patterns at Schiphol, this result is valid.

*Table 5-2 - daily number of passengers based on analysis results of 20 passenger determination runs*

| Whole day | | | | During peak periods | | |
|---|---|---|---|---|---|---|
| Average | Min | Max | Standard deviation | Average | Percentage of daily number of passengers | Average percentage of daily number of passengers per peak hour |
| 16,908 | 16,559 | 17,313 | 217 | 10,582 | 62% | 12% |

Besides passengers inside the vehicle, the passengers downstream the charging station are hindered by delayed departure of vehicles at the charging station. In order to estimate the total number of affected passengers, the number of passengers inside the vehicle is multiplied by a passenger factor, based on passenger occupation patterns per direction. First, the relevant basic occupation patterns, discussed in section 4.4.1, are chosen. For R-net line 356, basic occupation pattern A (Figure 4-10, section 4.4.1) is selected, because it connects two cores (Amsterdam and Haarlem), without serving Schiphol Plaza. Schiphol Plaza is an important bus station in the network where a lot of passengers are boarding and/or alighting. For all other lines, an adjusted version of basic occupation pattern B is chosen. All those lines are serving Schiphol Plaza. Therefore, a vertical line, indicating both a lot of boarding and alighting activities at Schiphol Plaza, is represented in Figure 5-4 (right figure). Secondly, the location of Schiphol Knooppunt Noord for each line and direction, relative to the total line distance is represented, by indicating each line at the right location in Figure 5-4. For instance, line 196a, starts at Schiphol Knooppunt Noord and drives via Schiphol Plaza to P30. Hence, 196a is shown in the lower left corner at a distance of zero. Third, a passenger factor, based on the number of passengers boarding the vehicle, downstream Schiphol Knooppunt Noord, is determined. After departing at Schiphol Plaza, it is considered that passengers are only alighting the vehicle. Therefore, only the passengers inside the vehicle are considered and the passenger factor of all lines at the right side of the figure have a passenger factor equal to one. All lines at the left side of the figure are upstream Schiphol Plaza, so a higher passenger factor is considered for those lines (Table 5-3).

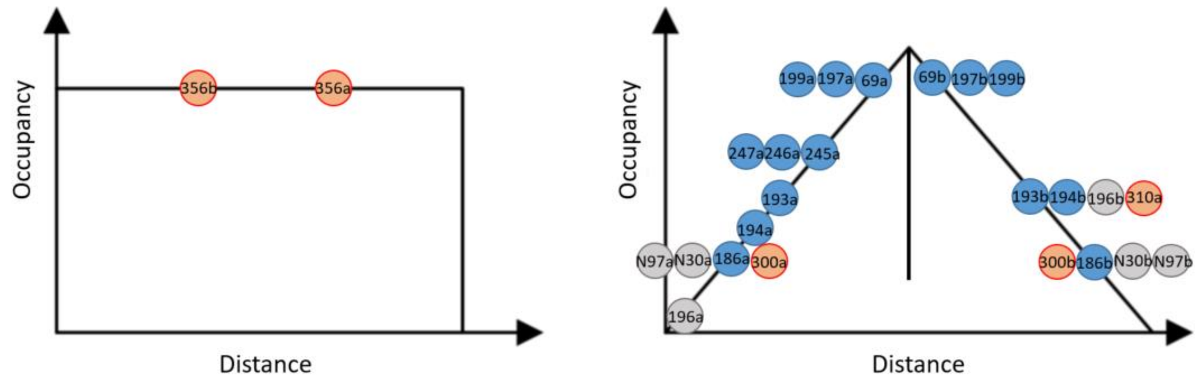



*Figure 5-4 - Location of Schiphol Knooppunt Noord on each line( direction) in relation to the occupancy pattern*

*Table 5-3 - Passenger factor per line and driving direction*

| Line (and direction) | 356a<br>356b | 186b<br>300b<br>N30b<br>N97b | 193b<br>194b<br>196b<br>310a | 69b<br>197b<br>199b | 69a<br>197a<br>199a | 245a<br>245a<br>247a | 193a<br>194a | 186a<br>300a<br>N30a<br>N97a | 196a |
|---|---|---|---|---|---|---|---|---|---|
| Passenger factor | 1 | 1 | 1 | 1 | 1.8 | 2 | 2.2 | 2.4 | 2.8 |

In short, Schiphol Knooppunt Noord is selected as only OC station in the network and only one electric vehicle type, the Solaris Urbino 18 electric PA, is chosen to perform the electric operations. Thursday 5 October is chosen as simulation day and the number of affected passengers inside the vehicle and downstream the OC station, is estimated.

## 5.3 Variants

Based on the model settings, discussed in the previous section, the bus station operations at Schiphol Knooppunt Noord could be modelled. In this section, the main variants are modelled. Thereafter, the model results are shown and analysed. According to section 4.5.3, 64 basic variants exist, plus the base case. However, for this application, F1a and F1b are considered as one group and C4 is not considered at all. The distinction in city and regional buses is not relevant here, because only the BRT lines are considered as regional lines. In the remainder of this chapter, F1a and F1b together are formulated as city buses. Here, no distinction is made between vehicles of GVB and Connexxion, so in case of F1, also the vehicles of GVB are electric. Besides, IMC is not a serious option for public transport operators (yet) and is not affecting the bus station operations, as mentioned in section 2.3.3.2. Therefore, the number of relevant variants is downsized to 33. These are shown in Table 5-4.

*Table 5-4 - Model variants based on charging mechanisms and development paths for Schiphol*

| 0 | Base case: all diesel and no charging necessary | | |
|---|---|---|---|
| C1 | Slow charging | F1 | City buses |
| C2 | OC pantograph | F2 | Only BRT |
| C3 | OC induction | F3 | All electric |

| | C1F1 | C1F2 | C1F3 | C2F1 | C2F2 | C2F3 | C3F1 | C3F2 | C3F3 |
|---|---|---|---|---|---|---|---|---|---|
| Min | | | | 4 | 9 | 14 | 19 | 24 | 29 |
| Max | | | | 5 | 10 | 15 | 20 | 25 | 30 |
| Peak | | | | 6 | 11 | 16 | 21 | 26 | 31 |
| Place | | | | 7 | 12 | 17 | 22 | 27 | 32 |
| Need | 1 | 2 | 3 | 8 | 13 | 18 | 23 | 28 | 33 |

The results of the variants are shown in spider graphs, because spider graph visualisation is a clear representation for multi indicator analysis results. First, the interpretation of spider graph results is explained on the basis of the preferred variant per stakeholder. These variants are based on the assessment criteria, mentioned in section 3.4 and repeated in Table 5-5. Based on this Table, the preferred variants per stakeholder are shortly explained.

*Table 5-5 - Assessment framework and stakeholders interests*

| Criterion | Variable | Stakeholder(s) |
|---|---|---|
| **Operations** | Disruptions | Operator, Passengers |
| **Level of service** | Delayed departure | Passengers, Authority |
| | Dispersion in departure times | Passengers |
| **Costs** | Delayed vehicle costs | Operator |
| | Energy/fuel consumption costs | Operator |
| | Vehicle investment | Operator |
| | Charging infrastructure investment | Authority |

- Passengers prefer the lowest costs for the level of service (delayed departure and dispersion in departure time) and the lowest number of disruptions. In contradiction to the slow charging methods, where the level of service costs are equal to those of the base case, some additional level of service costs are made in all other scenarios, however, reducing disruptions could compensate for those additional level of service costs.
- The operator(s) prefer(s) the lowest operational delayed vehicle and energy/fuel consumption costs as well as the lowest vehicle investment costs possible. Besides that, the disruption percentages and percentages of low variation delayed vehicle costs are considered. If the percentage of low variation delayed vehicle costs is high, it will be easier for operators to reduce the delayed vehicle costs by adjusting the timetables a bit. Hence, this is important information for an operator, although it is not considered as main assessment criterion.
- For the authority, the delayed departure and charging infrastructure investment costs are the main criteria, considering charging infrastructure investment by the authority, which will be

case dependent in real-life. Only full electric exploitation is considered here, because that is what authorities will interrogate for, in future concessions.

### Variant results

First, all variant results, relative to the base case (only diesel engine vehicles), are represented in Table 5-6. This means that all variant results minus the base case results, are shown. The different charging methods (C) and relevant charging mechanisms are represented horizontally and the shares of electrification (F) and assessment criteria are represented vertically. Based on this collection of model results, the preferred variant per stakeholder are graphically represented in a spider graph. Thereafter, bandwidths of the other variants are graphically represented as well.

Based on the stakeholders descriptions, the preferred variant for each stakeholder is selected and represented relative to the base case in Figure 5-5. Therefore, the base case is represented as black heptagon, scoring zero for all criteria.

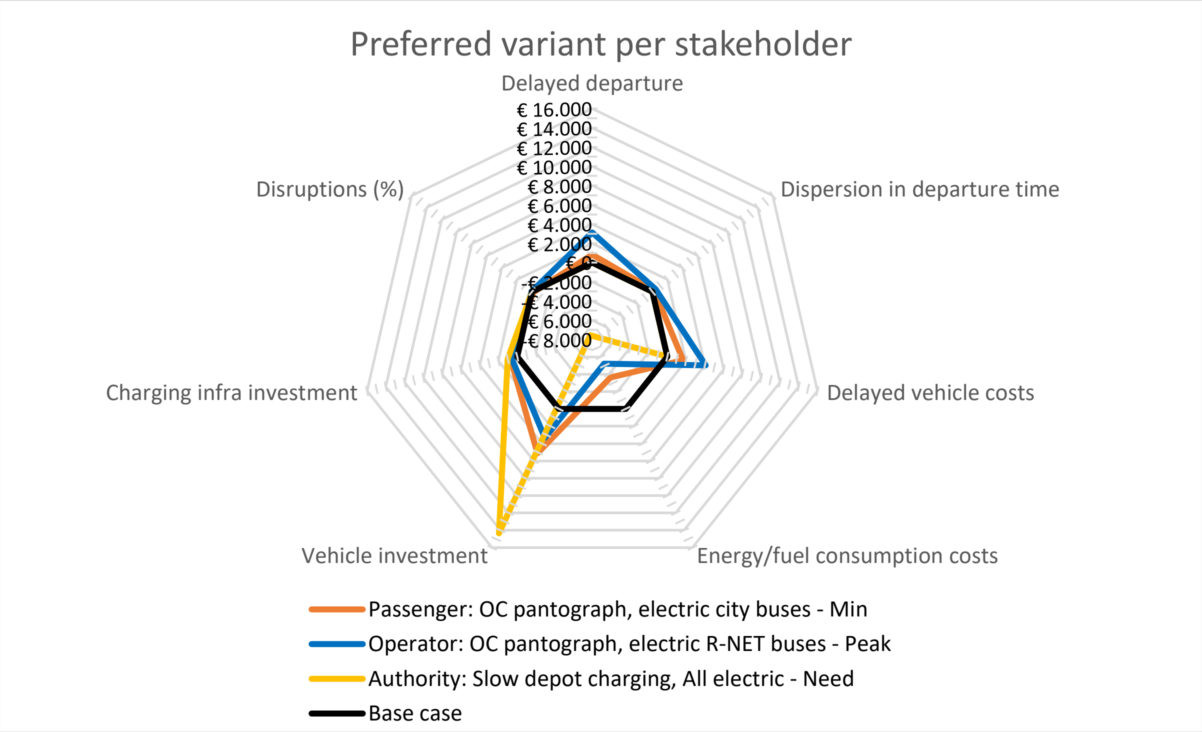



*Figure 5-5 - Daily scores relative to the base case for the preferred variants per stakeholder*

Most striking cost peak in Figure 5-5 is the vehicle investment for the preferred variant of the authority, primarily caused by a complete electric vehicle fleet, but also by a 43% fleet size increase in order to be able to replace empty vehicles by completely full ones. On the other hand, this variant results in large energy/fuel consumption cost savings, indicated by the negative cost peak in Figure 5-5. For the preferred variants of the passengers and operators, OC by pantograph takes place at the bus station, however, in the passengers preferred variant, the city and regional vehicles are electrified, while only the R-net fleet is electric in the preference variant of the operator. Comparing the preferred variants of passengers and operators, the vehicle investment and energy/fuel consumption costs are higher for the best variant from passenger perspective. Opposite, the costs of delays are lower for this variant.

*Table 5-6 - Model variant results relative to the base case, for the application at Schiphol*

| | | **C1** | **C2: OC by pantograph** | | | | | **C3: OC by induction** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Need | Min | Max | Peak | Place | Need | Min | Max | Peak | Place | Need |
| **F1** | *Operations* | | | | | | | | | | | |
| | Disruptions | 0,00% | -1,50% | 0,54% | 1,16% | 0,54% | 0,27% | -1,09% | 3,81% | 1,36% | 3,27% | 0,20% |
| | *Level of service* | | | | | | | | | | | |
| | Delta departure time | € 0 | € 828 | € 2.291 | € 1.102 | € 2.291 | € 1.078 | € 1.582 | € 4.409 | € 2.091 | € 4.396 | € 2.507 |
| | Dispersion in departure time | € 0 | € 206 | € 139 | € 94 | € 139 | € 1.175 | € 489 | € 744 | € 369 | € 756 | € 2.398 |
| | *Costs* | | | | | | | | | | | |
| | Operational delayed vehicle costs | € 0 | € 1.683 | € 3.745 | € 2.505 | € 3.745 | € 1.942 | € 3.223 | € 7.272 | € 4.841 | € 7.267 | € 4.494 |
| | Operational energy/fuel consumption costs | -€ 3.252 | -€ 3.642 | -€ 3.634 | -€ 3.851 | -€ 3.634 | -€ 3.621 | -€ 3.608 | -€ 3.559 | -€ 3.800 | -€ 3.559 | -€ 3.564 |
| | Vehicle investment | € 7.495 | € 5.126 | € 5.126 | € 5.126 | € 5.126 | € 5.126 | € 5.126 | € 5.126 | € 5.126 | € 5.126 | € 5.126 |
| | Charging infra investment | € 528 | € 733 | € 733 | € 733 | € 733 | € 733 | € 647 | € 647 | € 647 | € 647 | € 647 |
| **F2** | *Operations* | | | | | | | | | | | |
| | Disruptions | 0,00% | -0,34% | 0,54% | 0,27% | 0,54% | 0,07% | 3,88% | 13,06% | 5,37% | 2,65% | 1,56% |
| | *Level of service* | | | | | | | | | | | |
| | Delta departure time | € 0 | € 3.382 | € 4.948 | € 3.127 | € 4.948 | € 4.013 | € 7.402 | € 11.154 | € 7.402 | € 7.614 | € 9.538 |
| | Dispersion in departure time | € 0 | € 470 | € 240 | € 426 | € 240 | € 1.829 | € 1.524 | € 1.312 | € 1.524 | € 2.101 | € 4.162 |
| | *Costs* | | | | | | | | | | | |
| | Operational delayed vehicle costs | € 0 | € 4.005 | € 5.416 | € 4.085 | € 5.416 | € 4.237 | € 8.802 | € 12.055 | € 8.802 | € 9.343 | € 9.987 |
| | Operational energy/fuel consumption costs | -€ 5.218 | -€ 4.897 | -€ 4.888 | -€ 5.199 | -€ 4.888 | -€ 4.866 | -€ 4.799 | -€ 4.756 | -€ 4.799 | -€ 5.146 | -€ 4.751 |
| | Vehicle investment | € 7.959 | € 3.339 | € 3.339 | € 3.339 | € 3.339 | € 3.339 | € 3.339 | € 3.339 | € 3.339 | € 3.339 | € 3.339 |
| | Charging infra investment | € 512 | € 614 | € 614 | € 614 | € 614 | € 614 | € 528 | € 528 | € 528 | € 528 | € 528 |
| **F3** | *Operations* | | | | | | | | | | | |
| | Disruptions | 0,00% | 7,00% | 42,31% | 21,50% | 30,75% | 0,82% | 29,12% | 69,93% | 42,86% | 28,57% | 10,68% |
| | *Level of service* | | | | | | | | | | | |
| | Delta departure time | € 0 | € 4.221 | € 7.629 | € 4.221 | € 7.320 | € 5.099 | € 9.217 | € 17.673 | € 9.520 | € 8.907 | € 12.044 |
| | Dispersion in departure time | € 0 | € 431 | € 478 | € 431 | € 1.286 | € 3.091 | € 1.928 | € 2.511 | € 2.002 | € 2.009 | € 6.633 |
| | *Costs* | | | | | | | | | | | |
| | Operational delayed vehicle costs | € 0 | € 5.729 | € 9.554 | € 5.729 | € 9.229 | € 6.191 | € 12.342 | € 21.612 | € 14.886 | € 12.821 | € 14.484 |
| | Operational energy/fuel consumption costs | -€ 8.504 | -€ 8.533 | -€ 8.521 | -€ 8.533 | -€ 8.502 | -€ 8.469 | -€ 8.402 | -€ 8.315 | -€ 8.897 | -€ 8.396 | -€ 8.315 |
| | Vehicle investment | € 14.356 | € 7.603 | € 7.603 | € 7.603 | € 7.603 | € 7.603 | € 7.603 | € 7.603 | € 7.603 | € 7.603 | € 7.603 |
| | Charging infra investment | € 1.028 | € 1.034 | € 1.034 | € 1.034 | € 1.034 | € 1.034 | € 948 | € 948 | € 948 | € 948 | € 948 |

The assessment results of different charging methods and charging mechanisms are represented in Figures 5-6, 5-7 and 5-8 for respectively electric city and regional vehicles, electric R-net vehicles and all electric vehicles. In this representation, the differences between charging methods (C1, C2 and C3) in relation to the assessment criteria becomes visible. In Appendix H, comparable graphs including the same assessment results are shown, but this time represented per charging method, in order to compare the assessment results of different electric vehicle distributions (F1, F2 and F3). For slow charging, only one charging mechanism is considered, so the assessment of different criteria is represented by lines in the spider graphs. Each line corresponds with a different charging method. For the two OC methods, five charging mechanisms are considered. For each criteria, the minimum and maximum assessment result of the charging mechanisms are considered. Therefore, a plane becomes visible in the spider graphs. It should be mentioned here, that the minimum and maximum values for the assessment criteria not directly relate to the minimum and maximum charging time mechanisms. For instance, the maximum dispersion in departure time is always determined by Need, and Peak determines the minimum value for the delayed departure for OC methods in Figure 5-7 and 5-8. The investment costs (for vehicles and charging infrastructure) is equal for the charging mechanisms of each charging method and for each electric vehicle distribution. For the energy and fuel consumption costs, there are slight differences between charging mechanisms, however, they are not clearly visible in the spider graphs. At last, the disruptions is expressed as a percentage. The outer circle of the spider graphs correspond with 100% disruptions. The scales of Figure 5-6 and Figure 5-7 are equal, while the scale of Figure 5-8 is different.

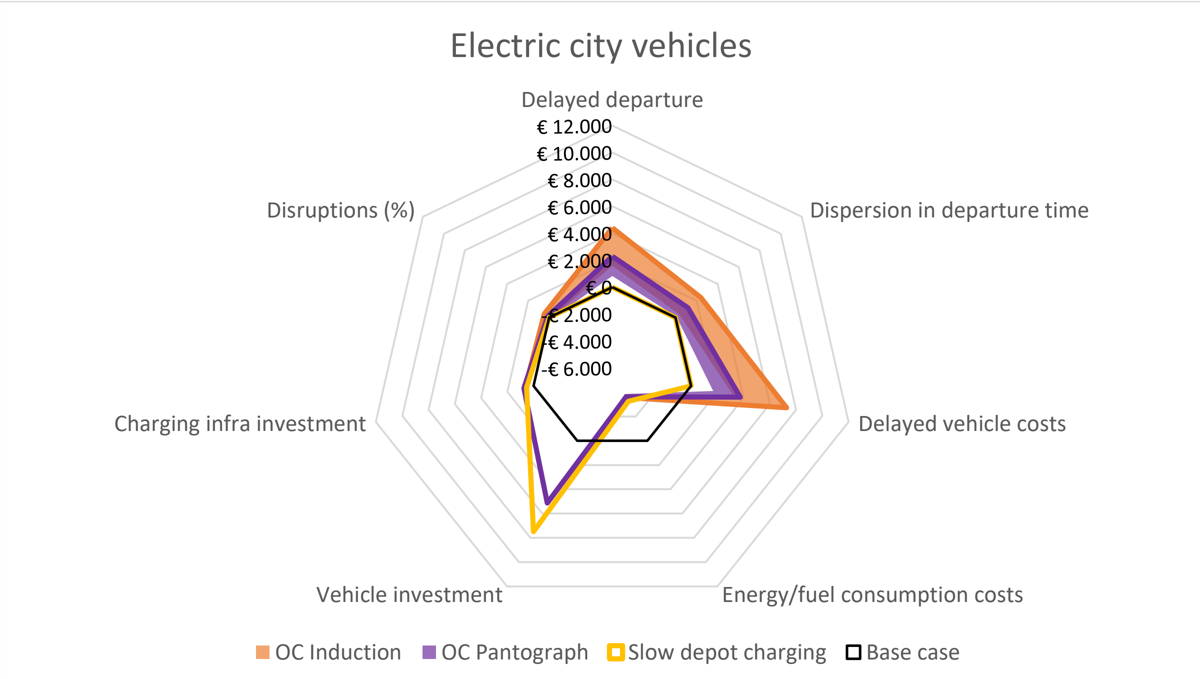



*Figure 5-6 - Daily scores relative to the base case for electric city vehicles*

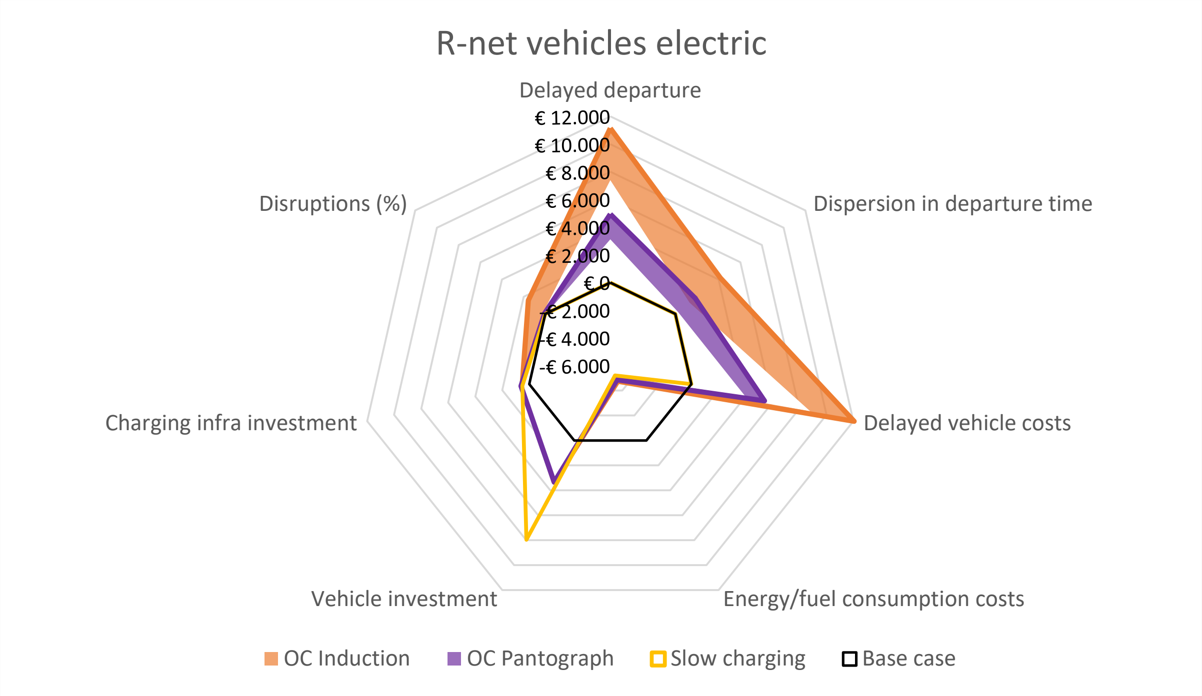



*Figure 5-7 - Daily scores relative to the base case for electric R-net vehicles*

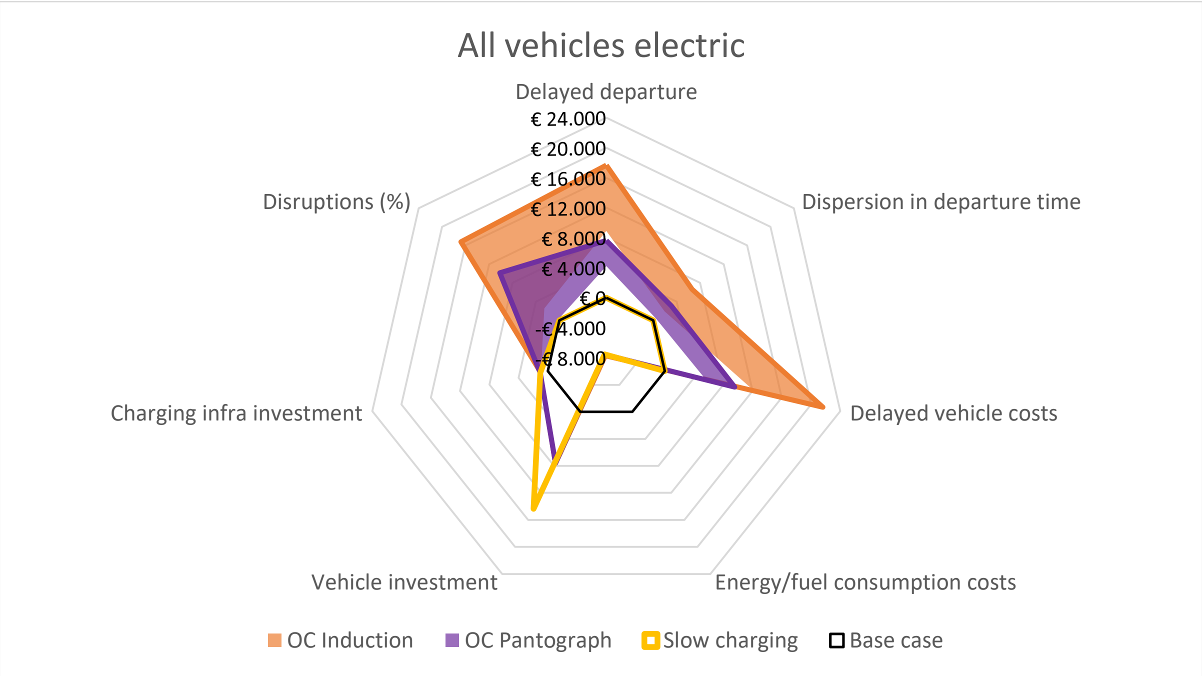



*Figure 5-8 - Daily scores relative to the base case for a completely electric fleet*

According to the variants results, there is an important trade-off between high vehicle investment costs and large energy/fuel consumption cost savings for slow charging at the depot. With respect to the base case, slow charging at the depot does not result in changes in delays and disruptions, because the number of required vehicles is upgraded in order to be able to perform the trips according to the conventional timetables. This is different for the OC methods, where fast charging activities at the bus station result in delays of departures. Comparing the two OC methods, the charging infrastructure investment costs for OC by pantograph are a little higher than those of OC by induction, however, the savings for the delay criteria and disruption criterion are definitely outweighing these extra investment costs. These structural higher scores for OC by induction compared to OC by pantograph is shown in all three figures.

Besides the differences per figure, there are also some differences between the figures. Electrifying R-net vehicles instead of the city and regional vehicles, result 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, according to the current plans, is therefore a deliberately decision. The (minimum and maximum) costs for that situation relative to the base case are represented in Table 5-7. Level of service costs (delayed departure and dispersion in departure time), operational costs (delayed vehicle costs and energy/fuel consumption costs) and (vehicle and charging infrastructure) investment costs are distinguished and expressed per year, because annual costs are easier interpretable by public transport experts. Those costs are calculated according to the following formula:

$$Annual\ Societal\ Costs = (\Delta\ Delayed\ departure + \ \Delta\ Dispersion\ in\ departure\ time) * 365$$

Negative costs are benefits. Besides, 5 October is considered as representative day and no distinction between week and weekend days is considered.

*Table 5-7 - Annual level of service, operational and investment costs for different charging methods*

| | | | Level of service costs | Operational costs | Investment costs |
|---|---|---|---|---|---|
| **C1** | **Depot charging** | | € 0 | -€ 1,187,000 | € 2,928,000 |
| **C2** | **OC by pantograph** | Min | € 337,000 | -€ 791,000 | € 2,139,000 |
| | | Max | € 1,265,000 | € 45,000 | € 2,139,000 |
| **C3** | **OC by induction** | Min | € 712,000 | -€ 211,000 | € 2,107,000 |
| | | Max | € 2,484,000 | € 1,355,000 | € 2,107,000 |

Full electric operations 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 certain amount of scarcity of charging points. In other words, there are too little charging points for the amount and duration of charging activities. The Need charging mechanism determines the lower bound for disruptions, so this charging mechanism offers a possibility for the reduction of disruptions in cases of charging points scarcity.

In short, electric exploitation results in energy/fuel consumption benefits compared to the exploitation of conventional diesel engine vehicles. However, higher investment costs are required, especially for slow, depot charging. For OC methods, higher delay costs and disruptions are involved, especially when lower charging system power is used. The choice for OC at the bus station or depot charging is determined by the trade-off between (vehicle) investment costs and delay costs (level of service).

## 5.4 Scenarios

In this section, some extreme situations and possible future events or developments are tested. Those scenarios are compared to the variant with pantograph OC and an electric regional and city buses fleet (C2F1). This variant highly corresponds with the current plans, so this is societally most relevant. First, the scenarios are summarized in Table 5-8 and further explained in more detail after that. Then, the model results of the scenarios are shown including the main conclusions.

*Table 5-8 - Model scenarios for Schiphol*

| | Weekend | | | Weekday | | | |
|---|---|---|---|---|---|---|---|
| Scenario number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Scenario name | Winter day | Black Saturday | Pre-summer Sunday | Accident | Flex charging | Reduced battery capacity | Green deal |
| **In- vehicle variables** | | | | | | | |
| Vehicle length | | | 12 m. | | | | |
| Battery capacity | -20% | | | | | -20% | |
| Energy consumption | +26% | +22% | +22% | | | | |
| **Charging system variables** | | | | | | | |
| # charging points | -1 | | | | +1 | | |
| Charging efficiency | -10% | | | | | | |
| Charging power | | | | | +33% | | |
| **External variables** | | | | | | | |
| Data | 07-01-2017 | 29-07-2017 | 02-07-2017 | | | | |
| # passengers | +10% | +10% | -10% | | | +15% | +15% |
| Roundup percentage | | | +10% | | | | |
| Battery buffer | | | | -10% | | +10% | |
| Route length | | | | +22% | | | |
| Electrification rate | | | | | | | +35% |
| Energy price | | | | | | | -43% |
| Fuel price | | | | | | | +21% |

### 1. Winter day:

- AVL data of Saturday 7 January 2017 is imported, because this was an extreme winter day in the Netherlands. In weekends, lines 186 and 194 are not in operation.
- The battery capacity is reduced by 20%, due to low temperatures.
- The energy consumption is multiplied by 1,26, by changing the season variable into winter.
- One charging point is defect, so just seven charging points remain.
- There are more energy losses due to the low temperatures, so the charging efficiency decrease with 10%.
- The number of passengers per trip increase with 10%, because more people use public transport in such weather conditions.

### 2. Black Saturday:

- AVL data of Saturday 29 July 2017 is imported, because this was a black Saturday at Schiphol.
- The energy consumption is increased by 22%, by selecting the Summer season in the season factor input box.

- The number of passengers per trip is multiplied by the ratio of number of travellers at Schiphol at 29 July 2017 divided by the average daily number of travellers at Schiphol in 2017. This ratio corresponds with an increase of around 10%.

3. Sunday:

- AVL data of Sunday 2 July 2017 is imported. At Sundays, line 310 is also out of operation and therefore, the frequency of line 69 is a bit higher.
- For all electric vehicles, another vehicle type is considered: Solaris Urbino 12 electric PA, instead of Solaris Urbino 18 electric PA. As mentioned in the name, the vehicle length has changed from 18 meters to 12 meters. Therefore, also the energy consumption decrease from 1.3 kWh/km to 0.9 kWh/km.
- At the same time, the energy consumption also increase with 22%, because 2 July is in the summer.
- The number of passengers per trip decrease with 10%, because a calm Sunday is considered.
- The roundup percentage has increased with 10%, in order to offer extra breaks for drivers, which is quite satisfying in times of striking bus drivers.

4. Accident:

- In this scenario, an accident in the Buitenveldertunnel, the bus tunnel parallel to the Schipholtunnel, is considered, which result in detours of 4 and 6.5 kilometres, dependent of the next bus station (Schiphol Knooppunt Noord or P40 respectively), as indicated in Figure 5-9. The detours result in an extra arrival delay of 4 and 7 minutes respectively.

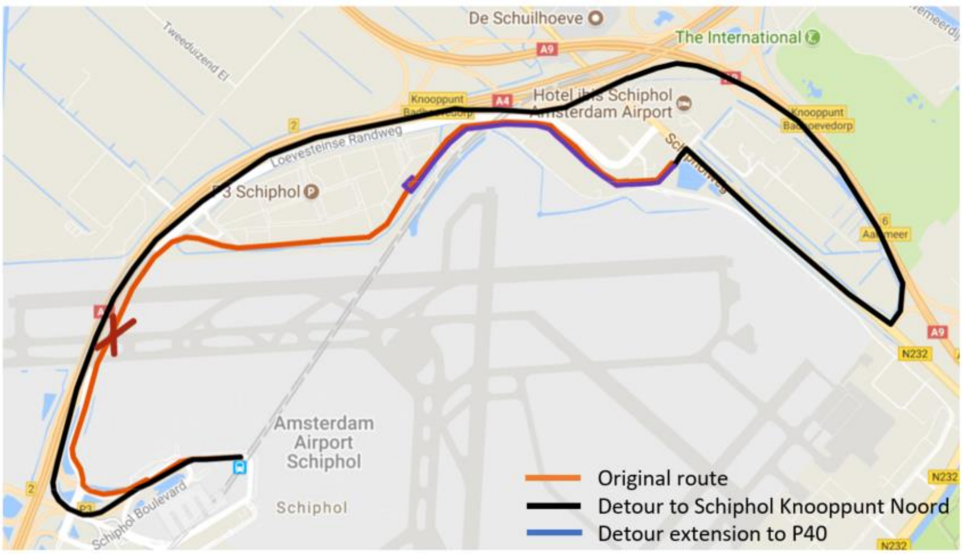



*Figure 5-9 - Detours due to an accident in the Buitenveldertunnel*

- Because of the temporarily character of the detours, a lower battery buffer is allowed. Instead of 20%, 10% is considered.

5. Flex charging:

- One extra, flexible charging point is added in this scenario in order to charge the vehicles of the line with most disruptions.
- This extra charging point has higher charging power: 600 kW instead of 450 kW.

6. Reduced battery capacity:

- In this scenario, the battery capacity is decreased to its end of life time battery capacity, which means 80% of the original battery capacity (section 2.2.3).
- The battery buffer is extended with 10% in order to limit the battery capacity degradation.
- The number of passengers per trip has increased with 15%. The lifespan of a battery is around five years (section 2.2.3) and based on expert judgement, 15% passenger growth is expected in the coming five years. Primarily employees at Schiphol make use of the buses and not that much passengers. However, the growth of flight and shop staff is more or less equal as the passenger growth (Terlouw, 2018).

7. Green deal:

- The fuel price increase with 21% to €1.384 per litre (diesel price at 8 January 2018), due to cancelled VAT-free regulations for polluting diesels by the government.
- At the same time, the energy price decrease by 43% to €0.05 per kWh, in order to stimulate electric transport. This price is based on the lowest energy price excluded VAT and excluded all taxes.
- The number of passengers per trip increase with the same amount as in the reduced battery capacity scenario. This means that the Green deal regulations are introduced in around five years.
- Due to the Green deal regulations, more electrification has taken place. The vehicles on one of the R-net lines, line 300 (the busiest one), including 27 vehicles, is also electrified.

### Scenario results

For both types of scenarios, the weekend scenarios and the development scenarios, other references are used. For the weekend scenarios, a weekend reference including data of Saturday 7 October 2017 is used. For the development scenarios the original C2F1 variant, concerning data of Thursday 5 October 2017, is used as reference. In Figure 5-10 and Figure 5-11, the results of the scenarios are shown. The scenario results are represented in percentage change relative to the reference. In this way, also absolute small, but relative larger cost reductions or increases, are visible in the graphs. The numeric results are included in Appendix I. At last, it should be mentioned here, that for all weekend scenarios, different data is used. On Sundays, for instance, line 310 is not serving Schiphol Knooppunt Noord. Hence some important differences in data characteristics, summarized in Table 5-9, are main reasons for the differences in the spider graph. The number of trips and number of vehicles are directly obtained from the data, while the daily number of passengers depends on the number of trips and on the input settings per scenario. For all development scenarios, the same data is used.

*Table 5-9 - Simulation day characteristics of the weekend scenarios*

| | Reference | Winter day | Black Saturday | Pre-summer Sunday |
|---|---|---|---|---|
| **Simulation day** | 7 October 2017 | 7 January 2017 | 29 July 2017 | 2 July 2017 |
| **Number of trips** | 1,015 | 1,109 | 928 | 851 |
| **Number of vehicles (whereof electric)** | 88 (56%) | 106 (63%) | 88 (57%) | 71 (63%) |
| **Nr. of passengers** | 9,952 | 12,035 | 10,443 | 6,414 |

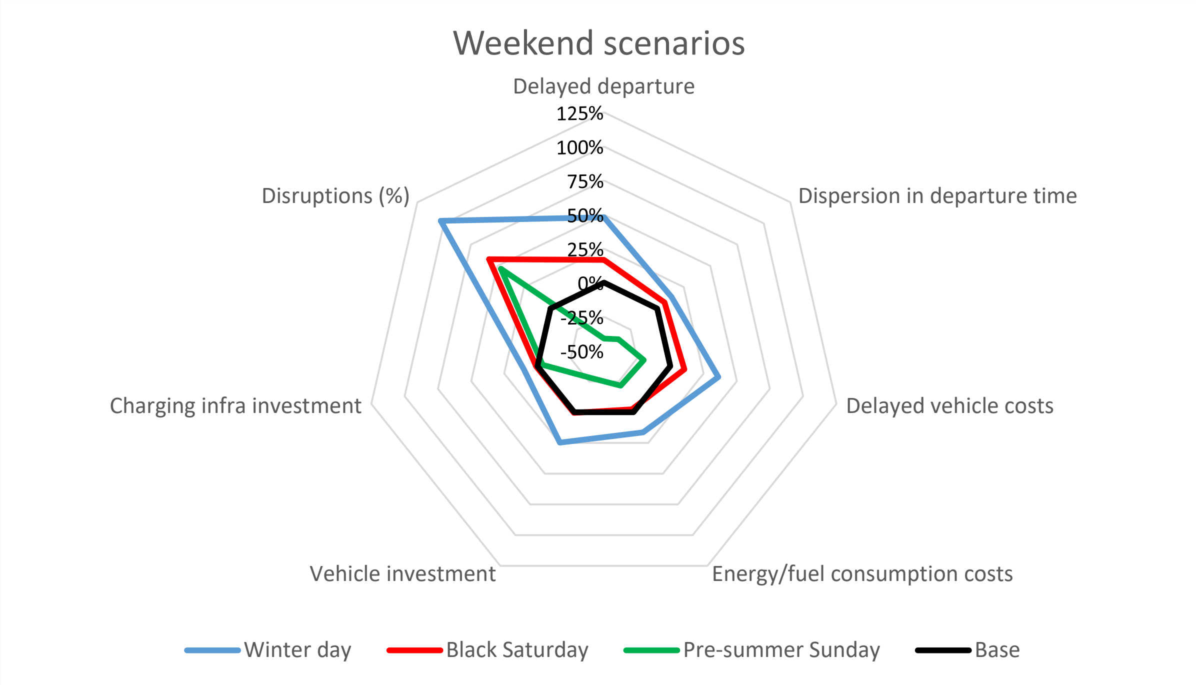



*Figure 5-10 - Daily differences relative to the reference day: 7 Oct, for the weekend scenarios*

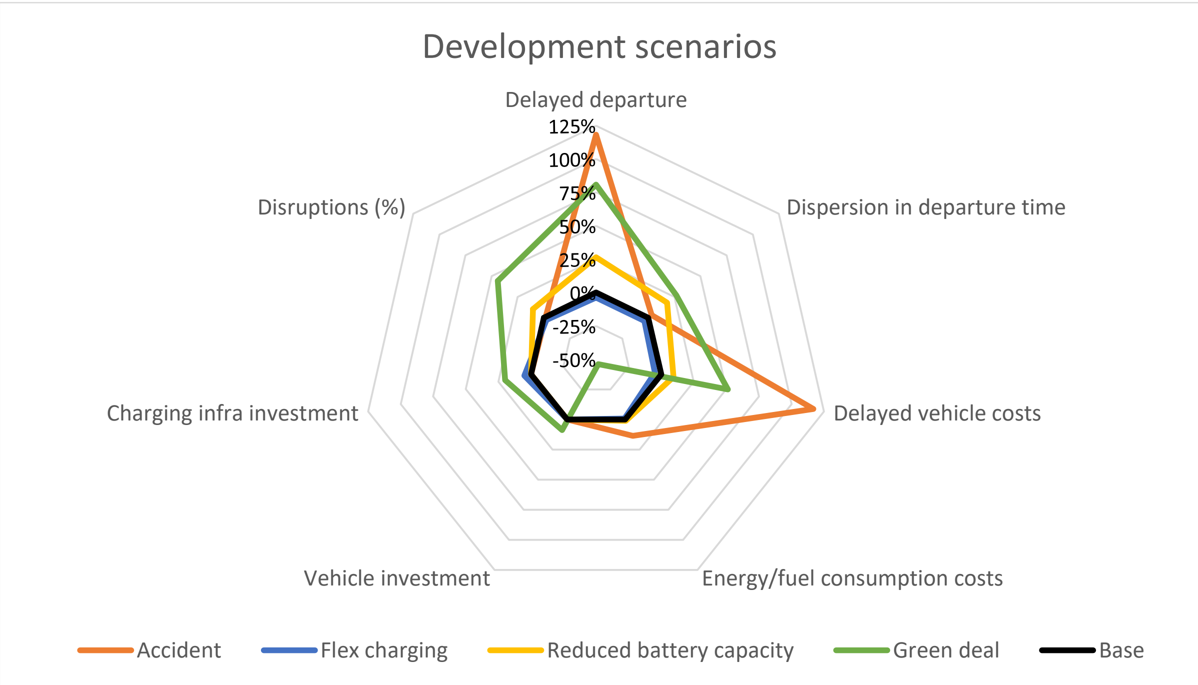



*Figure 5-11 - Daily differences relative to the reference day: 5 Oct, for the development scenarios*

For the weekend scenarios in Figure 5-10, it is striking that all scenarios, even the Sunday scenario, score high for the disruptions compared to the reference. This has to deal with slight timetable changes during the second half of 2017. In the reference data, a better spread in arrival times is scheduled at critique moments of the day.

The Winter day scenario leads for all criteria to higher costs, since most trips are performed, most vehicles are used an most passengers are transported (Table 5-9). Besides, there are larger delays in departure time, provoked by more delays in arrival time and longer charging times due to more inefficiency in the charging process.

For Black Saturday, there are no extra vehicles in operation. However, 11% extra delays occur, caused by more charging activities (300 instead of 252) as result of a higher energy consumption rate for cooling the cabin.

According to the development scenarios results in Figure 5-11, the Accident and Green deal scenarios result in most changes compared to the reference, especially caused by detour delays and the electrification of the operations on line 300 respectively. The detours in the Accident scenario are affecting some specific lines. Hence, the corresponding trips arrive at the bus station structurally too late. Therefore, high costs for delays are involved, but no substantial increase in the dispersion in departure time costs are involved. Moreover, this structural delay in arrival can be solved within a relatively short amount of time. The detours also cause an increase of the energy/fuel consumption costs of 13%.

The Flex charging scenario, where one flexible charging system is added, does not result in substantial changes in cases where scarcity of charging points does not play a role. However, the charging infrastructure investment is slightly higher, while all other criteria score a bit lower. In other words, a slight robustness improvement is realised by an extra charging infrastructure investment.

For the reduced battery capacity scenario, there are more delays, due to more charging activities (406 instead of 301). It is necessary to charge more often due to the reduced battery capacity and increased battery buffer.

At last, the Green deal scenario results in energy/fuel consumption cost savings of 46%, caused both by the electrification of more vehicles and the lowered energy costs. On the other hand, more electric vehicles result in higher vehicle and (depot) charging infrastructure costs, a higher number of disruptions and larger delays, caused by a doubling of the charging activities (595 instead of 301).

To conclude, the percentage changes relative to the weekend and weekday references respectively, are represented in Table 5-10. Most differences (relative and absolute) between the scenarios are obtained in the level of service (delayed departure and dispersion in departure time). Increasing costs for level of service criteria should be limited as much as possible in order to prevent an increasing rate of the passengers dissatisfiers (section 2.5.1).

*Table 5-10 - Scenario results relative to the reference days: 7 Oct. & 5 Oct.*

| | Weekend | | | Weekday | | | |
|---|---|---|---|---|---|---|---|
| Scenario number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Scenario name | Winter day | Black Saturday | Pre-summer Sunday | Accident | Flex charging | Reduced battery capacity | Green deal |
| Delayed departure | +48% | +17% | -41% | +118% | -4% | +26% | +81% |
| Dispersion in departure time | +13% | +7% | -36% | +3% | -4% | +18% | +27% |
| Delayed vehicle costs | +36% | +11% | -20% | +117% | -5% | +9% | +51% |
| Energy/fuel consumption costs | +17% | -2% | -22% | +13% | -1% | +1% | -46% |
| Vehicle investment | +25% | 0% | -28% | 0% | 0% | 0% | +9% |
| Charging infra investment | +10% | +1% | -4% | 0% | +5% | 0% | +20% |
| Disruptions (%) | +103% | +58% | +47% | -1% | -3% | +10% | +44% |

## 5.5 Sensitivity analysis

In the scenarios, a combination of relevant parameter settings has changed in order to evaluate extreme situations and possible, future situations. However, it does not indicate how much each variable influence the final results. Therefore, a sensitivity analysis is included in this research. For the most uncertain and the most influencing parameters, other settings are suggested and the new results are compared to the original ones. The variables for the sensitivity analysis and the used variation, are represented in Table 5-11 and further discussed below the table. Then the results are shown.

*Table 5-11 - Variables and used variations for the sensitivity analysis*

| | Variable | Variation | Clarification |
|---|---|---|---|
| **Cost/benefit model** | | | |
| **1** | Passengers | +30% | Expected growth in ten years |
| **2** | Passenger factor | +30% | Expected growth in ten years |
| **3** | Value of time | +48% | 4/5 $*VoT_{Commuters}$ + 1/5 $* VoT_{business}$ |
| **4** | E-bus price | -30% | Cost reduction in ten years |
| **5** | Charging infrastructure price | -30% | Cost reduction in ten years |
| **Charging time determination model** | | | |
| **6** | Battery buffer | -15% | High risk level of 5% |
| **7** | Charging power | +33% | 600 kW instead of 450 kW |
| **8** | Line length | +20% | Max line length of 60 km |
| **9** | Season factor: Winter | +26% | Changes energy consumption rate |

First, a distinction is made in 1) cost/benefit model variables and 2) charging time determination model variables. The first group contains of variables required for the conversion from the simulation results towards the assessment criteria results. This is the third module of the model. The second group contains of variables required for the determination of the charging times, so those variables are used in the first model module, before the simulation takes place.

Let start with the variables for the cost/benefit module. Due to the unavailability of chipcard data, the number of passengers is an further growing and estimated, and therefore, an uncertain, variable influencing multiple assessment criteria. Extrapolating the expected 15% passenger growth for the coming five years, results in an expected passenger growth of 30% in the coming ten years. This growth is used for the number of passengers, but also for the passenger factor. The number of passenger affected by delays, is the most uncertain variable in this research, because it consist of a multiplication of two uncertain variables: the number of passengers and the passenger factor. Both variables are tested in this sensitivity analysis individually. Third, the value of time has changed. Instead of an average value of time, a value of time based on the target groups, commuters and business travellers, is used. For every five passengers, it is considered that one passenger is a business traveller and four passengers are commuters. Then, a price reduction due to new battery developments, vehicle mass production and standardization (section 2.4.3), is considered for both the electric vehicles and the fast charging infrastructure systems. In ten years, a price reduction of 30% is considered, based on the battery price reduction mentioned in section 2.4.3.

For the second group, consisting of variables used for the charging time determination module, four different variables are tested in the sensitivity analysis. First, the battery buffer is reduced to 5%, instead of the original 20%. Here, the operator is taken a high risk in case of unexpected calamities and/or unplanned detours. Furthermore, such a low depth of discharge, result in a significant battery life time reduction, as mentioned in section 2.2.3. Secondly, a higher charging power system is provided (600 kW instead of 450 kW). Then, all lines are expanded with 20%. Now, the longest, electric operated line is 42.2 kilometres, which gives more insight in a larger variety of bus line types. At last, the energy consumption is increased by 26%, by selecting the winter season. In the winter season, the energy consumption is the highest, due to heating the vehicle cabin.

## Sensitivity results

First, the sensitivity results of input variables for the cost/benefit module are shown in Figure 5-12, followed by the sensitivity results of the input variables for the charging time determination module in Figure 5-13, both expressed as percentage of the reference (C2F1-min again). The numeric results are included in Appendix J. Because of the chosen reference, including charging mechanism Min, the number of charging activities is relatively high and the (average) charging times relatively short.

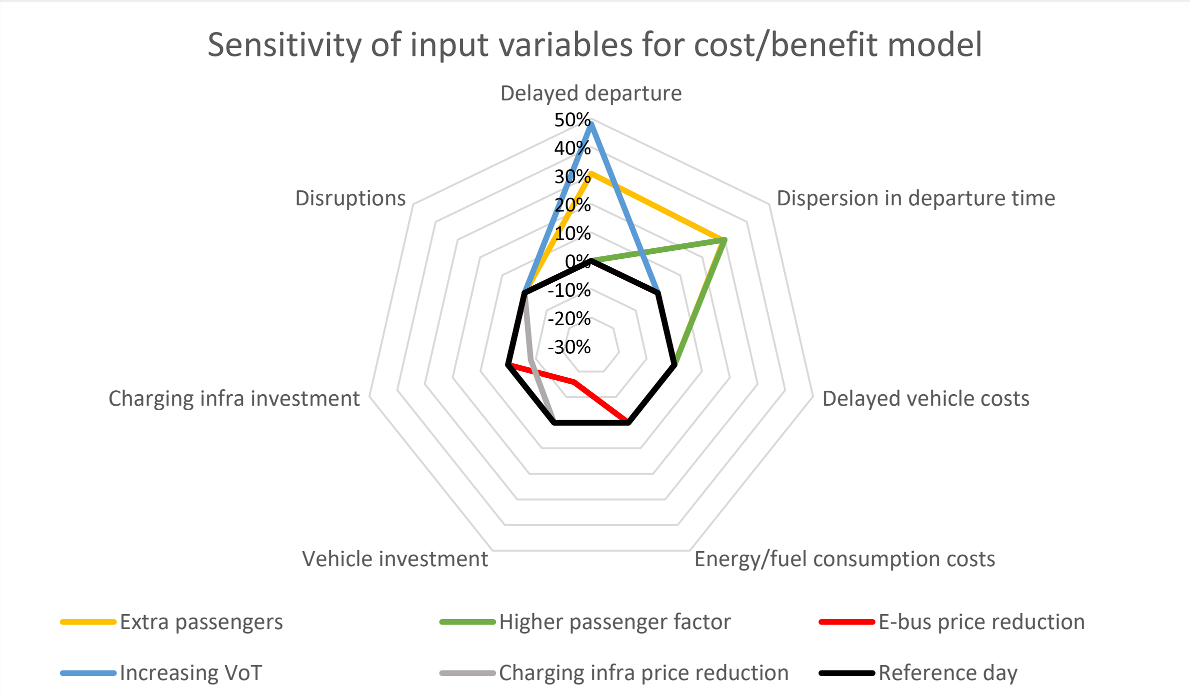



*Figure 5-12 - Daily differences relative to the reference day: 5 Oct, for the input variables for the cost/benefit model*

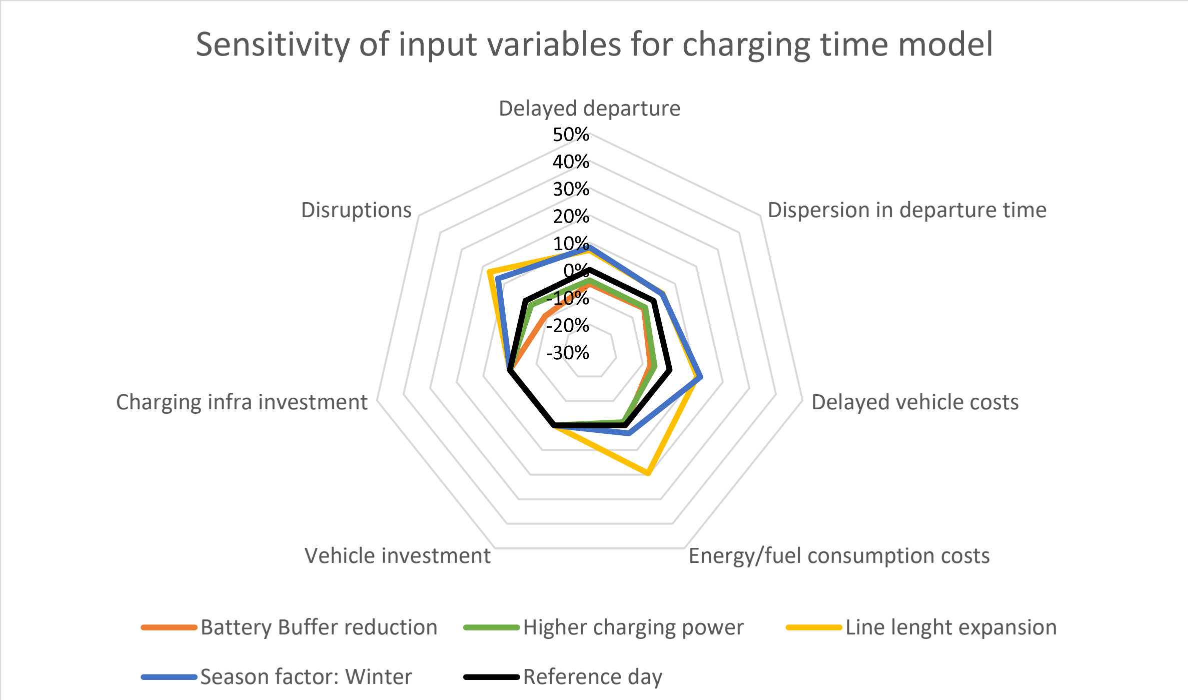



*Figure 5-13 - Daily differences relative to the reference day: 5Oct, for the input variables for the charging time model*

Variation of the variables shown in Figure 5-12, mostly affect one of the criteria, excepted the number of passengers, which influenced both the delayed departure and dispersion in departure time. For most variables, the chosen variation is equal to the variation in the results. For the price reduction of the E-bus and the charging infrastructure systems, this is not the case, because only the electric vehicles and fast charging infrastructure systems are subjected to these price reductions, while all vehicles and all charging infrastructure systems (also the overnight plug-in chargers) are involved in the results.

According to the sensitivity results of the variables of the second category, shown in Figure 5-13, variation of each variable results in variation of multiple criteria results. Just the vehicle and charging infrastructure investment remain unchanged for all variables. The battery buffer reduction and increasing charging power, result in lower costs and disruptions, compared to the reference. Especially for the battery buffer reduction, the 9% reduction of disruptions, caused by less required charging activities (228 instead of 301) is interesting. Excepted the disruptions, the reduced battery buffer and increased charging power, result in comparable results. The main reason for the cost reductions are the reduced charging times as indicated in Table 5-12. The line length expansion and Winter season factor, result in cost and disruption increases, especially caused by more frequent and longer charging activities (Table 5-12). Both variables result in higher energy usage, however, in contradiction to the Winter season factor, the amount of required diesel grows with the same amount as the energy usage for the line length expansion. Therefore, the 19% energy/fuel consumption costs peak, deviating from the score of the Winter season factor, is visible.

*Table 5-12 - Charging characteristics for the sensitivity analysis of input variables for the charging time model*

| | # Charging activities | Average charging time (sec.) |
|---|---|---|
| **Reference: C2F1-min** | **301** | **47** |
| Battery buffer reduction | 228 | 38 |
| Higher charging power | 301 | 36 |
| Line length expansion | 364 | 68 |
| Season factor: Winter | 363 | 72 |

In short, particular criteria results for changes in the input variables for the cost/benefit model are equal to the size of those changes. In contradiction, slight changes in the input variables for the charging time model, result in varying changes for multiple criteria. All percentage changes of all nine sensitivity checks compared to the reference are represented in Table 5-13.

*Table 5-13 - Sensitivity analysis results relative to the reference day: 5 Oct.*

| | Cost/benefit model | | | | | Charging time model | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Number** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
| Delayed departure | +31% | 0% | +48% | 0% | 0% | -5% | -4% | 7% | 8% |
| Dispersion in departure time | +29% | +30% | 0% | 0% | 0% | -5% | -4% | 4% | 4% |
| Delayed vehicle costs | 0% | 0% | 0% | 0% | 0% | -7% | -6% | 10% | 12% |
| Energy/fuel consumption costs | 0% | 0% | 0% | 0% | 0% | 0% | -1% | 19% | 3% |
| Vehicle investment | 0% | 0% | 0% | -16% | 0% | 0% | 0% | 0% | 0% |
| Charging infra investment | 0% | 0% | 0% | 0% | -8% | 0% | 0% | 0% | 0% |
| Disruptions (%) | 0% | 0% | 0% | 0% | 0% | -9% | -3% | 17% | 13% |

## 5.6 Improvement measure: adjusting timetables

According to section 7.2, the variation in delay is an important variable for the operator. Therefore, each group (Line number, direction and time of the day. E.g.: 69a-OS) is classified as low or high delayed departure time variation group. A group is labelled as low variation group if the average delay is at least twice the standard deviation in delayed departure times. In this section, the average delay for the low variation groups, is scheduled in the timetable. In other words, for the low variation groups, the charging duration is taken into account in timetable planning. Therefore, the scheduled average delays of the low variation groups are represented in Table 5-14. High variation groups are indicated by a dash. The minimum and maximum delayed departure time variation charging mechanisms (Max and Need) for two different fleet electrification and charging method combinations (C2F1 and C3F2), are shown. The electric city buses and OC by pantograph combination (C2F1) is indicated with a light background colour, while the electric R-net buses and OC by induction combination (C3F2) is represented in red on a more bright background colour. Based on the vehicle numbers from the trip data, R-net vehicles are also assigned to the trips on the N30 lines. Therefore, they are also represented in red. The delays of non-electric vehicles are not considered, because those are not caused by the charging processes.

*Table 5-14 - Rescheduled extra dwell times: C2=OC pantograph, C3=OC induction, F1=Electric city veh, F2=Electric R-net veh*

| | | | C2F1 / **C3F2** - Max | | | C2F1 / **C3F2** - Need | | |
|---|---|---|---|---|---|---|---|---|
| | Morning Peak | Evening Peak | Off-peak | Evening/ night | Morning Peak | Evening Peak | Off-peak | Evening/ night |
| 69a | 4,0 | 4,4 | 4,6 | 4,1 | - | - | - | - |
| 69b | 3,4 | 3,3 | 3,0 | 2,6 | - | - | - | - |
| 186a | - | - | 1,8 | - | - | - | - | - |
| 186b | - | 2,2 | 2,9 | 4,0 | - | - | - | 1,0 |
| 193a | - | - | 3,0 | - | - | - | - | - |
| 193b | 3,5 | 3,6 | 3,1 | 3,4 | - | 1,7 | - | - |
| 194a | 3,6 | 4,8 | 3,2 | 2,3 | - | - | - | - |
| 194b | 4,5 | - | 3,0 | - | - | - | 1,5 | 1,2 |
| 196a | - | - | - | - | - | - | - | - |
| 196b | - | - | - | - | - | - | - | - |
| 197a | 4,9 | 5,0 | 5,4 | 5,2 | - | - | - | - |
| 197b | 4,7 | 5,3 | 4,6 | 4,5 | - | - | - | - |
| 199a | 7,4 | 8,0 | 8,3 | 6,5 | - | - | - | - |
| 199b | - | 2,8 | 3,0 | - | 1,2 | 15,6 | - | - |
| 245a | - | - | - | 3,9 | - | - | - | - |
| 246a | - | - | - | - | - | - | - | - |
| 247a | - | - | - | - | - | - | - | - |
| **300a** | **18,7** | **21,9** | **21,7** | **19,2** | **-** | **-** | **-** | **-** |
| **300b** | **9,5** | **7,8** | **7,3** | **8,0** | **25,3** | **26,4** | **-** | **25,3** |
| **310a** | **7,8** | **9,3** | **9,3** | **-** | **-** | **-** | **-** | **-** |
| **310b** | **-** | **9,6** | **11,3** | **-** | **1,3** | **-** | **-** | **1,3** |
| **356a** | **13,5** | **11,2** | **12,5** | **11,5** | **-** | **-** | **-** | **-** |
| **356b** | **9,1** | **6,8** | **7,6** | **7,9** | **-** | **-** | **-** | **-** |
| N30a | - | - | - | **5,8** | - | - | - | - |
| N30b | - | - | - | **20,5** | - | - | - | - |
| N97a | - | - | - | - | - | - | - | - |
| N97b | - | - | - | - | - | - | - | 0,5 |

## Adjusted timetable results

In Figure 5-14, The results of the adapted timetable changes, relative to its references, are shown. The black heptagon represents four references: the C2F1-Max, C2F1-Need, C3F2-Max and C3F2-Need, original variants. The coloured lines, represent the adapted timetable versions of each original variant. The underlying numeric results are included in Appendix K.

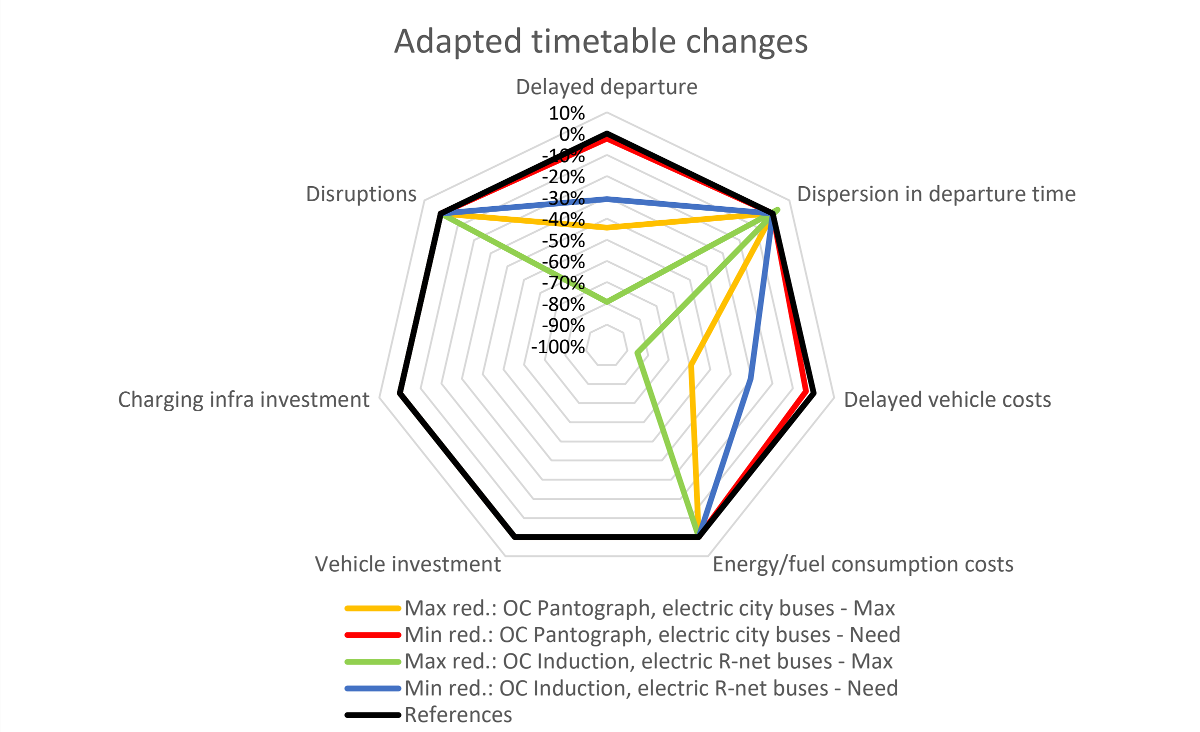



*Figure 5-14 - Daily differences relative to each original variant result for adapted timetables*

Figure 5-14 shows that a substantial delay cost reduction can be realised by adapting the timetables. It seems that only the delay costs components change, caused by an adaptation of the reference timetable. However, the dispersion in departure time slightly increase with values between 0.05% and 2.98%. For the highest variation group of C2F1 (red line), the delay reduction is quite small. This has to deal with the high variation in departure times: Only 15% is considered as low variation group. For the maximum delay reduction (yellow line), this percentage is 74%. Switching to an electric R-net fleet and OC by induction, the delay reduction become even larger. Both changes result in longer charging times: 1) R-net vehicles cover longer distances, so vehicles arrive with lower battery loads at the charging station. Therefore, longer charging times are required. 2) OC by induction takes place with lower charging power and lower charging efficiency, resulting in longer charging times. Scheduling longer charging times result in more delay reduction. Besides, the low variation percentages are 34% for the minimum delay reduction charging mechanism and 86% for the maximum delay reduction charging mechanism. Logically, for the adjusted timetable scenarios, these percentages decrease, as indicated in Table 5-15.

*Table 5-15 - Low variation group percentages for original variant results and for adjusted timetable results*

| | C2F1-Max | C2F1-Need | C3F2-Max | C3F2-Need |
|---|---|---|---|---|
| Original percentage low variation | 74% | 15% | 86% | 34% |
| New percentage low variation | 27% | 16% | 5% | 2% |

The remaining low variation groups are inside the groups of non-electric vehicles, so those low variation group classification is not caused by charging activities. For non-electric R-net vehicles, the average delay is sometimes at least twice as high as the average delay, especially on R-net lines 300a (from Haarlem to Amsterdam ArenA) and 310a (from Amsterdam Zuid to Nieuw Vennep). Therefore, the new percentage low variation is higher in case of non-electric R-net vehicles. In general, for non-electric city and regional vehicles, the average delay is quite low. Hence, the new percentage low variation for the C3F2 variants, are substantial lower.

The results of Figure 5-14 only show advantages of the adapted timetables. This is mainly caused by the assumption that departure time delays do not propagate to delayed arrival of the vehicle's next trip. Without that assumption, the whole timetables should be changed in order to account for the charging activities. That means that the frequency of the line operations decrease or the number of vehicles operating on those lines, increase. In contradiction to the determination of the frequency, the model is able to determine the number of required extra vehicles, since it uses the same algorithm as for the overnight charging variants. However, still fast charging power is considered and the driving time to the depots is set to zero, since the charging activities take place at the bus station. It should also be mentioned that only the number of required extra vehicles for Need can be determined, because all overnight charging variants are based on this charging mechanism. For C2F1-Need, five extra vehicles are required (two of GVB and three of Connexxion), which result in an increase of 4.4% of the vehicle costs. For C3F2-Need, ten extra R-net vehicles are required, resulting in a vehicle cost increase of 10.2%. Besides, deployment of extra vehicles result in extra vehicle hours, so the represented reduction of the delayed vehicle costs will not be that large in reality.

To conclude, the high delay costs for OC can be reduced substantially, especially when there is little variation in the delayed departure times. To realise this, other costs components, such as the vehicle investments, will increase.

## 5.7 Conclusions of model application Schiphol

Based on the results of the variants, the scenarios and the sensitivity analyses, multiple conclusions about the operations of electric vehicles at and around Schiphol, can be drawn. In general, this application shows an overall cost increase for operations of electric vehicles compared to operations of conventional diesel engine vehicles. More detailed conclusions per assessment criterion are drawn in the remainder of this section. Also conclusions concerning relationships between different criteria are mentioned.

First, it can be concluded that the delayed departure cost is always a substantial cost component in case of OC, especially when the share of electric vehicles increase and a longer overall charging time arise. The main reason for substantial delays is that Schiphol Knooppunt Noord is not a terminal, excepted for bus line 196, so no waiting times at this station are included in the conventional timetables. When longer distance trips or lower charging power is considered, the charging times and therefore, the delayed departure costs increase even further. In order to prevent an increasing rate of the passengers dissatisfiers, increasing costs for level of service criteria should be limited as much as possible. Min and Peak offer good possibilities for that. For slow charging at the depot, no extra delay occur, because this charging method is developed to prevent extra delays by purchasing enough extra vehicles. In other words, vehicles are taken out of operation for charging.

Secondly, in general, the dispersion in departure time costs grows with a comparable amount as the delayed departure costs. This only holds when the delay is caused by the fast charging activities. When for instance, detours should be made, the delayed departure cost are high due to delay in arrivals. This has no influence on the dispersion in departure time. The upper bound of the dispersion in departure time costs is determined by Need. By (partly) switching between charging mechanisms, the dispersion in departure time can be downsized. In general, Min and Peak result in the lowest dispersion in departure time. Furthermore, Max results in the least variation in delays inside each group, together with Peak or Place, dependent on the amount of charging point scarcity. It is proven that the delay costs can be downsized quite easily by slight timetable changes, especially for the low variation groups. However, this results in lower frequencies or, in case of a constant service level, in more required vehicles. Larger delay reductions, result in a larger number of extra vehicle required.

Then, the main conclusions from the cost criteria are elaborated, started with the vehicle delay costs. Although, the delays are multiplied by the costs per vehicle hour, since the delayed vehicle costs are for the operator, they grow with the same amount as the delayed departure costs due to the vehicle delay dependency of both indicators. The delay indicators are mostly determined by the number of charging activities and the duration of the charging processes. However, the delayed vehicle costs are higher than the delayed departure costs for the frequencies and number of passengers considered. Also this delay cost component can be reduced by some timetable adaptation.

Fourth, the benefits of energy consumption of electric vehicles over fuel consumption of conventional diesel engine vehicles are approved by this model application. In the assessment framework, the energy/fuel consumption costs are negative, so there is a benefit compared to the reference, which becomes even larger in cases of a high electrification rate of the total fleet. For the operators, these costs savings are the most important ones to earn back the high (vehicle and charging infrastructure) investment costs for electric operations. Compared to the electrification of city and regional vehicles, the electrification of the R-net vehicles result in even more energy/fuel consumption cost savings, because on a daily basis, more kilometres are driven by R-net vehicles (20,070 instead of 11,640 kilometres). Between different charging mechanisms, there are slight differences, however, these are mainly caused by deviations in the estimation of the overnight charging costs.

The next cost component, the vehicle investment costs, is often mentioned as main disadvantage for operators to switch to electric exploitation. The vehicle investment is substantial higher than purchasing a conventional diesel engine vehicle (factor 1.6 for a rigid bus and 1.8 for an articulated bus, including ICT). For slow charging, the electric vehicle investment is the highest, because of the fleet expansion of 26%, 70% and 43% in case of only electric city and regional vehicles, only electric R-net vehicles and all electric vehicles, respectively. Due to more necessary charging activities for R-net vehicles, a lot more extra vehicles are required. The advantageous of slow depot charging is that extra delays are prevented, because the charging process is not influencing the operations.

Then, it can be concluded that the charging infrastructure system costs are relatively low compared to the vehicle investment costs. This is primarily caused by the lower required number of fast chargers and relatively low piece price (€100,000 - €150,000, for induction and pantograph respectively). The number of slow chargers (for overnight charging) is equal to the number of vehicles, however, slow charging infrastructure is a factor four to six cheaper than fast charging systems. For Schiphol, more expensive charging infrastructure systems offering higher charging power possibilities, like pantographs over induction systems, are worth the investment, because the systems are highly used on a daily basis. The delay savings overcompensate the higher costs for the charging infrastructure. Furthermore, the Flex charging scenario proves improvements in robustness by adding one higher power charging system for one bus line.

The heptagon is completed by elaborating on the disruption results. It can be concluded that the disruptions become a relevant aspect when the number of electric vehicles and number of available charging points is unbalanced. For Schiphol, this is the case when all vehicles are electric. Disrupted vehicles should wait till the charging point or boarding and/or alighting platform where they are assigned to become available, which result in an extra delay. Therefore, the number of disruptions is also influencing the size of the two delay criteria. Regarding to the reduction of disruptions, the Place and especially Need offer good possibilities. Place is an improvement of Max in case of too little charging points relative to the electric fleet size. Need mostly determines the lower bound of the disruptions, excepted the cases when an improvement of the disruptions relative to the base case, take place. This happens three times: for C2F1-Min, C2F2-Min and C3F1-Min. Apparently, the charging processes leads to a better arrival pattern at the boarding platforms.

Finally, the influence of each charging mechanism on the operations, level of service (LoS) and costs are summarised in Table 5-16. A plus means that the charging mechanism offers opportunities in relation to the corresponding aspect, a zero means a more or less neutral relation and a minus indicates a negative effect of the charging mechanism. The charging mechanisms are scored relative to the other charging mechanisms. The only exception is for depot charging, because only Need is considered here. These scores are related to the scores of the OC methods.

*Table 5-16 - Influence of each charging mechanism on operations, level of service (LoS) and costs*

| | C1: Depot charging | | | C2: OC by pantograph | | | C3: OC by induction | | |
|---|---|---|---|---|---|---|---|---|---|
| | Operations | LoS | Costs | Operations | LoS | Costs | Operations | LoS | Costs |
| **Min** | | | | 0/+ | + | + | 0/+ | 0/+ | + |
| **Max** | | | | - | - | - | - | - | - |
| **Peak** | | | | -/0 | + | + | 0 | 0/+ | 0/+ |
| **Place** | | | | - | - | - | 0 | 0/+ | -/0 |
| **Need** | + | + | - | 0/+ | - | -/0 | + | -/0 | 0 |

In general, for OC methods, especially Min, but also Peak, offer the best opportunities. Therefore, Min is used as reference in the scenarios and sensitivity analysis (sections 5.4 and 5.5). However, when more scarcity of charging infrastructure arise, Place and especially Need become more attractive as well. This is indicated by higher scores for these charging mechanisms for C3 compared to C2.

# 6. Discussion

After a short introduction, the application results as well as the general model, are discussed in this chapter. In section 6.2, the model results are compared to the model results of other literature and an elaboration on the spatial generalisation is performed. After that, the limitations of the (Z)E-bus station operations model are discussed in section 6.3.

## 6.1 Introduction

In this research, a model is developed (chapter 4) and tested for application at Schiphol (chapter 5). However, not all variables and dynamics of the bus station operations can be modelled. A model tries to represent the real world as realistic as possible, but due to an innumerable number of factors influencing the real world, only a small number of variables fall within the scope of the model. In section 6.2, the model results are compared to other literature in order to compare the order of magnitude of the results and the model dynamics with existing literature. This reflection indicates the reliability of the model results. Deviations from the model results compared to values obtained in real-life are possibly caused by limitations of the model. They are discussed in section 6.3.

## 6.2 Discussion of the model and model results

In this section, the model and the model results are reflected. First, the model context is discussed in section 6.2.1. Also the spatial boundaries for model usage are included in that section. In section 6.2.2, the model results are reflected on. Specific aspects of the model application and numeric application results are reflected on.

### 6.2.1 Context for model use

The transition period towards zero-emission public bus transportation has started. However, there is a lack of information on the effects of zero-emission bus transport operations and a lot of uncertainty in the (near) future zero-emission bus (and battery) developments. This results in complicated decision making on how to realise zero-emission bus transport. The (Z)E-bus station operations model is a useful tool for public bus transport operators and authorities in order to provide insights in different solutions and effects of zero-emission bus transport in different and very specific situations and cases.

As long as proper AVL data is available, each specific case can be modelled by the (Z)E-bus station operations model, in order to find the most promising charging opportunities and to get insights in the effects. This can be done for different operators and/or authorities. The most important decision for which this model could be a useful supporting tool, is the charging method choice. Besides, the necessary number of charging points can be obtained from the model, which in its turn offers insights in the charging station allocation and the corresponding required bus station redevelopments. The model can also be used as supporting tool for decisions like the electric vehicle choice, charging power choice and the choice concerning the fleet electrification order. These decisions influence the necessary station (layout) redevelopments, as indicated in Figure 6-1. Such choices influence the charging method choice as well. This is indicated by the feedback loop in Figure 6-1.

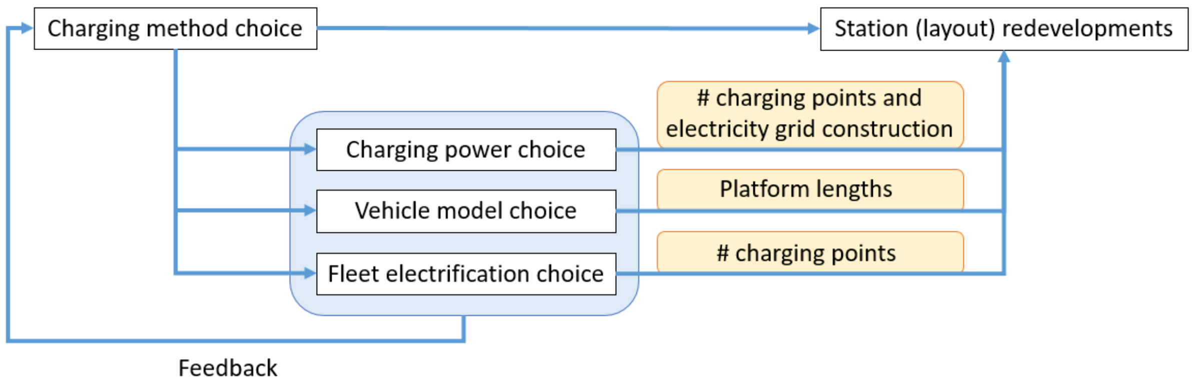



*Figure 6-1 - Charging method choices in relation to station redevelopments*

The (Z)E-bus station operations model supports operators and/or authorities in the decision making process concerning zero-emission public bus transportation. However, the type of electric vehicle choice: battery electric or fuel cell electric, could not be modelled, neither could the optimal charging location choice. These decisions are important problems for operators. Moreover, IMC is not included in the modelled charging methods, while it can be an opportunity, especially when its corresponding investment costs decrease in the next few years or when charging infrastructure is already (partly) available.

#### *6.2.1.1 Spatial generalisation*

In this research, the model is applied for Schiphol airport, however, multiple candidate locations were considered. Interesting bus stations to model in the future are the bus station at Leiden Central Station and the bus station at Haarlem Central Station, in order to obtain insights in the number of required charging points and the advantages of OC compared to depot charging. Considerations of number of charging points and charging method are problems, operators have to struggle with. However, till which spatial boundaries is it possible to use the model? An important requirement for modelling a bus station is the availability of AVL data of the bus lines serving the bus station. This data is provided via CROW-NDOV and only provides data of public transport operations in the Netherlands. Therefore, only an adapted version of the (Z)E-bus station operations model, synchronized for other data formats, will function abroad. Without a recalibration of the vehicle and charging infrastructure database, the model is not valid outside of Europe, because both databases are based on electric bus operations in Europe. Moreover, outside of Europe, the view on electric bus exploitation is different. For instance, in China, the focus is on long range batteries and/or battery swapping and the opportunity of OC is appreciated less compared to European views.

### 6.2.2 Reflection on the model results

The model application at Schiphol delivered interesting results regarding the influence of different charging methods on the operations, level of service and costs. In paragraph 6.2.2.1, the application is reflected on general electric operations and in paragraph 6.2.2.2, the numeric application results are compared to existing literature about public (zero-emission bus) transport.

#### *6.2.2.1 Reflection on model application Schiphol*

In order to validate and test the model, the model is applied to Schiphol, a deliberately chosen application. However, since the modelling dynamics are highly case dependent, the modelling results will be case dependent as well. General conclusions, based on the application results, should be drawn with a certain degree of caution. A reflection on the model application is performed in order to get insights in the distinction of specific conclusions for Schiphol and general conclusions.

First, the considered bus station, Schiphol Knooppunt Noord, is not a terminal, except for night line 196. In section 2.3.3, it is mentioned that combined bus stations and terminals are well-established locations for OC, because of the slack in time at those locations. Therefore, the delay related costs for OC at Schiphol Knooppunt Noord are higher compared to the costs for OC at a terminal.

Secondly, it is important to consider some differences between the actual plans and the modelled situation at Schiphol. In this research, only one charging location is considered in order to model the covered routes in a detailed way. In reality, two fast charging locations are planned. Besides, the electric vehicle model is different. The planned electric VDL vehicles are not included in the electric vehicles database, because no energy test results are obtained in the ZeEUS E-Bus reports for this vehicle model. Therefore, a comparable vehicle, in terms of vehicle length and corresponding charging system and power, is used.

Finally, IMC is not included in the model and tested in model application Schiphol. In paragraph 2.3.3.2, it is mentioned that IMC by pantograph offers opportunities for Arnhem and even for Amsterdam. A trolleybus charging infrastructure network and electricity grid connection points of under stations of the tram system respectively, are already available. In this research, it is mentioned that IMC is often not considered as a serious option, yet. However, the opportunities for Arnhem and Amsterdam and the realised (partly) IMC system in Lucerne, prove that IMC could offer promising opportunities for certain cases.

#### *6.2.2.2 Numeric reflection on the application results*

In order to reflect on the application results, the results are compared to the findings in other scientific literature. Important aspects to reflect on are 1) the level of service and 2) investment and operational costs. Other criteria, like delayed vehicle costs and number of disruptions are related to point 1. Moreover, point 2 is an important trade-off considered by operators.

To start with the level of service, the application results are compared to the results of the Master Thesis of A. L. Durand: Managing disruptions in public transport from passenger perspective (2017), where disruptions in the Rotterdam metro network are researched. Considering 60 incidents per year, a maximum of €900,000 of societal cost savings can be realised. For this research, considering the variants corresponding to Schiphol's plans, the annual societal costs (delayed departure and dispersion in delay) relative to the lowest societal cost variant, the base case, are between €378,000 and €887,000 (calculation is discussed in section 5.3). These values are based on small daily delays, while the study of Durand is based on 60 large scale disruptions. Therefore, additional research should be conducted in order to compare disruptions on such different levels of scale.

Secondly, the investment and operational costs results of this research are compared to other literature. Laizans, et al. (2016) performed a case study in Latvia, where the economic viability from regional perspective of electric and diesel engine vehicles are compared. Both, the initial vehicle investment and the operational vehicle propulsion costs are compared and expressed in percentage change, as indicated in Table 6-1. This is also done for the maximum and minimum investment and operational energy/fuel consumption cost charging mechanisms for complete electric exploitation, compared to the base case, concerning only diesel engine vehicles.

*Table 6-1 - Comparison between results of Laizans et al (2016) and this research*

| | Vehicle investment | | | Energy/fuel consumption costs | | |
|---|---|---|---|---|---|---|
| | Diesel | Electric | Δ% | Diesel | Electric | Δ% |
| **Laizans et al. (costs per vehicle)** | €332,493 | €550,000 | **+ 66,9%** | €60,000 | €8,648 | **-85,6%** |
| **Model results – Min (cost per day)** | €8,271 | €15,874 | **+91,9%** | €11,731 | €3,198 | **-72,7%** |
| **Model results – Max (cost per day)** | €8,271 | €15,874 | **+91,9%** | €11,731 | €3,262 | **-72,2%** |

*Based on Laizans et al (2016)*

The prices between the two studies are quite different, due to the fact that the prices of Laizans' et al. research is expressed per vehicle, while the vehicle (consumption) prices of the model results are expressed per day and include the total fleet. However, the percentages are interesting to compare, because the costs/benefits of electric vehicles relative to diesel engine vehicles, can be expressed. For the vehicle investment, the delta of the model results are larger, because the average price of a diesel engine vehicle, varying from €250,000 to €350,000, is lower. For electric buses, the same vehicle price is considered, because only electric, articulated buses are considered in the model application. The delta energy/fuel consumption costs are less. Laizans et al. consider higher costs for diesel, because they do not exclude VAT, while the considered Latvian energy tariffs are slightly lower. To conclude, the results of both studies roughly show the same pattern.

## 6.3 Limitations of the (Z)E-bus station operations model

The quantitative (slight) differences between the results of Laizans et al. and this research, discussed in section 6.2.1, may have been caused by differences in assumptions due to national differences, different vehicle use or different network characteristics. However, they can also be caused by one or more limitations of the model. All (Z)E-bus station operations model limitations are sorted by the model module in Table 6-2 and further discussed in the remainder of this section.

*Table 6-2 - Model limitations per model module*

| 1. Charging time calculation model | 2. Bus station operations model | 3. Cost/benefit calculation model |
|---|---|---|
| 1. Roughly estimated last battery load determination for first arriving vehicles, not originating from the depot | 1. Overestimated charging times by Simbus result in overestimated disruptions | 1. No environmental, maintenance and management costs included<br>2. Electricity grid costs and constraints are not considered<br>3. Battery downsizing opportunities are not considered<br>4. Roughly estimated battery load for arriving vehicles at the depot |

**1. Charging time calculation model**

The first model limitation is caused by uncertainty in the battery load determination in the beginning hours of the daily charging time modelling. When a vehicle arrives at the charging station for the first time and is not originating from the depot, there is uncertainty concerning origin and covered route of the vehicle. Therefore, some assumptions concerning the last battery load and covered route are made here. In general, these assumptions results in relatively high last battery loads (80%), so the necessity of charging those vehicles could be underestimated. This is partly compensated by a high battery buffer of 20%. If a vehicle arrives at the station for the second, third, fourth, etc. time, the origin of the vehicle and the covered route is exactly known, therefore the battery load determination of that (much greater) part is more accurate. Hence, the charging time calculation is more accurate as well.

**2. Bus station operations model**

As Simbus has never been used for simulations of electric vehicles, the use of the short term buffer place as charging location has one important limitation: each vehicle goes to the short term buffer till the allocated alighting platform becomes available. Hence, vehicles wait at the charging point till their alighting platform is free. Therefore, the charging times following from the simulation are longer than the charging times calculated in the static charging time calculation model, especially for simulations where the number of charging activities is relatively high. Considering efficient use of the charging infrastructure systems, the static charging times are used for the delayed departure time and delayed vehicle cost criteria. However, the number of disruptions are based on the overestimated charging times, resulting from the simulation, so they are (possibly) also overestimated.

**3. Cost/benefit calculation model**

The assessment criteria of this research are selected based on differences between charging methods obtained from literature. Hence, some other, important aspects for electric exploitation are not included in the assessment framework. No environmental costs concerning polluting emissions, are considered, while they are mentioned as main incentive to move to zero-emission transport. However, certain aspects only declare differences between diesel engine vehicles and electric vehicles and do not result in differences between different charging methods. The same yields for aspects like noise hindrance, comfort, accessibility, public health and employment. Furthermore, maintenance and management costs are not considered either. Information about these aspects for electric buses is scarce and in addition, also these aspects mainly declare differences between diesel engine and electric vehicles.

Secondly, the charging infrastructure investments are relatively low cost components in this research, mainly caused by incomplete cost estimates. Only fixed costs per charging infrastructure system, are included in the charging infrastructure costs. These costs are fixed and do not augment for higher charging power systems, because there is a lack of information about these price dynamics. System suppliers do not provide public data about this. Furthermore, the costs for constructing the electricity grid in order to deliver the required amount of charging power is not considered at all. The order of magnitude of these costs are case dependent. However, this falls outside the scope of this research. Therefore, the boundary conditions for the charging power, set by the electricity grid, are not taken into account either. The preference for a higher power charging system is not that obvious as the results of this research show.

Third, as discussed in section 2.2.4 of the literature review, battery downsizing results in lighter and therefore cheaper vehicles and vehicle operations. However, this mechanism is not included in the model, due to a lack of reliable data concerning this trade-off. Hence, a fixed price per vehicle type (rigid/articulated) is considered. If information about battery (size) dependent prices becomes available, it could be implemented in the model.

At last, the calculation of the overnight charging costs, included in the operational energy/fuel consumption costs, is based on a reload of the batteries to 100% at the depot. For a lot of vehicles, the battery load at depot arrival is unknown. Therefore, the average arrival battery load at the depot is considered to be equal to the average departure battery load at the charging station. For a constant charging process during the day (charging mechanisms Min and Max), this will be a valid assumption (considering relatively short deadheading distances), however, for variations between minimum and maximum charging times during the day, this assumption will result in less reliable results. The overnight charging costs could be under- or overestimated in such situations. Therefore, the overnight charging costs should be considered as rough estimates. In general, the overnight charging costs are a small part of the total energy/fuel consumption costs, so the resulting under- or overestimation is permissible for this research.

## 6.4 Conclusions of the discussion

In this chapter, the context for using the model is discussed first. Based on the charging method choice and other important decisions concerning electric operations, the required station (re)developments for shifting toward electric buses, is determined. The (Z)E-bus station operations model is developed to do this for operators and authorities in different regions in the Netherlands. For applications abroad, the model should be synchronized for other input data formats. Without significant changes in the databases and model settings, the model will not be applicable outside Europe.

Secondly, the application results are discussed. The research station, Schiphol Knooppunt Noord, is not a terminal, so delay related costs are relatively high. In contrary to the actual plans, just one fast charging location is considered and one other vehicle type, including energy consumption test results, is considered. Thereafter, the application results are reflected upon existing literature. The operational costs and those of the level of service are reflected on the Master Thesis results of Durand. This reflection only gives an indication about the order of magnitude of disruption related costs, since slightly disrupted buses are compared with large scale metro disruptions. The second reflection, on the results of Laizans' et al. research (2016), is quantitatively more valuable, since both studies concern the comparison between diesel engine buses and electric buses. Roughly, both studies show the same relationship between vehicle investment cost and operational energy/fuel consumption costs.

Also the model limitations are discussed in this chapter. Three limitations, concerning the derivation of the last battery load, the overestimation of the dynamic charging time and the estimation of the battery load for overnight charging are showing model related shortcomings. The charging infrastructure and vehicle costs related limitations, as well as the exclusion of certain assessment criteria are caused by a lack of detailed information.

# 7. Conclusions & recommendations

In this final chapter, the research findings are elaborated on. After a short introduction, the main conclusions are drawn in section 7.2. The main research question and the sub research questions are answered in this section. Finally, in section 7.3, recommendations for the public bus transport sector are rendered, following by recommendations for further research and for further model developments.

## 7.1 Introduction

In this research, a literature review was performed in order to develop the (Z)E-bus station operations model. The model has been applied at Schiphol in order to further develop and test the model. Theoretical variables and dynamics obtained from literature were supplemented by practical observations from the application and interviews with different stakeholders in the field as well, in order to develop the model. An assessment framework is developed for the assessment of the Simbus simulation results. The application results are discussed. Based on a reflection of the application and its cost related results plus a summation of the model limitations, the reliability of this research is qualified. Based on the reliability check and the model application results, in combination with the existing literature, conclusions are drawn and recommendations are formulated further on in this chapter.

## 7.2 Conclusions

In this section, the main conclusions are drawn. First, in section 7.2.1 the answer on the main research question is elaborated on. In section 7.2.2, sub questions 1 and 3, related to different charging methods, are discussed. Sub questions 2 and 4, concerning charging mechanisms, are discussed in section 7.2.3.

### 7.2.1 Effects of the charging infrastructure choice and charging regulations

The main research question, formulated in the first chapter, is:

| **Main 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? |

Overall, it can be concluded that the total costs increase for operations of electric vehicles compared to operations of conventional diesel engine vehicles. The purpose of the Zero-emission agreement is to improve the sustainability and liveability. 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, the following main charging methods are distinguished in this research:

1) Slow depot charging
2) Fast charging/opportunity charging (OC)
3) In-motion charging (IMC)

Slow charging at the depot 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. Hence, compared to non-electric operations, the operation and level of service (LoS) remain constant. Though, higher costs are involved, because an oversized fleet is necessary and more deadheading trips (to the depot) should be performed. For relatively short distance (city)lines, the fleet overcapacity is limited, so slow depot charging could be considered for such line operations. However, for longer distance lines, like BRT and long distance regional lines, substantial vehicle investments are involved, since the required fleet size could be up to 70 percent higher compared to the original fleet size.

Secondly, OC is a fast (re)charging process of the vehicles during the operations. Often, OC takes place at a bus station, preferably a combined bus station and bus terminal, in order to limit the extra dwell time of a vehicle. In case of space requirements at bus stations, OC can be shifted towards the depot. At bus stations, 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. Scarcity of charging infrastructure systems results in disrupted vehicles and delayed trips, which deteriorate the operations and level of service. In order to reduce the charging related delays, higher power charging systems are recommended for frequently used systems on a daily basis. Corresponding timetable adaption is recommended as well. Charging related delays could be prevented completely, by constructing multiple OC stations in the network, in order to reduce the charging times to the dwell times. In addition, the corresponding battery downsizing opportunities could cut the vehicle investment costs. However, these large scale bus station redevelopments result in high charging infrastructure investments. All discussed delay reduction and/or prevention measures contain trade-offs between level of service and investment costs.

IMC combines the charging and operation time, so no level of service problems could occur. However, substantial charging infrastructure investments are involved, since IMC is still in its infancy stage yet. The relationship between level of service (and operations) and investment costs for different discussed charging methods for electric operations, relative to non-electric operations, are outlined in Figure 7-1.

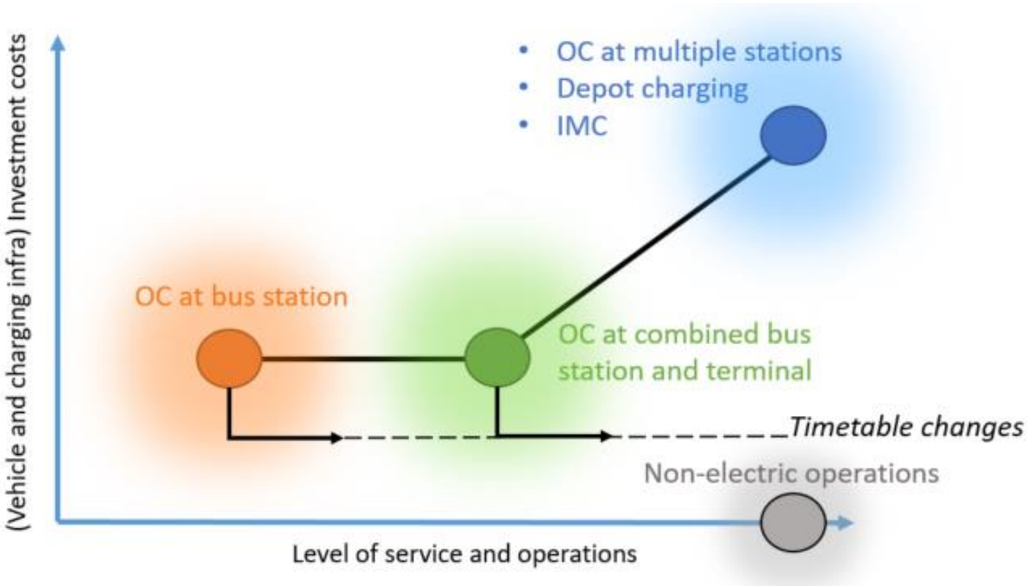



*Figure 7-1 - Relationship between level of service and investment costs for charging electric vehicles*

In order to research opportunities for efficient planning of the charging process, five different charging mechanisms are considered in this research: Min, Max, Peak, Place and Need, which are discussed in more detail in section 7.2.3. In regards to operations, Need offers the best opportunities, because the number of charging activities is minimized. Considering the level of service, Min offers the best possibilities. For an increasing difference between peak and off-peak passenger loads, Peak becomes advantageous as well. In the end, a dynamic mechanism, varying between different charging mechanisms at the right moments, will result in an even more efficient charging time planning.

### 7.2.2 Assessment framework of charging methods

Different battery charging methods for electric, public bus transportation, are applied all over the world or will (possibly) be applied in the (near) future (Figure 7-2). In this research, an assessment framework is developed in order to compare different charging methods. The charging methods circled in Figure 7-2, are modelled in the (Z)E-bus station operations model and therefore analysed in more detail. In Figure 7-2, the main limitations of the remaining charging methods are mentioned.

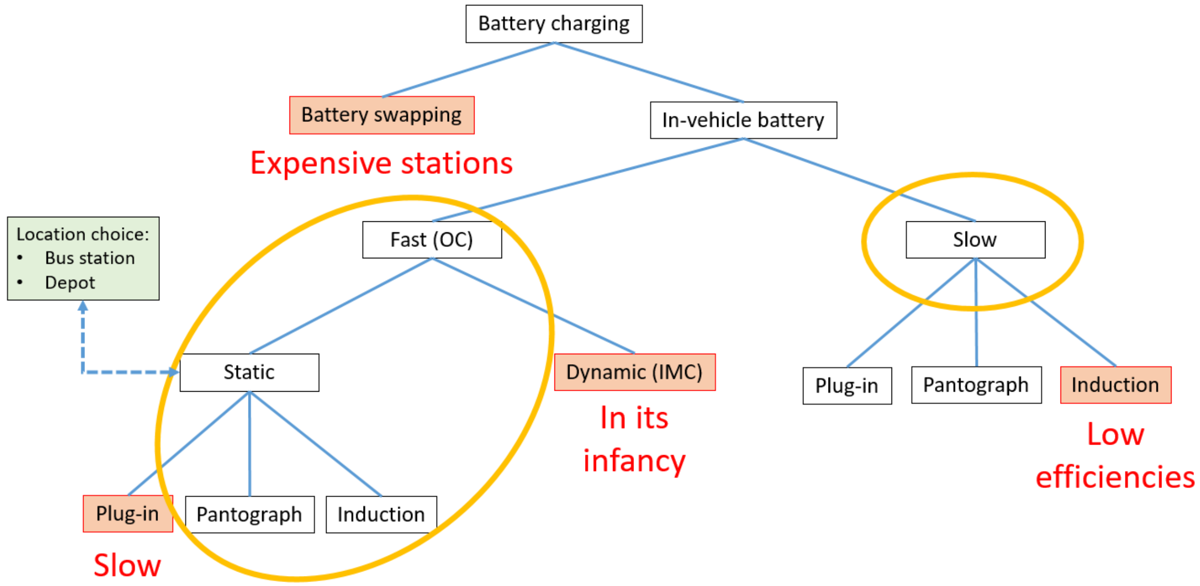



*Figure 7-2 - Charging methods. Circled charging methods are modelled in this research*

In Table 7-1 is mentioned for each charging method whether the conventional timetables and vehicle schedules could be complied. Also the main advantages and disadvantages per charging method are summarized. Both aspects are further explained per charging method in the remainder of this section.

*Table 7-1 – Degree of compliance of conventional timetables and vehicle schedules for the main charging methods including their main advantages and disadvantages*

| | Conventional timetables | Conventional vehicle schedules | Advantages | Disadvantages |
|---|---|---|---|---|
| **Slow depot charging** | Yes | No | • Low electricity grid investments | • Oversized fleet required<br>• Increasing number of deadheading trips |
| **OC** | No/possibly | Yes | • Short charging times | • Risk of reducing level of service<br>• Space requirements at bus stations |
| **IMC and Battery swapping** | Yes (Possibly for battery swapping) | Yes | • Charging times are basically irrelevant | • Expensive charging infrastructure |

**Slow charging**

Most vehicles are charged with moderate charging power (slow charging), in the depot during the night, when they are out of operation. For overnight charging, the charging power could be lowered, because the charging process can be spread over the night. Despite the fact that the number of charging systems in the depot is equal to the number of electric vehicles in this research, the investment costs for these systems, such as plug-in cables or pantographs, are relatively low (around €25,000 per system), especially when they are compared to the vehicle investment costs. In practice, slow charging by induction is scarce due to the relatively low charging efficiencies of induction systems (90%).

Besides overnight charging, slow charging at the depot could also be done during the daily operations. In this research, slow charging at the depot does not result in necessary timetable changes, because extra delays are prevented by purchasing extra vehicles. Hence, extra vehicles, as well as extra deadheading trips between the end/start station and the depot, should be fitted into the conventional vehicle schedules. This result in high vehicle investments, especially in case of electrification of BRT or other relatively long distance lines. Then, the required number of extra vehicles becomes substantial higher: at Schiphol, the overcapacity of the fleet size rises to 70% for electric R-net buses, towards 25% when only the city buses are electrified. If only overnight charging is considered in the Schiphol application, the overcapacity of the fleet size becomes between 50% and 300%.

**Opportunity charging**

In practice, OC is often combined with overnight charging, however, for OC, additional fast charging infrastructure is necessary. These fast charging systems are around four to six times more expensive than slow chargers and could be installed at two different locations: 1) At (a) bus station(s), and 2) At the depot. In regards of (operators) costs, fast charging systems at bus stations are preferred. Especially combined bus stations and bus terminals are well-established locations for OC, because multiple vehicles arrive there and substantial charging related delay costs could be saved. If there is no place for fast charging activities at suitable bus stations, for instance in dense urban environments, OC can be performed at the depot. In that case, all energy facilities are situated at one location and could be kept in own management. However, deadheading trips should be made and an oversized vehicle fleet is necessary.

OC offers opportunities for electric operations according to conventional vehicle schedules and even according to conventional timetables when a higher numbers of OC stations are implemented. A highly frequent use of OC during the day, result in shorter charging times and battery downsizing possibilities, so in lighter and cheaper vehicles. However, more OC stations in the network result in higher investment costs for the electricity grid. In general, the number of charging systems and the number of electric vehicles should be balanced, in order to prevent inefficient use of charging infrastructure on one hand and disrupted and delayed vehicles on the other. A slight overcapacity of infrastructure systems is recommended in order to improve the robustness.

If the charging times becomes higher than the dwell time at the bus station, conventional timetable schedules could not be complied anymore. Charging related delays occur, especially when the system charging power is relatively low. For OC by induction, with a maximum charging power of 200 kW, higher costs for operations and level of service are included than for OC by pantograph, with a maximum charging power around 1000 kW. Therefore, higher power charging infrastructure systems, are recommended in order to limit the charging related delays. In addition, these delays could be limited, (up to 85 percent for application Schiphol) by slight timetable changes as well, especially when the variation in delays is small compared to the actual delays. Considering the timetables from line and/or network perspective, lower line frequencies should be tolerated or extra vehicles should be deployed in order to deal with these timetable changes.

**Remaining charging methods**

In-motion charging (IMC) methods, by induction or by pantograph, combines the charging process and vehicle operation time, so both conventional vehicle schedules and timetables could be complied. At the moment, IMC is accompanied with major charging infrastructure investments, because these methods are still in its infancy stage. Yet, IMC is only a serious option for situations where IMC infrastructure is already (partly) available.

Finally, for battery swapping, till now only applied in China, a vehicle can continue operations while the battery is (re)charged outside the vehicle. However, these swapping activities also take a substantial time (seven to ten minutes) and the battery swapping stations are large and expensive.

### 7.2.3 Charging mechanisms

In this research, five different charging mechanisms are developed: 1) Min, 2) Max, 3) Peak, 4) Place, and 5) Need in order to obtain charging regulations and provide insights in the optimization of the charging processes. Min and Max represent the assignment of the minimum and maximum charging time, calculated by the model, to each trip arriving at the charging station. The other three mechanisms assign the minimum or maximum charging time to a trip, dependent on a certain charging principle, as indicated in the blue part of Table 7-2. For charging at the bus station, all charging mechanisms could be relevant, while for depot charging only Need is considered, since this charging mechanism minimizes the number of empty (deadheading) trips between the bus station and the depot.

In this research, the ranges of the model results are presented. The derived minimum and maximum values for each criterion are not directly related to Min and/or Max, which means that other charging mechanisms could be improvements, but also deteriorations. Per main criterion, the score for each charging mechanism is globally represented in the orange part of Table 7-2 (+ is a positive effect and – is a negative effect) and further described below.

*Table 7-2 - Charging mechanisms and their scores in regards to operations, level of service (LoS) and costs*

| Charging mechanism | Charging time | Charging regulation | Operations | LoS | Costs |
|---|---|---|---|---|---|
| **Min** | Minimum | Minimum charging if charging is necessary | + | + | + |
| **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 | - | + | + |
| **Place** | Charging place dependent | Maximum charging if possible and minimum charging at the last available charging point | --/+ | -/++ | -/+ |
| **Need** | Necessity dependent | Maximum charging if charging is necessary | ++ | - | - |

**Operations**

According to the assessment framework, one criterion is indicated in the operation box, the disruptions. Need offers the best opportunities in regard to the reduction of disruptions, due to a minimization of the number of charging activities. The minimized charging times in Min, also result in a low number of disruptions. Max performs the least. In case of too little charging points relative to the electric fleet size, Place shows improvements in operations compared to Max. Under these conditions, also this charging mechanism offers opportunities.

**Level of service (LoS)**

In general, Min and Peak offer the best possibilities in regard to level of service, because both charging mechanisms result in less delays and dispersion in delays. Larger differences in peak and off-peak passenger loads, result in more preference for Peak. In case of charging infrastructure scarcity, Place becomes the most attractive charging mechanism. Max scores the worst for the level of service criteria, however, for this charging mechanism, most improvements in delay reduction can be obtained by realising some timetable adjustments.

**Costs**

For the investment cost components, the model assessment results do not show differences between charging mechanisms. However, based on the model calculations, the number of required charging points and therefore the charging infrastructure investments, can be reduced, especially in case of Place. In contradiction to the operational energy/fuel consumption costs, there are some differences in the operational delayed vehicle costs between charging mechanisms. These differences are caused by charging time related delays, which can be reduced by the same delay limitation mechanisms as discussed for the level of service.

Finally, for an efficient charging time planning, a fixed charging mechanism is not suitable. A dynamic mechanism, varying between different charging mechanisms dependent on the number of charging points, affected passengers and vehicle arrivals, will result in a more efficient charging time planning.

## 7.3 Recommendations

Based on the discussion and conclusion, several recommendations can be formulated. In this final section, recommendations for further research are summed up, followed by recommendations for expansions of the (Z)E-bus station operations model. First, general recommendations for the stakeholders are rendered.

### 7.3.1 Recommendations for operators and authorities

The main recommendation for both stakeholders are represented in Figure 7-3.

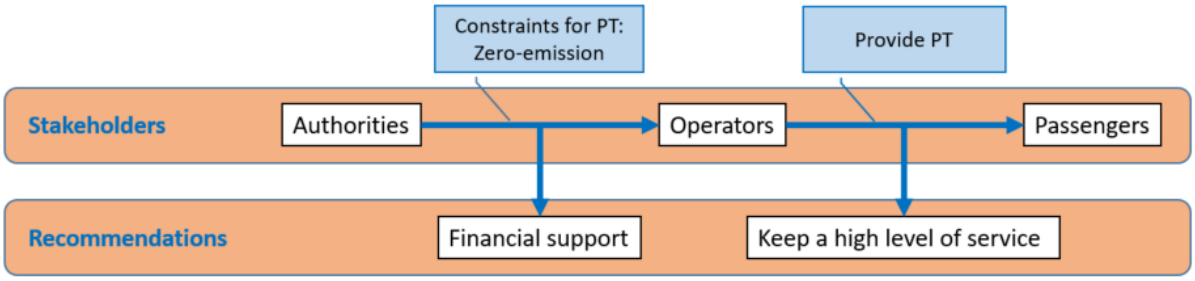



*Figure 7-3 - Main recommendations for operators and authorities*

For operators, it is recommended to realise a high level of service by limiting delays for passengers as much as possible, when considering the trade-offs between (investment) costs and level of service. When negative effects of electric operations are limited, only positive effects, such as travel comfort and more sustainable cities (for everybody) are effectuated for passengers. In order to prevent disadvantaged passengers, operators should invest a lot in charging infrastructure and/or in (extra) electric vehicles. Therefore, it is recommended for authorities to financially support operators. Authorities could maintain and manage the charging infrastructure or provide subsidies for electric exploitation. Both measures unburden operators financially and contribute to a faster and more secure transition towards zero-emission public bus transport.

In order to keep the level of service high and minimize the corresponding investment costs, multiple decisions should be made by operators. First, the charging station location choice is important. For fast charging, it is recommended to install the charging systems at combined bus stations and terminals in order to limit the delays. For short distance lines, such as city lines, the charging process could be shifted towards the depot and vehicles could be replaced by fully charged ones. For the charging location choice, at a bus station or at the depot, a trade-off between level of service aspects and investment costs is considered. At least, it is important that the depot is located close to the bus station served by all electric operated lines. For longer distance lines, like BRT lines and regional lines, a substantial fleet overcapacity is required for depot charging, so this will not be advantageous at all. OC at the bus station is recommended for those lines. Though, longer distance lines require more and/or longer charging activities. More and/or higher power charging systems should be installed in order to prevent and/or limit disruptions and delays. On the other hand, the benefits related to the energy consumption relative to the fuel consumption, are the highest for longer distance lines. Yet, IMC is not recommended for operators at all, except in cases where required charging infrastructure is already (partly) available. The described trade-offs and decisions are summarised in an operators decision tree, represented in Figure 7-4.

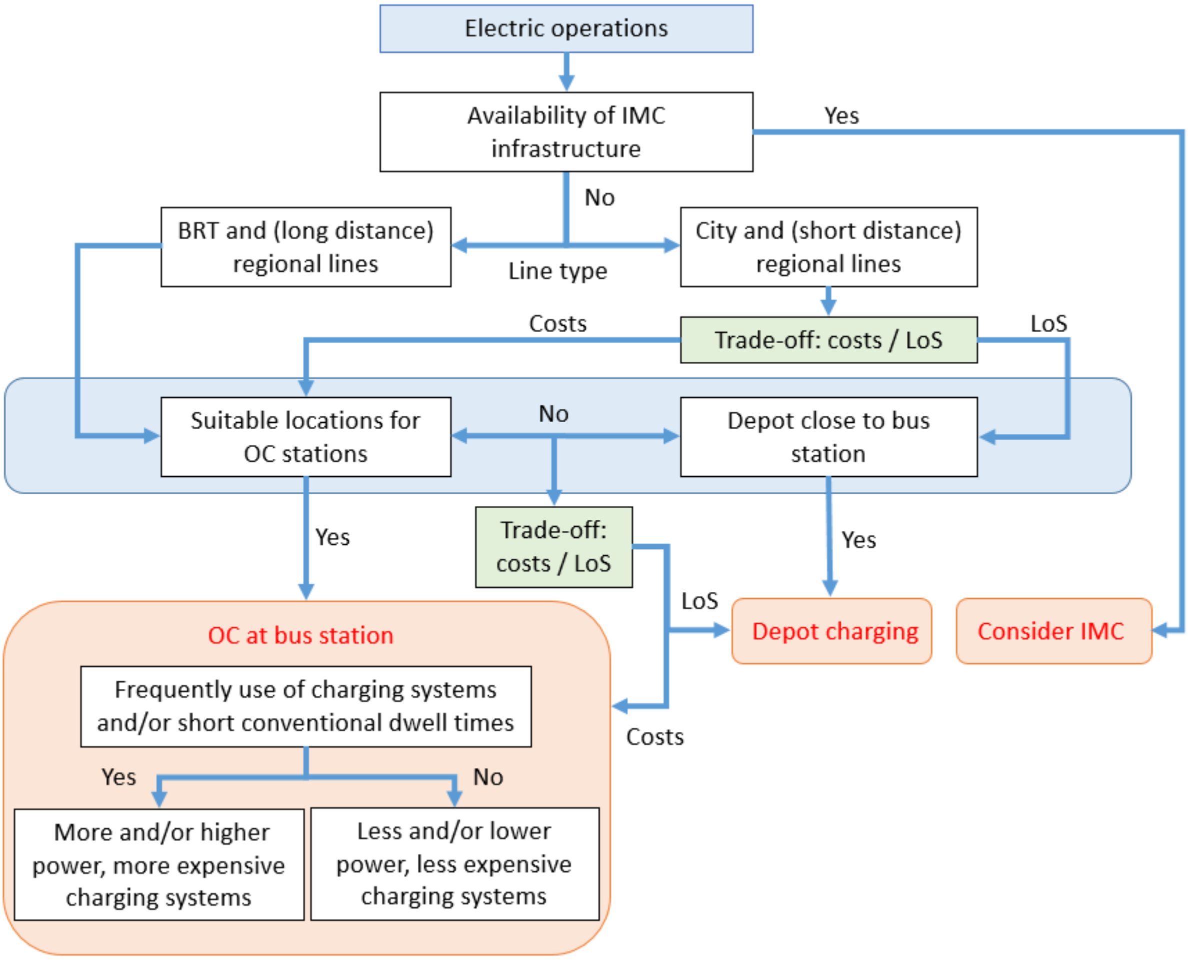



*Figure 7-4 - Charging method decision tree for operators*

### 7.3.2 Recommendations for further research

This research is a first step in the standardization of the charging method choice for electric buses. Therefore, these research results will be an interesting source for further research. Besides, electric public bus transportation is societally a relevant topic, especially caused by the Zero-emission agreement in the Netherlands and in broader perspective, the climate agreement of Paris. An enumeration of recommendations for further scientific research and research concerning the model application at Schiphol, is shown in sequence.

**Recommendations for further scientific research**

- The results of this research could be implemented on line level and even on network level. In this research, charging related delays are not propagating to the next trip, however, it is interesting to research how these delays will propagate. This is also necessary in order to develop new timetables for electric operations.
- It is also interesting to include the charging times for OC resulted from this research, into a transport model. In this way, the influence of each charging method and charging mechanism on the passenger's mode, route and trip choice could be modelled. This could result in different numbers of passengers per charging method and/or mechanism, which could be implemented in the (Z)E-bus station operations model afterwards.
- This research focusses on battery electric buses, however, according to different experts, fuel-cell (hydrogen) vehicles also offer opportunities, especially for longer distances, regional bus

lines in less dense areas. Therefore, it is interesting to conduct research in order to find the break-even point of battery cell and fuel-cell vehicles, considering different relevant network characteristics in relation to the total cost of ownership.

- Notwithstanding IMC is seen as future opportunity, it is interesting to get insights in the required amount of charging infrastructure and the optimal routes in relation to the total network, to install charging systems. An optimisation problem could be formulated in this research.
- It is also interesting to research possibilities of multimodal use of charging infrastructure, including corresponding scheduling aspects.
- More research in battery downsizing opportunities and its relation to the battery (and vehicle) price reduction is recommended. Multiple scientist mentioned that vehicle prices reduce when batteries are downsized, however, this has never been researched quantitatively.
- It is also recommended to research the optimal battery buffer in relation to 1) reliability, and 2) optimal battery usage. Formulating a multi criteria optimization problem could result in one (case dependent) optimal battery buffer.
- At last, further research in battery development in order to improve the Li-ion battery characteristics, is recommended. Besides the range expansion research, which is performed often, an expansion of the battery fast charging limit will also be a desired development. In current literature, the maximum fast charging level is considered to 80% of the total battery capacity in order to not overheat the battery. Higher rates result in more advantageous results for OC.

**Recommendations for further research concerning the model application at Schiphol**

- The first recommendation in order to optimise the results for application at Schiphol is to model (at least) the (most important) variants again, but this time with passenger loads based on smart card data. This should be done commissioned by Connexxion and GVB in order to gain access to the smart card data.
- It is recommended to run the model again, based on trip data obtained after the introduction of 100 electric vehicles at Schiphol. This is an interesting model validation as well as a validation of the current plans. The electric operations could be represented as base case, in order to compare several other charging methods with.
- For Schiphol, combined charging infrastructure use with electric garbage trucks, also having well-known operating conditions of energy consumers, is an interesting opportunity to research.

### 7.3.3 Recommendations for model expansions

During the model development phase, a lot of relevant aspects are considered. Some aspects did not fall within the scope of this research or trade-offs between expected amount of work and relevance of obtained results, have led to choices to not consider certain aspects. Besides, there are some model limitations, mentioned in section 6.3. Recommendations for model expansions concerning the current model limitations are discussed first, followed by recommendations concerning other relevant aspects outside the (model)scope of this research.

**Recommendations concerning current model limitations**

- First, a separate charging buffer in Simbus is recommended. In case of non-availability of boarding platforms, a vehicle is assigned to the short term buffer after charging at the charging buffer. In this way, charging times could be simulated in Simbus. These times could be used for the calculation of the OC costs, instead of the statically derived charging times from the charging time calculation model.

- Secondly, it is recommended to include electricity grid investments in the charging infrastructure costs. Therefore, more insights in the electricity network and required components should be provided. The electricity grid will set requirements to the maximum charging power of each charging system. The fixed charging infrastructure system prices could be replaced by variable prices, dependent on the height of the charging system power.
- Another model limitation is the ignorance of battery downsizing. It is recommended to implement findings concerning the relationship between battery downsizing and cost reduction into the model.
- It is also recommended to find a more reliable determination of the battery load of vehicles arriving at the depot. If these battery loads can be calculated precisely, the overnight charging costs can be calculated instead of being estimated, which result in more accurate operational energy/fuel consumption costs.
- The last recommendation is based on a spatial limitation of the model. As discussed in section 6.2.2, the model can be used directly, only in the Netherlands. However, since the model components refer to an input sheet, the model can be made compatible for other data sheet formats in order to use the model abroad.

**Recommendations concerning aspects not included in the current model(scope)**

- Other interesting modes outside the scope of this research could be implemented into the model as well. First, hybrid electric vehicles offer possibilities for the transition period, so it is interesting to add it to the model by defining a set of rules, describing the operations of hybrid electric vehicles in a realistic way. Secondly, based on expert judgement, fuel-cell (hydrogen) vehicles provide an alternate mode for long distance lines in less dense areas. Adding those vehicle types are opportunities for further development of the model.
- Another opportunity for further model development is the introduction of IMC. For slow charging, the model determines the number of extra required vehicles in order to prevent charging related delays. For IMC, the share of the route that should be provided with IMC infrastructure, based on the charging power, charging efficiency, vehicle speed, vehicle type and several network characteristics, is interesting information where the model should be able to provide answers on.
- More charging mechanisms could be developed. First, the dynamic mechanism, discussed in section 7.2.3, can be developed. This mechanism switches between the existing charging mechanisms at the right moment, in order to optimise the charging processes. Secondly, by formulating an optimization problem, also charging times between the minimum and maximum charging time ranges, could be provided. Optimization problems could be defined as minimization of the disruptions, the delayed departure (costs) or the number of charging points.
- Since smaller batteries result in lower vehicle costs, the interest in multiple OC stations could grow, especially when charging infrastructure costs will decrease. However, the accurate distance determination of each trip is based on one OC station in the network. It is recommended to extend the model for multiple OC station cases, without a deterioration of the distance determination accuracy.
- In terms of efficiency, it is also recommended to research possibilities of charging vehicles arriving to early at the bus station.

- At last, it is recommended to add a variable energy price to the model. Between normal periods and off-peak periods, different energy prices exist. According to Jacobs (2017), 15% lower electricity costs could be obtained when an efficient time planning for charging and power use is considered. Moreover, it is interesting to identify the effects on the operations and level of service when a minimum energy cost charging mechanism is considered.

The introduction of (some of) these recommended model expansions will result in a second version of the (Z)E-bus station operations model. This version will have more opportunities compared to the first version and become a more valuable tool to use in advising different stakeholders about zero-emission bus transportation.

Finally, a personal reflection is done after conducting this research. This reflection is not publicly available, so it is included in confidential Appendix M.

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# Appendices

## Appendix A – Interviews

The following interviews have taken place in order to perform this research:

| | | |
|---|---|---|
| 12 October 2017 | A. Lensvelt, | Process manager, Schiphol Group |
| 3 November 2017 | A. Veenendaal, | Transport planner, Arriva |
| | G. Naber, | Zero-emission manager, Arriva |
| 6 November 2017 | H. Visser, | Transport developer, RET |

## Appendix B – Bus station design and modelling

**Bus station layout**

According to Baker (2011), the two main types of bus station design are DIRO (Drive In Reverse Out) and DIDO (Drive In Drive Out) (Figure I). For DIRO vehicles are required to reverse on departure, which increase dwell time, but there are less conflicts with pedestrians and the use of space is more efficient compared to DIDO. According to best practice guidelines, DIRO is preferred if the bus frequency is six to eight departures per hour, while DIDO is recommended if the bus frequencies become eight to twelve departures per hour (mva consultancy, 2011).

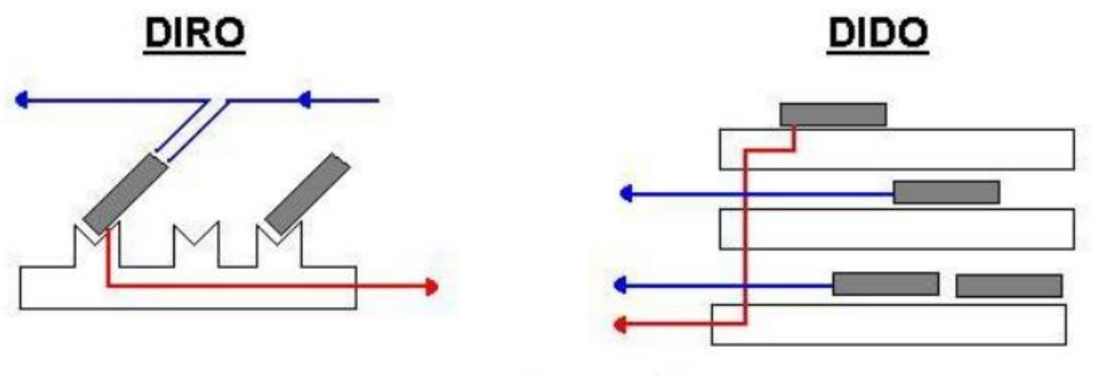


*Figure I - Two main types of bus station design. Blue: vehicle manoeuvring lines; Red: passengers desire lines. Source: Baker (2011)*

Minimizing and managing the pedestrian/vehicle conflict is one of the key safety considerations Baker mentiones. Because of that, and in order to better regulate the pedestrian flows, separate boarding and alighting places are often realised at bus stations. Between those places are buffer spaces, where vehicles stand during drivers' breaks and/or till it is time to start a new trip. The platform lengths for both boarding and alighting platforms are determined by the length of the largest vehicle arriving and/or departing at that platform. In Table I, minimum platform lengths for standard vehicle lengths according to multiple Dutch guidelines, are given. The required platform height in the Netherlands should be 18 cm in order to provide easy access, also for disabled passengers (Geurts & Winkel (2007); Wingen & Hommes (2012)).

*Table I - Minimum platform lengths in meters for different maximum vehicle lengths according to different guidelines*

| | 12 meter | 18 meter | 2X 12 meter | 2X 18 meter |
|---|---|---|---|---|
| **Guidelines Province Noord-Brabant** | 16.0 | 22.0 | 32.0 | 44.0 |
| **Guidelines municipality of Maastricht** | 12.0 | 18.0 | 28.0 | 40.0 |
| **Guidelines CROW** | 12.0 | 18.0 | - | - |

*Based on Geurts & Winkel (2007),* CROW (2010) and *Wingen & Hommes (2012)*

**Basic bus station modelling principles**

According to Fernández (2000), any transfer station is described by transport objects (passengers) and transport modes (buses). The basic formula for bus station operations modelling, expressing the number of buses that can be served is:

$$Transfer\ capacity\ \left(\frac{buses}{hour}\right) = \frac{\#\ loading\ positions * availability}{Occupancy\ time}$$

where the numerator is described by the availability of places where a vehicle can stand for transfer activities and the denominator is described by the dwell times. These dwell times depends on the number of passengers boarding and alighting the vehicle, the accessibility of the vehicle (ground-level entry) and the service payment method. Fernandez concludes that the effect of arrival patterns of buses and passengers, obstructions to pull out from the berth, marginal boarding times and bus capacities are also important factors for bus station operations.

## Appendix C – In- and output variables

| Input parameter | Choices | Dependencies | Obtained from CROW data |
|---|---|---|---|
| **1. General** | | | |
| Season factor | Summer / Autumn, Spring / Winter | Depends on time of the year | Directly |
| **2. Block (choice per block)** | | | |
| Deadheading distance (from depot) | X km | Depends on location | No |
| Deadheading time (from depot) | X min. | Depends on location | No |
| Roundup percentage | % | Independent | No |
| Start and ending times line operations | 00:00 | Depends on location | Directly |
| **3. Line (choice per line number)** | | | |
| *General line characteristics* | | | |
| Authority | X | Independent | No |
| Operator | GVB / HTM / RET / Connexxion / Arriva / X | Depends on location | Directly |
| Minimum waiting time at line end | X min. | Depends on operator | Directly |
| Driver breaks | X min. | Depends on operator | No |
| Vehicle composition | Electric / Diesel % | Independent | No |
| Battery buffer | X% | Independent | No |
| *Line characteristics before arrival* | | | |
| Line type factor | City / Regional | Depends on location | No |
| Dwell time | X min. | Depends on location | Indirectly |
| Covered distance from last charging location | X km. | Depends on location | Indirectly |
| Dispersion (delay) | X min. | Data, calculation | Indirectly |
| *Line characteristics after departure* | | | |
| Line type factor | City / Regional | Depends on location | No |
| Dwell time | X min. | Depends on location | Indirectly |
| Distance to next charging location | X km. | Depends on location | Indirectly |
| **4. Trip (choice per trip)** | | | |
| Vehicle | Refer to Input Vehicle | Independent | No |
| Timetable (arriving and departure time) | 00:00 | Data | Directly |
| Passenger load per vehicle and per line | X | Depends on vehicle passenger capacity, timetable, location | No, only in case of availability of chipcard data |
| Trip continuation | Same line / Depot / Break / Line number X | Depends on vehicle schedule | Directly |
| **5. Station** | | | |

| | | | |
|---|---|---|---|
| Charging method(s) | Refer to Input charging methods | Independent | No |
| # charging points | X | Independent | No |
| Driving time to charging location | X min. | Depends on location and charging method | No |
| Platform length | X m. | Depends on location | No |
| # platforms | X | Depends on location | No |
| # entrances, exits | X | Depends on location | No |
| **6. Charging method** | | | |
| Overnight charging method | Plug-in / Pantograph | Independent | No |
| Opportunity charging method | Pantograph / Induction / Plug-in / IMC trolley / IMC induction | Independent | No |
| Charging system power | X kW | Depends on charging method | No |
| Charging efficiency | X% | Depends on charging method | No |
| Maximum opportunity charging rate / failure rate charger | X% | Independent | No |
| Maximum charging time | X min. | Independent | No |
| Charging infrastructure costs | €X | Independent | No |
| Charging infrastructure lifetime | X year | Independent | No |
| Charging infrastructure discount rate | X% | Independent | No |
| **7. Vehicle** | | | |
| Vehicle model | Chose from list based on ZeEUS E-bus Reports | Depends on charging method | No |
| Vehicle length | X m. | Depends on vehicle model | No |
| Passenger capacity | X | Depends on vehicle model | No |
| Energy / fuel consumption | X kWh/km<br>X l/km | Depends on vehicle model | No |
| Fuel consumption factor for articulated bus | X | Depends on vehicle length | No |
| Battery storage capacity | X kWh | Depends on vehicle model | No |
| Battery buffer (DoD) | X% | Independent | No |
| Vehicle costs | €X | Depends on vehicle model and length | No |
| Vehicle propulsion costs | €X / kWh<br>€X / l | Depends on vehicle model | No |
| Vehicle lifetime | X year | Independent | No |
| Vehicle discount rate | X% | Independent | No |
| **8. Assessment framework (additional)** | | | |
| Cost per vehicle hour | €X | Independent | No |

| | | | |
|---|---|---|---|
| VoT and VoR | €X / hour | Independent | No |

| Output parameter | Unit | Dependencies |
|---|---|---|
| **1. Excel (output vehicle X on line Y)** | | |
| # electric and diesel buses | X | Depends on electric vehicle composition |
| Charging time (static calculation) | X hours | Depends on covered distance from last charging location, distance to next charging location, charging system power, charging efficiency, max OC rate, maximum charging time, roundup percentage, operators break times, start and ending times of line operations, battery buffer, battery storage power, energy consumption, season factor |
| Required # charging points consider no extra waiting time | X | Depends on charging time, arrival time |
| Average departure battery load | X% | Depends on charging time |
| Average battery storage power | X kWh | Depends on vehicle models |
| Required daily amount of diesel | X litres | Depends on covered distance from last charging location, distance to next charging location, # diesel vehicles, fuel consumption, fuel consumption factor articulated bus, vehicle length |
| Required # extra vehicles for Hermes problem | X | Depends on arrival time, charging time, deadheading time (to depot) |
| **2. Simbus (output vehicle X on line Y)** | | |
| Δ departure time | X min. | Depends on arrival time, dispersion, charging time, # platforms and platform lengths, vehicle lengths, # charging points, driving time between station components |
| Disruptions | X% | Depends on Δ departure time |
| **3. Assessment framework (further discussed in section 3.4)** | | |
| Disruptions per group | X% | Depends on disruptions, total number of trips |
| Total delayed departure costs | €/day | Depends on Δ departure time, # passengers (per vehicle), VoT |
| Dispersion in departure time costs | €/day | Depends on Δ departure time, # passengers (per line), VoR |
| Delayed vehicle costs | €/day | Depends on Δ departure time, cost per vehicle hour |
| Energy/fuel consumption costs | €/day | Charging time, charging system power, average departure battery load, average battery storage capacity, required daily amount of diesel, vehicle propulsion costs, |
| Vehicle investment | €/day | Vehicle costs, # electric and diesel buses, vehicle lifetime, vehicle discount rate |
| Charging infrastructure investment | €/day | # charging points, overnight and opportunity charging method, charging infrastructure costs, charging infrastructure lifetime, charging infrastructure discount rate |

## Appendix D – Stakeholder identification

**Passengers**

An important stakeholder in public transport is the group of people where the transport service is provided for: the passengers. Most important interest for a passenger is the ability to reach a certain destination, within a relatively short amount of time and for a reasonable price. Besides the time and cost aspects, some other practical or quality aspects, like car-ownership or travel comfort, are relevant for passengers. All aspects together determine the trip generation choice, route choice, mode choice and departure time choice of a traveller. For public transport, the quality factors are described by the pyramid of Maslow (discussed in section 2.5.1), where the dissatisfiers must be sufficient in order to not discourage travellers for using public transport, while the satisfiers contain additional quality aspects.

**Public transport operators**

Public transport operators are the parties providing public transport. These parties are profit organisations, so they strive to maximize profit. Therefore, they should attract a lot of passengers by providing fast, safe, comfortable and reliable public transport for a reasonable price and minimize the investment and operational cost for providing the service. In the Netherlands, at the start of 2017, ten different regional public transport operators provide public transport. These are: Arriva, Connexxion, Hermes, Qbuzz, Syntus, EBS, OV Regio IJsselmond, GVB, HTM and RET (Kennisplatform CROW, 2017). The last three operators are urban public transport operators in Amsterdam, The Hague and Rotterdam respectively.

**Public transport authorities**

Public transport authorities are responsible for public transport in a certain region. Authorities set requirements to public transport services which are provided by the operators. In the Netherlands, thirteen decentralised public transport authorities exist: ten individual provinces, provinces Groningen and Drenthe together in one cooperation and two separate urban regions: Amsterdam and Rotterdam/The Hague (Figure II).

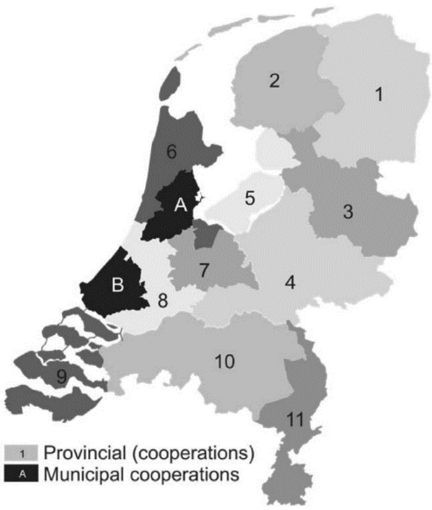


*Figure II - Public transport authorities in the Netherlands. Source: Veeneman (2016)*

## Appendix E – Variables in formulas

$Av\ Batt\ load_{dep}$: Daily average battery load of vehicles when they depart at the charging station (%)

$Batt\_load_{ar}$: Arriving battery load (%)

$Batt\_load_{last}$: Last calculated/derived battery load (%)

$Batt\_load_{req}$: Minimum required battery load to reach the next charging location (%)

$BB$: Battery buffer (%)

$BSP$: Battery storage power (kWh)

$C_{del\ dep}$: Daily costs of delayed departures (€)

$C_{dispersion}$: Daily costs of dispersion in departure time (€)

$C_{ds}$: Diesel costs (€/litre)

$C_{el}$: Electricity costs (€/kWh)

$C_{inv,veh}$: Vehicle investment costs (€)

$C_{inv,ci}$: Charging infrastructure investment costs (€)

$C_{land}$: Costs for land (€/m$^2$)

$C_{OCi}$: Costs per opportunity charging point (€)

$C_{op,c/f}$: Daily costs for operational energy or diesel consumption (€)

$C_{op,del}$: Operational delayed vehicle costs (€)

$CP$: Charging power (kW)

$C_{SCi}$: 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 (€)

$d_{covered}$: Distance covered between location of last calculated/derived battery load and charging station (km)

$Dr$: Discount rate (%)

$d_{to\ cover}$: Distance to cover before the vehicle can be charged again (km)

$EC$: Energy consumption (kWh/km)

$Eff$: Charging efficiency (%)

$FC$: Fuel consumption (litres diesel/km)

$F_{season}$: Season factor

$Lt$: Life time of vehicles and/or charging infrastructure (# days)

$Max\ OC$: Maximum OC rate (%)

$NPV$: 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$^2$)

$t_{charge,min/max}$: minimum or maximum charging time (min)

$\#Veh_{ds}$: 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)

# Appendix F – Distance matrix

| | | | Uitstap | Uitstap | Buffer | Buffer | Buffer | Buffer | Buffer | Buffer | Buffer | Buffer | Instap | Instap | Instap | Instap | Instap | Instap | Instap | Instap | Uitgang | Uitgang |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A | E | BF1 | BF2 | BF3 | BF4 | BF5 | BF6 | BF7 | BF8 | D | C | B | A | H | G | F | E | 1 | 2 |
| | | | | | | | | | | | | | I1 | I2 | I3 | I4 | I5 | I6 | I7 | I8 | UIT1 | UIT2 |
| A | 1 | | 0 | 0 | 242 | 254 | 242 | 254 | 242 | 254 | 242 | 254 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 186 | 38 |
| E | 2 | | 0 | 0 | 88 | 100 | 88 | 100 | 88 | 100 | 88 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 252 |
| BF1 | 1 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 62 | 84 | 106 | 132 | 204 | 226 | 248 | 274 | 30 | 170 |
| BF2 | 2 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 74 | 96 | 118 | 144 | 216 | 238 | 260 | 286 | 42 | 182 |
| BF3 | 3 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 66 | 88 | 110 | 136 | 208 | 230 | 252 | 278 | 26 | 174 |
| BF4 | 4 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 78 | 100 | 122 | 148 | 220 | 242 | 264 | 290 | 38 | 186 |
| BF5 | 5 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 62 | 84 | 106 | 132 | 204 | 226 | 248 | 274 | 30 | 170 |
| BF6 | 6 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 74 | 96 | 118 | 144 | 216 | 238 | 260 | 286 | 42 | 182 |
| BF7 | 7 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 66 | 88 | 110 | 136 | 208 | 230 | 252 | 278 | 26 | 174 |
| BF8 | 8 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 78 | 100 | 122 | 148 | 220 | 242 | 264 | 290 | 38 | 186 |
| D | 1 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 102 |
| C | 2 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 232 | 80 |
| B | 3 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 210 | 58 |
| A | 4 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 184 | 38 |
| H | 5 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 94 | 0 |
| G | 6 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 72 | 200 |
| F | 7 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 50 | 178 |
| E | 8 | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 30 | 0 |
| IN | 1 | | 130 | 270 | 22 | 34 | 22 | 34 | 22 | 34 | 22 | 34 | 66 | 88 | 110 | 130 | 0 | 222 | 244 | 0 | 274 | 218 |
| IN | 2 | | 292 | 108 | 248 | 260 | 248 | 260 | 248 | 260 | 248 | 260 | 0 | 318 | 296 | 324 | 44 | 66 | 88 | 108 | 164 | 362 |

## Appendix G – General input settings for Simbus

| | |
|---|---|
| | @ Busstation Schiphol Knooppunt Noord 5 sept 2017 @ |
| | @ met onafhankelijk vertrek en aankomst @ |
| 0000 | @ START starttijdstip simulatie [24-uurs-notatie] @ |
| 1439 | @ DUUR simulatieduur in minuten @ |
| 1 | @ AANTRUN aantal herhalingsruns @ |
| 500 | @ rijsnelheid bus op station (meters/minuut) @ |
| 1 | @ LEN-HP halteplaats eenheid (in meters) @ |
| 4 | @ TUSU tussenruimte tussen bus en voorligger op **uitstap** perron (in meter) @ |
| 4 | @ TUSLB tussenruimte tussen bus en voorligger op **lange termijn buffer** perron (in meter) @ |
| 4 | @ TUSKB tussenruimte tussen bus en voorligger op **korte termijn buffer** perron (in meter) @ |
| 4 | @ TUSI tussenruimte tussen bus en voorligger op **instap** perron (in meter) @ |
| 353637 | @ GAMI seed voor interval-loting @ |
| 123456 | @ NORMM seed voor inmeldtijd-loting @ |
| 987654 | @ NORMU seed voor uitstaptijd-loting @ |
| 357975 | @ NORML seed voor lt-buffertijd-loting @ |
| 246897 | @ NORMK seed voor kt-buffertijd-loting @ |
| 135798 | @ NORMI seed voor instaptijd-loting @ |
| N | @ Meenemen wachttijd voor halte (wachttijd) in VISSIM output @ |
| N | @ Meenemen wachtijd op halte (bloktijd) in VISSIM output @ |
| N | @ INFO animatie busafhandeling (N) of informatievoorziening (J) @ |
| J | @ SPREIDING procestijden inclusief spreidingen @ |
| N | @ GEENGDA gem. vertrekafwijking ook op 0 @ |
| N | @ REGELMAAT onregelmatigheidstoeslag (j/n) @ |
| J | @ OPTREK geen schaduwplaatsen / altijd optrekken (j/n) @ |
| N | @ GAR aparte lbuf-, kbuftijd- en halteertijdgarantie invoeren (j/n) @ |
| | @ indien J dan deze drie tijden per lijn invoeren @ |
| N | @ AFSTEMMEN synchronisatie (J/N) @ |
| N | @ OVERLOOPBUF gebruik overloop bij synchronisatie (J/N) @ |
| N | @ OPSTELU gebruik specifieke opstelplaatsen per uitstapperron (J/N) @ |
| N | @ OPSTELL gebruik specifieke opstelplaatsen per lt-bufferperron (J/N) @ |
| N | @ OPSTELK gebruik specifieke opstelplaatsen per kt-bufferperron (J/N) @ |
| N | @ OPSTELI gebruik specifieke opstelplaatsen per instapperron (J/N) @ |
| 99 | @ IN_BEREIKBAAR alle instapperrons bereikbaar vanaf kb-perron 1 t/m ... @ |
| N | @ CYCL toewijzing volgens Leidse principes (J/N) @ |
| | |
| | @ als CYCL = N lineaire optimalisatie van de toewijzing @ |
| N | @ PROC20 alleen procedure 20 (J/N) @ |
| N | @ DOESTAR starre perrontoewijzing op alleen voorkeurperron (J/N) @ |
| N | @ DOEUVKPRANGE gebruik voorkeurperronrange uitstap (J/N) @ |
| N | @ DOELVKPRANGE gebruik voorkeurperronrange lange termijn buffer (J/N) @ |
| N | @ DOEKVKPRANGE gebruik voorkeurperronrange korte termijn buffer (J/N) @ |
| J | @ DOEIVKP gebruik voorkeurperron instap (J/N) @ |
| J | @ DOEIVKPRANGE gebruik voorkeurperronrange instap (J/N) @ |

| | |
|---|---|
| 0 | @ CONFMARGE marge conflicten volgens DR @ |
| 1000 | @ MAXINLIJN maximum buslijnnummer: welke lijn mag onder 'maxinbus' vallen @ |
| 24 | @ MAXINBUS maximum busperronnummer in de voorkeurperronsrange instap @ |
| | |
| | @ als CYCL = J  cyclische optimalisatie van de toewijzing @ |
| N | @ TRACE trace-mogelijkheid toewijzing vlg Leidse principes aan (J/N) @ |
| 3 | @ VKM vooraankondigingsduur [min.] @ |
| 60 | @ LTG grenstijd voor toewijzing aan lange termijnbuffer [min.] @ |
| 1 | @ FORC forceringsmoment [min. voor emavp] @ |
| 2 | @ MAXWS max. wachttijd voor bussen in spits [min.] @ |
| 5 | @ MAXWD max. wachttijd voor bussen in dal [min.] @ |
| 0645 | @ S_O tijdstip start ochtendspits [24-uurs-notatie] @ |
| 0915 | @ E_O tijdstip einde ochtendspits [24-uurs-notatie] @ |
| 1600 | @ S_A tijdstip start avondspits [24-uurs-notatie] @ |
| 1830 | @ E_A tijdstip einde avondspits [24-uurs-notatie] @ |
| 8 | @ GEWICHT1 gewicht aspect 1: lijn-perroncombinatie @ |
| 2 | @ GEWICHT2 gewicht aspect 2: overlappende bezettingen @ |
| 8 | @ GEWICHT3 gewicht aspect 3: lijn-bestemmingscombinatie @ |
| 2 | @ GEWICHT4 gewicht aspect 4: kans op vertraging @ |
| 1 | @ GEWICHT5 gewicht aspect 5: aankomsttijd @ |
| 5 | @ GEWICHT6 gewicht aspect 6: capaciteitsbenutting @ |
| 3 | @ GEWICHT7 gewicht aspect 7: actuele vertraging @ |

*The explanations are between @s, because Simbus does not consider parts between @'s in text-files.

## Appendix H – Variant results per charging method

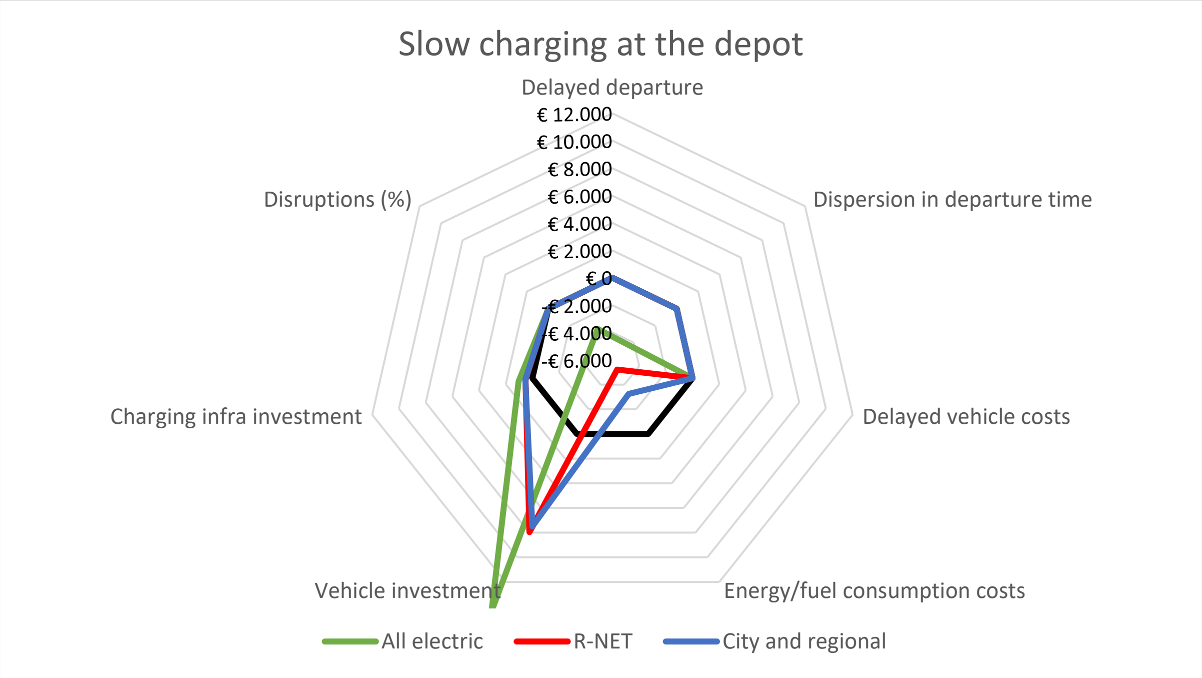


*Figure III - Daily scores relative to the base case for slow charging at the depot*

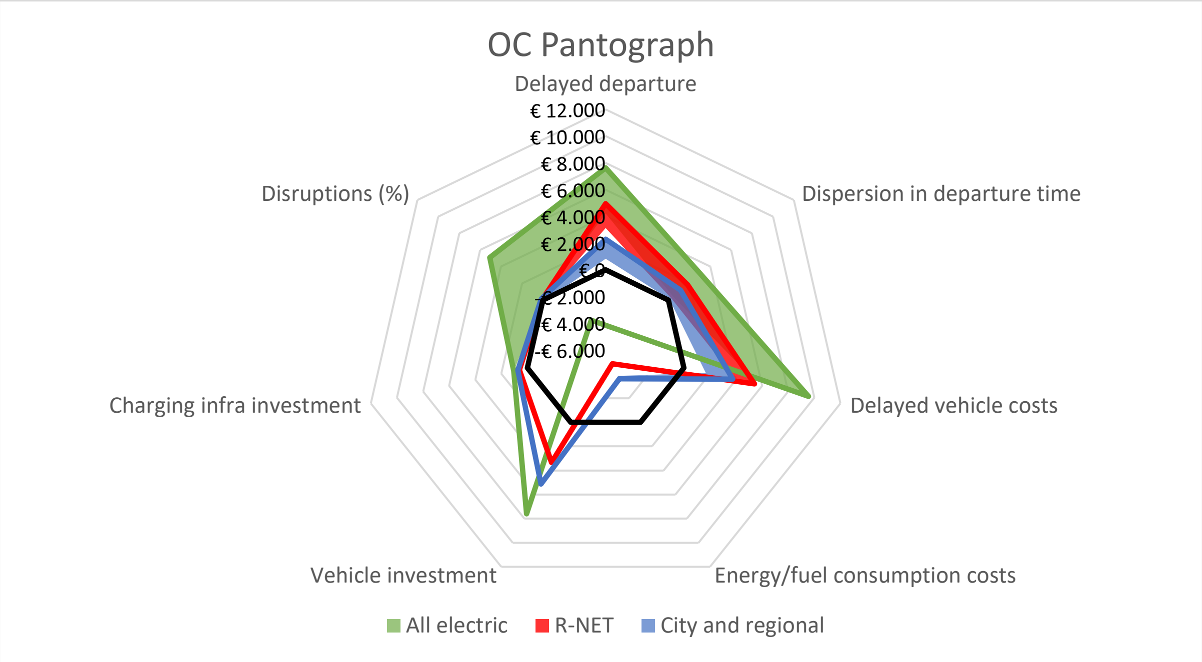


*Figure IV - Daily scores relative to the base case for OC by pantograph*

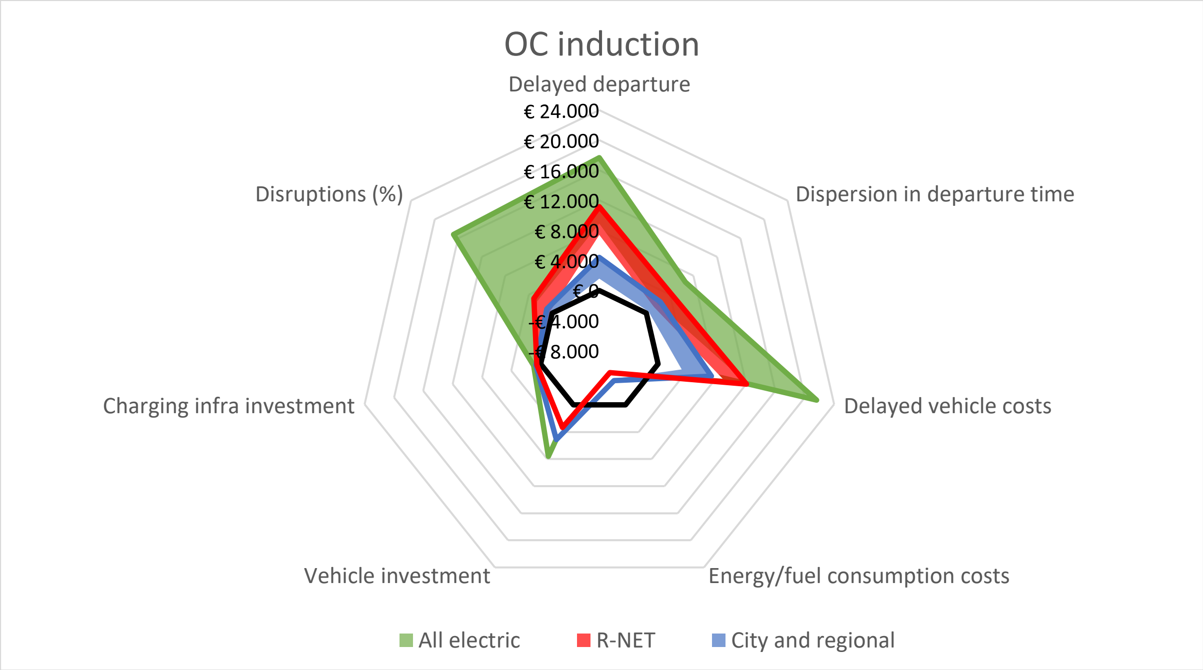


*Figure V - Daily scores relative to the base case for OC by induction*

# Appendix I – Scenario results

| Absolute values | Delayed departure | Dispersion in departure time | Delayed vehicle costs | Energy/fuel consump-tion costs | Vehicle investment | Charging infra investment | Disruptions (%) |
|---|---|---|---|---|---|---|---|
| Reference | | | | | | | |
| C2F1-Min | € 4.182 | € 2.348 | € 5.778 | € 8.089 | € 13.397 | € 733 | 5,24% |
| Saturday Ref. | € 2.670 | € 1.422 | € 4.362 | € 5.664 | € 8.723 | € 577 | 0,89% |
| Scenarios | | | | | | | |
| Winter day | € 3.950 | € 1.613 | € 5.936 | € 6.600 | € 10.877 | € 636 | 1,80% |
| Black Saturday | € 3.116 | € 1.521 | € 4.823 | € 5.525 | € 8.766 | € 582 | 1,40% |
| Calm Sunday | € 1.576 | € 907 | € 3.489 | € 4.438 | € 6.279 | € 555 | 1,30% |
| Incident | € 9.121 | € 2.425 | € 12.532 | € 9.177 | € 13.397 | € 733 | 5,17% |
| Flex charging | € 4.022 | € 2.263 | € 5.494 | € 8.029 | € 13.397 | € 770 | 5,10% |
| Red. battery cap. | € 5.285 | € 2.771 | € 6.326 | € 8.179 | € 13.397 | € 733 | 5,78% |
| Green deal | € 7.566 | € 2.980 | € 8.742 | € 4.369 | € 14.560 | € 878 | 7,55% |

## Appendix J – Results of the sensitivity analysis

| Absolute values | Delayed departure | Dispersion in departure time | Delayed vehicle costs | Energy/fuel consump-tion costs | Vehicle investment | Charging infra invest-ment | Disrup-tions (%) |
|---|---|---|---|---|---|---|---|
| Reference | | | | | | | |
| C2F1-Min | € 4.182 | € 2.348 | € 5.778 | € 8.089 | € 13.397 | € 733 | 5,24% |
| Variables for cost/benefit model | | | | | | | |
| Extra passengers | € 5.464 | € 3.041 | € 5.778 | € 8.089 | € 13.397 | € 733 | 5,24% |
| Higher passenger factor | € 4.182 | € 3.053 | € 5.778 | € 8.089 | € 13.397 | € 733 | 5,24% |
| Increasing VoT | € 6.195 | € 2.348 | € 5.778 | € 8.089 | € 13.397 | € 733 | 5,24% |
| E-bus price red. | € 4.182 | € 2.348 | € 5.778 | € 8.089 | € 11.265 | € 733 | 5,24% |
| Charging infra price red. | € 4.182 | € 2.348 | € 5.778 | € 8.089 | € 13.397 | € 673 | 5,24% |
| Variables for charging time model | | | | | | | |
| Battery Buffer red. | € 3.970 | € 2.241 | € 5.367 | € 8.087 | € 13.397 | € 733 | 4,76% |
| Higher charging power | € 4.022 | € 2.255 | € 5.456 | € 7.981 | € 13.397 | € 733 | 5,10% |
| Line length expansion | € 4.483 | € 2.448 | € 6.380 | € 9.661 | € 13.397 | € 733 | 6,12% |
| Season factor: Winter | € 4.526 | € 2.442 | € 6.452 | € 8.352 | € 13.397 | € 733 | 5,92% |

# Appendix K – Adjusted timetable results

| Absolute values | Delayed departure | Dispersion in departure time | Delayed vehicle costs | Energy/fuel consump-tion costs | Vehicle investment | Charging infra invest-ment | Disrup-tions (%) |
|---|---|---|---|---|---|---|---|
| References | | | | | | | |
| C2F1-Need | € 4.432 | € 3.317 | € 6.038 | € 8.109 | € 13.397 | € 733 | 7,01% |
| C2F1-Max | € 5.645 | € 2.281 | € 7.841 | € 8.097 | € 13.397 | € 733 | 7,28% |
| C3F2-Need | € 12.892 | € 6.304 | € 14.083 | € 6.980 | € 11.609 | € 528 | 8,30% |
| C3F2-Max | € 14.508 | € 3.455 | € 16.150 | € 6.975 | € 11.609 | € 528 | 19,8% |
| Adjusted timetable model results | | | | | | | |
| Min red.: C2F1-Need | € 4.328 | € 3.319 | € 5.816 | € 8.109 | € 13.397 | € 733 | 7,01% |
| Max red.: C2F1-Max | € 3.146 | € 2.288 | € 3.198 | € 8.097 | € 13.397 | € 733 | 7,28% |
| Min red.: C3F2-Need | € 8.921 | € 6.310 | € 9.784 | € 6.980 | € 11.609 | € 528 | 8,30% |
| Max red.: C3F2-Max | € 3.009 | € 3.557 | € 2.388 | € 6.975 | € 11.609 | € 528 | 19,8% |

| Relative to the references | Delayed departure | Dispersion in departure time | Delayed vehicle costs | Energy/fuel consump-tion costs | Vehicle investment | Charging infra invest-ment | Disrup-tions (%) |
|---|---|---|---|---|---|---|---|
| Adjusted timetable model results | | | | | | | |
| Min red.: C2F1-Need | -2% | 0% | -4% | 0% | 0% | 0% | 0% |
| Max red.: C2F1-Max | -44% | 0% | -59% | 0% | 0% | 0% | 0% |
| Min red.: C3F2-Need | -31% | 0% | -31% | 0% | 0% | 0% | 0% |
| Max red.: C3F2-Max | -79% | 3% | -85% | 0% | 0% | 0% | 0% |