

TECHNISCHE UNIVERSITÄT MÜNCHEN

Ingenieur fakultät Bau Geo Umwelt

Professur für Siedlungsstruktur und Verkehrsplanung

**Suitability of battery electric vehicles and opportunity charging for urban freight transport: an evaluation framework**

Tharsis Teoh Ghim Han

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Vorsitzender: Prof. Dr. Constantinos Antoniou

Prüfender der Dissertation:

1. Prof. Dr. Gebhard Wulfhorst
2. Prof. Yiik-Diew Wong, Nanyang Technological University, Singapur
3. Prof. Dr. Oliver Kunze, Hochschule Neu-Ulm, Deutschland

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## Abstract

Electrification of urban freight transport is a key strategy in decarbonizing the transport sector. However, battery electric vehicles (BEV) for logistics purposes are still disadvantaged in comparison to diesel vehicles, due to their limited driving range, reduced payload capacity, and high purchase prices. Evaluation studies can play a role to inform decision makers and stakeholders about the advantages of BEVs and the best strategies to successfully promote the technology.

Existing evaluation studies often reduce vehicle requirements to simple travel distances, which has severe consequences for the validity of their recommendations. Existing studies also do not incorporate a wider conceptual solution space of electric mobility, particularly, the use of opportunity charging.

The evaluation framework proposed here deals with the gaps in existing studies, as well as proposes a novel method to evaluate electric mobility for urban freight transport in terms of operational, financial, and environmental suitability.

The study uses a comparative case analysis on six case studies of different urban freight transport operations in Singapore. Using information gathered from interviews, a detailed vehicle activity model is developed. For each case, scenarios are built, which primarily show how distinct types of opportunity charging and charging technology can be integrated into the logistics operations. A BEV parametric model is used to adapt vehicle parameters (i.e. battery capacity and vehicle weight) to operational requirements based on the results of the vehicle activity model. Financial suitability is evaluated based on the lifecycle cost analysis of owning and using the electric fleet, while the environmental suitability is analysed based on the well-to-wheels carbon dioxide emissions.

The results show a varying degree of suitability of BEVs for the different urban freight transport cases. They point to a complex set of factors that have profound influences especially on financial suitability. Opportunity charging strategies were found to be the best ways to improve both financial and environmental suitability.

The sensitivity of the suitability indicators to the assumptions in the vehicle activity models shows the need for detailed and well-tested models to accurately evaluate the suitability of BEV to urban freight transport operations. It also shows the need for further research into designing systems and business models that support opportunity charging, since it was found to be the most influential factor in increasing the suitability of BEVs in the urban freight transport sector.



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## List of abbreviations

ARF	Additional registration fee
AVA	Agri-Food & Veterinary Authority
BEV	Battery electric vehicle
BSS	Battery swapping station
CCA	Comparative case analysis
CEP	Courier-Express-Parcel
COE	Certificate of entitlement
CO <sub>2</sub>	Carbon dioxide
CVRP	Capacitated vehicle routing problem
DC	Distribution centre
DEC	Driving energy consumption
DV	Diesel vehicle
DOD	Depth-of-discharge
ESI	Environmental suitability indicator
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
FCEV	Fuel-cell electric vehicle
FCL	Full container load
FSI	Financial suitability indicator
GPS	Global Positioning System
GVW	Gross vehicle weight
HDUDDS	Heavy Duty Urban Dynamometer Driving Schedule
HEV	Hybrid electric vehicle
HGV	Heavy goods vehicle
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
IEC	Idle energy consumption
INDC	Intended Nationally Determined Contribution
kg	Kilogramme
kwh	Kilowatt-hour
LCC	Lifecycle cost
LGV	Light goods vehicle
MJ	Mega Joule
NEDC	New European Driving Cycle
NPV	Net Present Value
OR	Operations research
PHEV	Plug-in hybrid electric vehicle
REEV	Range extended electric vehicle
REC	Refrigeration energy consumption
RQ	Research question
SOC	State-of-charge
UFT	Urban freight transport
VAM	Vehicle activity model

VHGV    Very heavy goods vehicle  
VRP    Vehicle routing problem



# 1. Introduction

Urban freight transport is a fundamental activity of every urban region, providing its inhabitants with the essentials, the trivial and the lavish. However, concerns about the negative impacts of transport, and in particular those caused by freight trucks (McKinnon, 2012), have made the search for methods to achieve a sustainable urban freight transport (UFT) system extremely pertinent.

Sustainability is a branding that has proven to be adaptable to any aspect or type of human activity, often obscuring the meaning behind the term (Mitcham, 1995, p. 311). It is a normative ideal, often tied to “sustainable development”, defined in the Brundtland Commission, as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). For better or worse, the term was never meant to be a rigorously defined template for how society should progress. Yet, many scientific research programmes have sought to apply “sustainability” in the many facets of economy and social activity (Sartori et al., 2014). The outcome of this may not be clarity of the concept, but it has definitely spawned a large variety of approaches to evaluate sustainability (Sneddon et al., 2006, p. 261).

Despite much academic work in sustainable UFT, a definition that clarifies the ideal is still missing (Melo, 2010, p. 21). Focus has instead been on defining and adapting “sustainability indicators,” which are most often used to evaluate the “unsustainability” of UFT. The tendency is partly due to the notion that it is easier to define what is undesirable, rather than what is the intended state of transport according to the vague definition of sustainability.

The indicators measure the negative impacts of UFT activity and are usually associated with the use of road vehicles in the urban area. The indicators can be categorized into four broad categories: those that pertain to air quality, fossil energy use, traffic and infrastructure (Behrends, 2011). The present technology used to power freight vehicles is predominantly based on the combustion of fossil fuel. Its vehicle, characterised by the powertrain technology, is called the internal combustion engine vehicle (ICEV). The deficiency of this technology is well-known: worsening air quality in cities around the world, dependence on fluctuating supply and demand of petroleum, and the emissions of greenhouse gas. However, recent technological developments and increasing claims for sustainability have ignited interest in transforming the current fossil fuel-based UFT system into one based on electric mobility.

Simply put, electric mobility is “movement using an electric vehicle.” The electric vehicle itself is defined as any road vehicle that uses electrical energy for propulsion (Sandén, 2013), but it typically refers to the so-called battery electric vehicle (BEV). The other variations of the concept of electric mobility will be described later. The BEV features an electric powertrain<sup>1</sup>,

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<sup>1</sup> The powertrain of the vehicle is its subsystem that is responsible for propulsion. It typically covers all the components from the engine (or electric motor) to the wheels.

which draws electrical energy solely from a battery. The battery is an energy storage unit. Hence, the battery must be supplied with electricity from an external power source with the support of a charging system. This contrasts with the diesel motor or a fuel cell, which are two types of machines that generate energy (mechanical and electrical) from a fuel source.

These two features – an electrified powertrain and the use of an external power source - give BEVs an extraordinary advantage in terms of reducing its negative impacts when compared to the dominant fossil fuel-based system. First, there are no local exhaust emissions. The emission of air pollutants (if any) are localized at the electricity power plant. This reduces the direct exposure of the population to harmful air pollution. Second, the production of energy via\_renewable means can be integrated into the transport system. Whereas the ICEV is dependent on oil products for its energy source, the BEV can use any electricity source that is integrated into the electricity grid from which the battery of the vehicle is charged. The use of renewable energy is vital in the efforts to reduce greenhouse gas emissions and combat global warming. Third, the powertrain efficiency of a diesel engine is significantly lower than that of an electric motor (Sandén, 2013, p. 54). The higher efficiency reduces the need for energy production (either in terms of electricity or fuel). Although more can be said about the advantages of BEVs, the three above-mentioned aspects are most significant for the present work, since they relate directly to the negative impacts of UFT.

But, how does using a BEV affect the freight carriers themselves? The most obvious advantage regards the energy and maintenance costs, both of which are expected to be significantly lower than that of the ICEV. The factors leading to a reduced energy cost, as compared to fuel cost for the ICEV, are a combination of the energy efficiency and the lower energy prices in dollars per kilowatt-hour (\$/kWh) (Siang & Chee, 2012, p. 83). Maintenance costs are also expected to be lower for the BEV, since it has fewer moving parts and the parts have lower failure rates. In addition, while several cities have, in order to reduce air pollution or congestion, imposed restrictions or additional fees on vehicles within or entering the city area, the BEVs have in some cities been exempted from these restrictions (Transport for London, 2016 [accessed 7 October 2017]). Furthermore, the relatively quiet BEV is also a prerequisite for freight carriers to perform off-hour deliveries (Kloth et al., 2013) in cities, which have late-hour restrictions on vehicles. This means that, in addition to having lower operational costs, the movement and access of BEVs (in environmentally conscious cities) are also less regulated and may be organized more efficiently.

Despite these advantages, there are significant challenges, if not barriers, for using BEVs in UFT from the viewpoint of the freight carriers. Since the BEV is a relatively new entry to the vehicle market, there may be imperfections in the quality of engineering or production (Vermie, 2002) and a lack of market-ready products\_(Quak & Nesterova, 2014). Such problems can easily be resolved, as manufacturers improve their production quality and develop more

products for the market. However, there is a more fundamental weakness in the BEV, due to its main component, the battery.

Even the best market-ready battery technology, the lithium-ion battery, is significantly disadvantaged as a source of energy, when compared to fossil fuel. The root of this problem is the battery's low energy-to-weight ratio (i.e. the capacity in kilowatt-hours per weight in kilograms of the battery) and its high cost-to-energy ratio (i.e. the price in dollars per capacity in kilowatt-hours of the battery). These technical constraints have a bearing on the design of the vehicle and limit the driving range; they reduce the load bearing capacity and increase the manufacturing cost (and, by extension, the purchase price) of the vehicle. Furthermore, because it also takes significantly longer to recharge a battery than it is to refuel an ICEV, manufacturers need to ensure that the EV can last the duration of their target market's duty cycle without recharging or provide quick charging capabilities. With regards to the battery, there are also concerns about its lifetime and the degradation of its capacity over time. For example, the estimated lifetime of the lithium-ion battery in terms of charge cycles are about 2,000 to 3,000 cycles, which at one charge per day lasts less than 9 years. The battery can be replaced, but since the price of the battery can reach up to a third of the vehicle's life-cycle cost, it is an additional significant cost that should feature into the already expensive BEV.

Manufacturers (and users) are not ignorant of these limitations. Hence, other vehicle architectures have been developed to reap the benefits of using electricity for propulsion, while minimizing or eliminating some of the drawbacks of relying purely on the battery as an on-board source of energy. There are two approaches to this: first, by augmenting the powertrain; second, by improving the flexibility and efficiency of the charging process. The first approach is responsible for creating the many variations of electric vehicles, differentiated by powertrain categories. The second approach focuses on providing the appropriate infrastructure for "opportunity charging", which is an approach to charge whenever time permits.

The variety of electric vehicles (EVs) commonly found in literature (Sandén, 2013, Pollet et al., 2012) are shown in Table 1-1. Different powertrain types may require a different on-board energy source and reenergizing infrastructure. These types can be viewed as using two different approaches to improving operational capability. The first is to have two types of powertrains in the vehicle that complement each other. The ICE powertrain has the range and quick refuelling, but the electric powertrain is silent and clean. This approach underlies the HEV and PHEV types. Though these variants usually only have a small battery, which saves the cost of the vehicle, it also has an additional powertrain system, which costs and weighs double the conventional ICEV. The battery in the PHEV can be charged from an external source (hence the term "plug-in"), but the HEV cannot. Both, however, are also charged from a proportion of unused energy generated from running the ICE. The clean driving benefits are also heavily dependent on how the vehicles are programmed to make use of the electric

powertrain and whether drivers make use of it. For example, driving at slow speeds and in stop-and-go conditions will use the electric powertrain, but driving on the highways will switch to the ICE. The benefits of the PHEV are potentially much higher, since the battery can also be charged from electricity grid.

Table 1-1 Variety of electric vehicles according to powertrain configuration and energy sources

Vehicle type	Primary powertrain	Secondary powertrain	On-board energy source	Reenergizing infrastructure
Internal combustion engine vehicle (ICEV)	Internal combustion engine (ICE)	-	Fuel	Refuelling station (Petrol/Diesel)
Hybrid electric vehicle (HEV)	Internal combustion engine (ICE)	Electric powertrain	Fuel, Battery	Refuelling station (Petrol/Diesel)
Plug-in hybrid electric vehicle (PHEV)	Internal combustion engine (ICE)	Electric powertrain	Fuel, Battery	Refuelling station (Petrol/Diesel), charging station
Range extended electric vehicle (REEV)	Electric powertrain	-	Battery, ICE-based generator	Refuelling station (Petrol/Diesel), charging station
Fuel-cell electric vehicle (FCEV)	Electric powertrain	-	Fuel cell system, Battery	Refuelling station (Hydrogen gas)
Battery electric vehicle (BEV)	Electric powertrain	-	Battery	Charging station

The second approach is to improve the sub-system providing electricity to the electric powertrain. For the BEV, the only on-board energy source is the battery, and thus it must be charged from an external source, such as at a charging station. The electricity supplied to the charging station is generally from, but not limited to, the electricity power grid, and ultimately the power plants. However, the REEV and the FCEV have on-board electricity generators, which can charge the battery, when its levels are low. The REEV uses an ICE-based generator, while the FCEV uses the fuel cell, which most commonly uses hydrogen gas. The REEV differs from the PHEV in that the ICE-based generator is not a part of the powertrain system, and can therefore always operate at its most efficient state, whereas the operating speed and thus the energy efficiency of the ICE, when used as a powertrain, is dependent on the vehicle’s speed and the gearbox. Nevertheless, the REEV still emits tailpipe pollutants and thereby does not address one of the main reasons why a change in vehicle types is sought after in the first place.

On the other hand, the FCEV does not produce tailpipe pollutants, and is often considered an all-electric vehicle, just as the BEV is. However, it is dependent on hydrogen refuelling stations, which are still rare today. Though certainly a potentially useful technology, especially in case the costs, weight and size of the fuel cell equipment is reduced, at its current state, the FCEV is still considered less viable than an BEV. For further details on the characteristics of these main vehicle types, readers are directed to the reviews by van Vliet et al. (2010), Pollet et al. (2012), and Tie & Tan (2013).

Additions to the powertrain and on-board energy source are easily able to address the limitation of the BEV driving range. However, cost saving using these technology is dubious,

and the environmental benefits are generally much smaller. A less explored approach that does not double the on-board machinery and maintains the electric powertrain may perhaps deserve closer attention.

The principle of opportunity charging is “to charge the vehicle when it is convenient for the driver, so as not to alter the route or work schedule of the driver.” This will therefore restrict the duration and location of charging to the time and space allowed by the operational and work activity of the driver. This restriction is a matter of reducing the negative effects to the performance, caused by the limitations of charging, to the operational performance of the BEV. Consider that refuelling an ICEV - from empty to full tank - does not affect the operations schedule of a driver, since it happens in matter of minutes. In contrast, recharging a BEV, which already has a comparatively short driving range, may require a couple of hours, which cannot be set aside during the vehicle cycle exclusively for charging.

Opportunity charging usually does not refer to charging overnight, which is considered the default option for both passenger and freight BEVs, and happens when the vehicle is “not-in-operation”. Instead, opportunity charging explicitly occurs during the operation schedule of the vehicle. This can take place, while the vehicle is stationary, such as during loading and unloading activities, or while the vehicle is being driven on a highway. When and how the charging occurs depends on the type of charging system used.

Opportunity charging, if properly implemented, certainly offers the possibility of retaining the benefits of the BEV, while enhancing its operational capability and reducing its financial burden. Unfortunately, research exploring in-depth the potential of using opportunity charging in the UFT setting is limited in terms of the extent of options available. Such research requires a careful analysis of the way vehicles are used in the urban freight context. In other words, an analysis of the potential must be conducted based on a detailed description of the UFT activity.

Based on existing definitions of UFT<sup>2</sup>, one realizes that there are a few central descriptors of UFT. First, the main purpose of the movement is the delivery (and collection) of non-human objects. Non-human objects can range from waste to retail products, to mail or animals. It is often difficult to ascertain the “main purpose” of a trip, and there may be ad hoc reasons why one type of trip is included, but not the other. For example, in furniture delivery with installation services, the installation service provided might be considered the “main purpose”, and the delivery secondary. Second, the range of transport activity should take place within the urban area. While in some cases one can consider vehicle trips that run through, originate from outside, or terminate outside the urban area, the scope is more commonly limited to vehicle trips that start and terminate within the same urban area without leaving the it. Third, it is often useful to specify the types of vehicles that are used in UFT. There is a wide-

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<sup>2</sup> Term includes also urban goods transport or urban goods movement.

range of obvious vehicle types, such as vans and trucks. Trucks may also come in many shapes and sizes, such as waste collection trucks, cement mixers, and refrigerated trucks. What may be less clear for the definition of urban transport is the situation when light duty vehicles or two- and three-wheelers are used for “freight transport”. The very common example is parcel delivery using a car or a motorcycle, which, although takes the unassuming form of a passenger vehicle, should nevertheless be counted as UFT. Fourth, the vehicle movement for UFT is generally an outcome of a complex series of strategic, tactical and operational decisions, rendering generalization across or even within industry very difficult.

The above descriptions of UFT, especially the first, third and fourth aspects, make the evaluation of the application of BEVs in UFT very challenging. This may be one of the reasons for the only few truly extensive studies, whose subjects are the wide variety of UFT. In addition to the complexity of UFT, the data requirements for such an evaluation would include information on the routes, schedules, types and amount of shipment, which is typical for a particular UFT type. In fact, research in this area generally focuses on simplified operational requirements for the UFT activity, such as driving range or vehicle size.

In summary, there are several gaps in research on application areas of BEVs in UFT. The neglected extensive range of charging systems and the flexibility of exploiting opportunity charging can have a significant effect on the suitability of the BEV. Furthermore, there is a dearth of research aiming to understand how the heterogeneity of the transport operations can influence its compatibility with BEV (or in particular, the opportunity charging type). And finally, studies dealing with the subject area generally lack specificity in defining the conditions under which a BEV would be suited for the transport operations.

## **1.1. Research problem**

The problem dealt with in this study can be described as the suitability problem of using BEVs for UFT. In this study, a BEV is suitable, if it satisfies the requirements set by the relevant decision makers in the UFT system. An evaluation of suitability produces only one of two outcomes: either it is suitable or not. The problem of suitability refers to the requirements that are not met by BEVs vehicles. In this study, only two decision maker types set the requirements: the freight carrier and the public authorities. Both set requirements according to their individual interests: the freight carrier considers requirements that ensure that its transport operations can be conducted efficiently as well as cost-effectively; the public authorities have the mitigation of negative impacts of the current transport system in mind. Their specific roles and the roles of other stakeholders (who have yet to be mentioned) are discussed in Section 2.1.1.

Based on these requirements, three aspects of suitability have been identified and should be fulfilled. This can be achieved using the latest developments in charging systems

and the available opportunity charging methods. The three aspects of suitability are operational, financial and environmental suitability.

Operational suitability requires that the technical capabilities of the BEV are sufficient for the drivers to use it for the entirety of their current transport task. Hence, issues such as limited driving range, long charging times, and reduced payload capacity of the vehicle are addressed. The charging system and strategy need to be adjusted to accommodate the energy demands of the BEV. This aspect of suitability is vital: if a transport system cannot perform its task, then persuading the freight carriers to use the system will be extremely challenging or impossible.

Financial suitability requires that the cost of purchasing and using the vehicle is comparable to that of the current vehicle system. The system that is designed and the battery that is placed in the vehicle should have the least number and size of necessary components to achieve operational suitability. This minimum viable product is assumed to incur the least costs. For example, the battery should be sized in accordance to the energy demands. It is also necessary to calculate the total financial transactions that should be borne by the freight carrier, which includes the purchase of the vehicle, the operation and maintenance, replacement of battery (if needed) and the resale. This aspect of suitability is necessary to ensure that the economic viability of the freight carrier is not threatened by a purchase that is a financial burden in the long term.

Environmental suitability requires that environmental impacts are reduced to a certain degree compared to the current system. The categories directly relevant to BEVs are the emissions of air pollutants, the dependence of fuel-based energy, and the emission of greenhouse gas. Here, it is expected that there will be a significant improvement, which will perhaps meet the goals set by the policy or charters, such as the Paris Agreement (UNFCCC, 2016). This aspect of suitability serves as the motivation for the public authorities (and private companies) to embark on such a project, in order to ensure that the urban freight activities are not damaging public health, energy security and the environment.

## **1.2. Research purpose**

The purpose of this study is to develop a framework that evaluates the suitability of BEVs as a substitute for ICEVs in UFT. In particular, the study includes complementary charging concepts in the analysis, as necessary for the suitability of BEVs. Also, the three aspects of suitability – operational, financial, and environmental - are integrated into the evaluation framework. This evaluation methodology is then tested on several case studies of UFT companies.

The study can be framed as the evaluation of the following hypothesis:

*“Battery electric vehicles, when used with opportunity charging, are suitable for urban freight transport operations.”*

It is expected that the currently available (both as market-ready and prototype) charging technology, when used in opportunity charging, can ensure the suitability of the BEV for the UFT operation. This evaluation entails a careful analysis of the options for opportunity charging in the daily activity schedule of freight carriers, and a comprehensive solution space of the BEV and charging concepts, both of which are integrated in the suitability evaluation methodology. The use of a standardized methodology in several case studies allows for contrast between the factors that affect operational, financial and environmental suitability.

### **1.3. Research questions**

Guiding the research are three research questions (RQ), which serve as intermediate milestones and build up to support the research hypothesis.

*RQ1 : What is the set of necessary requirements that needs to be fulfilled by the electric mobility system, in order to be considered suitable for the urban freight transport operation?*

It is necessary that well-fitting requirements, as defined by the relevant stakeholders, are used in the evaluation. These need to be operationalized and represented by measurable indicators that accurately describe the need or concern of the stakeholders and can be calculated or measured within the limitations of the research. To this end, existing research literature on the use of BEVs in UFT is conducted, the choice of aspects and requirements considered are defended, and methods to measure them are proposed.

*RQ2 : What are the significant attributes that give rise to the solution space of a BEV-based urban freight transport system?*

The solution space of a BEV-based UFT system is a mapping of the combinations of current and future BEVs, charging systems and opportunity charging modes. Based on this solution space, the suitability of BEVs for UFT can be completely evaluated. This will require a review of research on the topic, modelling of these attributes, and testing of the impacts on the suitability of BEVs.

*RQ3 : What are the quantitative and qualitative attributes of urban freight transport, which influence its suitability with an electric mobility system?*

It is expected that the solution space mapped out in the RQ2 will have different levels of suitability depending on the case study application. The objective of RQ3 is to analyse the possible factors contributing to these differences. Based on the factors identified, it will be argued whether these factors will have a wider general application to other UFT types not considered within the scope of this study. Some factors are qualitative, such as the type of

industry the transport operations serve, while others are quantitative, such as the distance travelled by the fleet.

## **1.4. Delimitations, limitations and assumptions**

The study contributes to a niche problem faced in using BEVs. In the following sections, the delimitations of the study, limitations faced during the study, and the assumptions made in the study are briefly discussed.

### **1.4.1. Delimitations**

The study is a part of research project to study the various facets of electric mobility in Singapore, from the engineering of vehicle, charging, grid and road systems, to studies on planning strategies to overcome implementation barriers of electric mobility. Hence, as part of the study, the geographical scope of the study is limited to the city of Singapore, and the case studies were obtained from interviews with companies operating in Singapore. The study makes no attempt to assume that the case studies are “typical” transport operations in any other urban area. Instead, where applicable, conclusions, which may be generalized to other urban areas, will be properly contextualized.

The study is limited to UFT that facilitates the economic activity related to the production and consumption of goods (as distinct from services). Also, the transport activity is confined to the trips that originate and terminate in the same urban area, such that the entirety of the trip runs in the road network of Singapore.

As mentioned, the study focuses on BEVs and the various charging systems and strategies. The focus differs from previous studies, which focus on powertrain influences, and ensures that the solution space in this direction (of charging system and strategy variation) is comprehensive.

### **1.4.2. Limitations**

The case study approach was chosen to enable a deep analysis in the nuances of transport operations carried out by the various companies. This is inherently a small-n sample study, designed for depth rather than extent. The aim is also different from large-n studies, such that the emphasis is on exploration of the subject and the problem, rather than an estimation of market share or ownership. Generalization of the findings will not depend on statistical representation, but rather on the discovery of relationships between attributes and indicators.

A general problem in UFT modelling is the collection of data from companies who wish to keep their information confidential. This is also a general problem, but the methodology employed minimizes the need for highly accurate confidential data, restricting it to the average or median snapshot of their situation.

### **1.4.3. Assumptions**

The study searches a solution space of BEV and charging systems and strategies, and it assumes that the technical systems will be manufactured and installed. But, since the market is still in its infancy, these are potential solutions and not actual solutions. Hence, the study assumes that these potential solutions, such as a particular BEV design or as-yet prototypic charging system, do exist and will have the characteristics not deviating far from current forecasts. It is assumed that there are no barriers to manufacture, install and operate the vehicles and charging infrastructure according to the specifications of the solution space.

The study also considers UFT activity to be static, in terms of reactions to the use of BEV and land-use changes. In short, the transport activity is a snapshot of how transport is conducted now, and it does not change although external factors may. This is chosen to avoid complications in forecasting the progression of the transport operations, which may be riddled with uncertainty. The focus of the study, however, aims to evaluate the requirements of the electric mobility system. For that purpose, just a single snapshot of the activity is sufficient.

## **1.5. Organization of dissertation**

The dissertation follows the general structure of most scientific documents in building upon successive chapters to describe the work that has been done and to clarify the rationale for the decisions. Following this introductory chapter, the next chapter presents the relevant scientific concepts and existing studies relevant to this study. Following that, the research design and methods are presented in two separate chapters. While the research design describes the core stages in the methodology, the methods' chapter describes the specific data collection sources, calculation models and algorithms used to answer the research questions. Then, the results of the individual case studies are presented. Subsequently, the results are discussed in terms of broader research objectives and cross-case study analyses. Next, criticisms to the methodology and methods are discussed with the aim of defending the work and improving future research. Finally, the dissertation concludes with the main results and need for further research.

## **2. State-of-the-art**

This chapter presents knowledge about the core subject areas relevant to this study in three sections: UFT, electric mobility, and suitability of electric mobility to UFT. Each subject field is broad and covers many topics which may not be relevant to this research. Hence, the first two topics are dealt with briefly, to highlight the general concepts that form the basis of the analysis of existing studies - the third topic in this chapter. The analysis of the existing studies is the starting point for the development of the methodology, as presented in Chapter 3.

### **2.1. Urban freight transport**

Understanding the possible requirements and expectations placed upon the electric mobility system requires a clear comprehension of the stakeholders involved in and the activity of UFT. A basic definition of UFT is “the movement of things (as distinct from people) to, from, within, and through urban areas” (Ogden, 1992, p. 15). In contrast to passenger transport and service transport, the focus is on the “movement of things”, which results in the delivery and collection of goods (MDS Transmodal, 2012, p. 2). Additionally, it should be noted that in transport infrastructure or traffic studies, the focus is not on the movement of things per se, but rather on the movement of freight vehicles, which are used to transport the things. The distinction is necessary, if one wants to also capture trips, where the freight vehicles are empty – the so-called “empty trips” (Holguín-Veras & Thorson, 2003, p. 131).

The scope of urban transport, in general, encompasses any vehicle movement that uses roads within the urban area for at least a part of its trip. A trip is defined here as “an unbroken movement of a vehicle from a single origin to a single destination on the road network”. The origin and destination are stops where the driver performs a personal or operation-related activity, or where an action is performed on or with the vehicle. For example, a personal activity could be a lunch break; an operation-related activity could be the loading and unloading of shipments from the vehicle; and an action performed on the vehicle could be refuelling of the tank. The definition, which includes trips “to, from, within, and through urban areas” simply refers to the location of the stops, whether both the origin and destination of the vehicle trip lies within or outside the urban area. For our purposes, the discussion focuses on trips that originate and terminate within the same urban area, and excludes to-, from-, and through-trips.

The following sections look at several important characteristics of UFT. First, the different stakeholders are identified. This is primarily a question of which human institutions or entities are involved in this UFT, who might have an interest in the use of BEV. Second, UFT is described from an activity-based perspective, and looks at it as a derived demand, caused by a complex interaction between different entities in the economy. Third, the transport logistics

operations involved in UFT are described. Fourth, the evaluation of the transport system from multiple perspectives is described.

### **2.1.1. Stakeholder interactions**

There are several models of stakeholder interaction, which are useful in understanding UFT. In general, a stakeholder is defined as “any group or individual that can affect or is affected by the achievement of an organization’s objectives” (Freeman & McVea, 2001). Naturally, the effect should be considered “important by at least one stakeholder” (Brucker et al., 2011, p. 6) for it to be relevant. In the context of stakeholder engagement, the parties selected are usually related by “geographic proximity, special interest, or similar circumstances to address issues affecting the well-being of those people” (US EPA, 2013). Hence, often the scope of stakeholder analysis is limited to those who are sufficiently important.

The roles of different stakeholders and interactions among them is a complex phenomenon with many subtleties. Nevertheless, in the context of UFT activity, the stakeholders can be represented by six groups (see Figure 2-1). It is important to note that these groups are discussed here in terms of their functional role, and not their ontology or economic status. In other words, it is not *who they are or how they identify themselves*, but rather *what they do* in the urban freight. This is an important distinction, because from different perspectives and in different situations, each entity could play a different or even multi-functional role.

The two main stakeholders – who initiate the transaction – are the “trader” and the “customer”. Thus, transport is predominantly a derived demand, fulfilling the role of supporting other human activities or transactions. In the case of UFT, transport supports the “goods sales” between a “trader” and a “customer”. The “transport service” should be of a sufficient quality and at reasonable price, both of which are set by contract.

Either the “trader” or the “customer” may engage the services of the “logistics service provider” to complete the trade. The “logistics service provider” carries out the “transport service” at the lowest possible cost, in order to maximize its profits. However, carrying out the traffic activity might “produce transport externalities”. The types of externalities most commonly associated with transport activity are traffic congestion and air pollution.

Transport externalities affect many levels of society and the environment. The “resident” represents any category of persons, who “suffer transport externalities” caused by UFT. Transport externalities can affect not only the locals in the city, but also in the region or globally, depending on the type and magnitude of the externality (Behrends, 2011). For example, a body that represents the global “residents” is the United Nations Framework Convention on Climate Change, which aims to reduce the global production of greenhouse gases for the sake of preventing global warming (UNFCCC, 2017). The differences in scale of the externalities also affect the urgency of implementing mitigation measures.

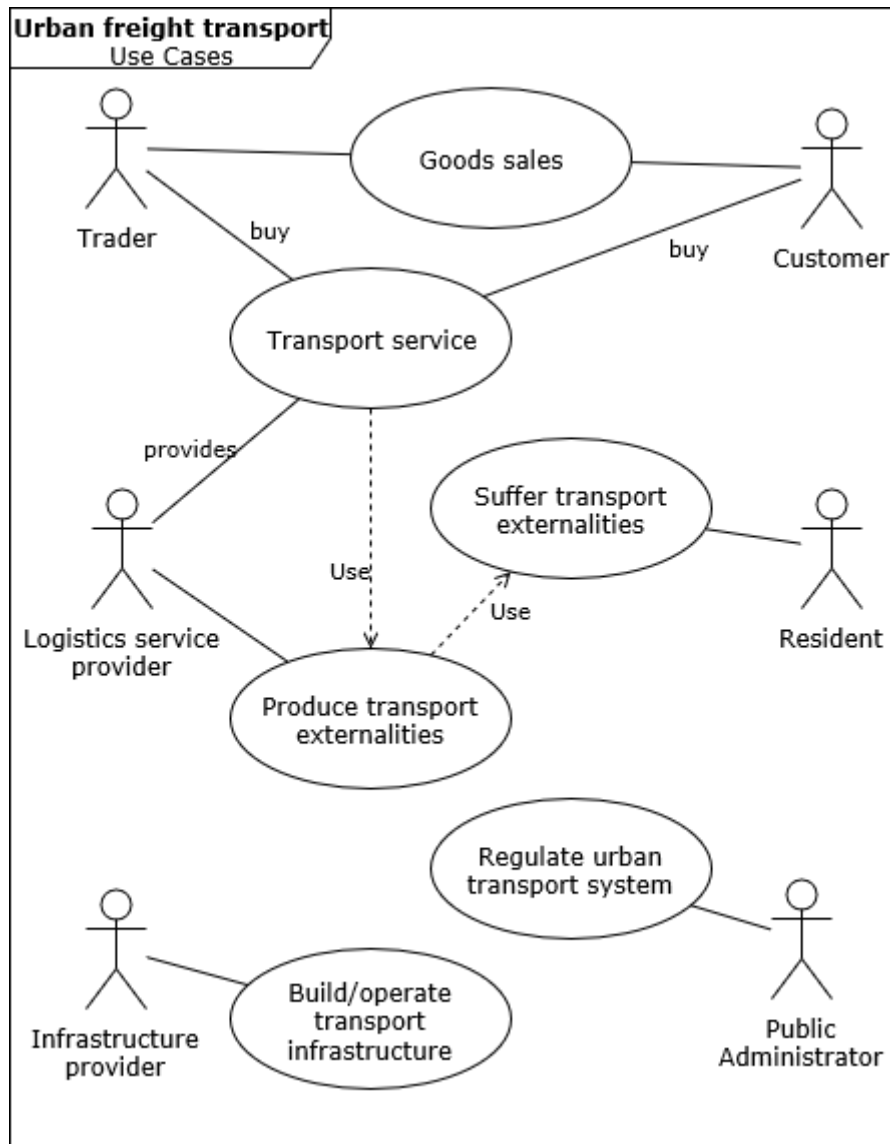


Figure 2-1 Interactions between the main stakeholders of urban freight transport (Adapted from Kunze et al. (2016) and Lindholm (2013).)

The role of the “public administrator” is to “regulate the urban transport system”, thus ensuring that the externalities produced by all transport system users (including passenger transport) are reduced. Typically and in an absence of “regulatory regimes that induce significant fear of punishment from non-compliance” (Thornton et al., 2009, p. 431), governed by the public administrator, businesses base their actions on economic concerns with limited consideration of the environmental impact of their operation. The public administrator has at its disposal a myriad of policy instruments for an effective mitigation of negative traffic impacts, while ensuring that the economic actors are not unfairly debilitated (Santos et al., 2010). Note also that the public administrator has the authority (and often the financial means) to promote improvements of the transport system, which in addition to restrictive policy, also include the provision of infrastructure, thereby facilitating the consolidation of freight flows (Lindholm, 2013, p. 16). Figuratively, the public administrator both threatens with the “stick” and offers the “carrot” to affect change in the transport system.

Finally, the “infrastructure provider builds and operates transport infrastructure.” Transport infrastructure is not limited to roads and traffic signals, but includes also refuelling stations and intermodal hubs. Adequate infrastructure is crucial for a transport service to be at an appropriate level. Note that this category is not commonly included as a stakeholder (compare Lindholm, 2013), but is actually important since functionally many new innovations involve new infrastructure, including digital infrastructure, or in the case of BEVs, charging infrastructure.

### **2.1.2. Urban freight transport from an activity-based approach**

The primary focus of the activity-based approach is the “decisions concerning activities which affect the demand” (Axhausen & Garling, 1992, p. 324). In other words, the focus is shifted from the freight vehicle traffic to the decisions, made by the relevant actors that led to the demand for freight transport. These relevant actors are found in the sometimes overlapping economic domains: the commodity market, the inventory-logistics service market, and the transport logistics service market (Tavasszy & Jong, 2014, p. 3). The activity-based approach allows to bridge these different domains and discuss them jointly, as shown in the following discussion.

In its essence, the commodity market encompasses the trade of goods. The seller and buyer, or producer and consumer – key actors in the commodity market - are often spatially dislocated. From here emerges the demand for transport services. Acting as a buffer in between the commodity market and the transport-logistics service market, is the inventory-logistics service market. It provides capacity for inventory holding, thus facilitating consolidation or deconsolidation of freight flows (Tavasszy & Jong, 2014, p. 9). As a result of the interactions between the three domains, the initial or primitive transport demand does not retain its original spatial (and temporal) pattern. In fact, the primitive transport demand can be seen as segmented by many buffers that form new transport demand.

UFT is concerned with localized transport demand, which results in vehicle trips from and to locations within the urban boundary. The inventory-logistics service market creates logistics networks to support the trade of goods for each company. How then does the logistics network finally look like? Chopra (2003) reviews the performance attributes of several types of distribution channels focusing on two characteristics: the customer’s access to the goods (either delivery to the customer or for customer’s pickup) and the use of any intermediary (with various transitory states). For example, a common chain is from factory to regional distribution centre to wholesaler to retailer with the customer collection at the retailer. With similar results, though from a different perspective, Rushton et al. (2010) provides three broad categories of distribution channels: manufacturer-to-retail, direct deliveries, and the miscellaneous “different structures”. The freight flows can develop into a variety of transport tours, such as one-to-one, one-to-many, many-to-one, and many-to-many tours (Daganzo, 2005). This is usually decided

within the transport logistics service market, and will be covered in more detail in the next section.

Distribution channels are commonly organized hierarchically in a network that optimizes transport flow bundles and inventory costs, such that multiple intermediate storage may be used in one transport chain (Chopra, 2003, p. 126). Examples of these intermediate stops are warehouses and cross-docks. Also, sea- and air-ports and other intermodal transport hubs may function as major transport demand generators (Fwa et al., 1996) and are key elements in a logistics network.

Besides the type of shippers, receivers and intermediate locations, another key aspect is the “scheduling of product flows” (McKinnon & Woodburn, 1996, p. 150), which organizes the demand in time. This aspect though not new is a critical factor in modern production systems (e.g. Just-in-time logistics) and entails coordination with scheduled transport modes (e.g. cut-off times for express delivery via air), and increasing service demands for private customers (e.g. time windows for home delivery services). Finally, in between the negotiations with the inventory-logistics service market and the transport logistics service market, decisions are made regarding the optimal shipment size and frequency of transports, and the size and number of inventory holding facilities (Combes, 2009).

The shipper could be any individual or company, from whom the physical freight proceeds from, including factories, warehouses, or retail outlets. The “shipper” and the “freight carrier” participate in the transport logistics service market to produce a micro-level transport demand, which are then fulfilled by freight vehicles resulting in a freight vehicle trip. In the following section, the generation of freight trips is discussed.

### **2.1.3. Urban freight transport operations**

Though the previous section describes the process of transport demand generation as a step-by-step process, the description of the decision makers in “markets” should alert readers that the decisions are made in a very complex manner with compromises made at many turns. At an operational level, a company makes decisions to fulfil transport demand in time and space, usually also by optimizing the resources used to do so (McKinnon & Woodburn, 1996). Included are decisions on when and with which vehicles freight will be transported, and how the vehicles need to move in the road network to reach customers’ locations during particular time windows. Specifically, some of the decisions reached are the routes taken by the driver, the number of routes driven by each driver, and the size of the vehicle payload capacity.

Besides the transport of goods, other tasks are also included in transport operations. They include loading and unloading activities, or other services rendered to customers (such as repair or assembly) in addition to transport of products. These activities require time, the availability of equipment (such as cranes or tail-gate lifts), and place for the vehicle to park. The activities may also be undertaken by on-site personnel.

The sequence of activities and the corresponding vehicle states (i.e. moving or stationary) of a vehicle can be considered its vehicle cycle, which is defined as “the annual (or daily) operational pattern” (Manheim, 1979, p. 217). Though even in the same fleet, vehicles may have different vehicle cycles, as each driver will not receive the same tasks. But, each vehicle would follow an approximate schedule, planned by the logistics planner (or someone with a similar role). The schedule gives information to drivers on the start of operations, break times, shift changes, and the end of operations.

#### **2.1.4. Transport system requirements**

It is uncontroversial and therefore presumed that the transport system is expected to enable transport activity. Hence, the requirements and expectations of a transport system are often centred around “other” important facets, such as costs. In one of the few studies on fleet electric vehicle preferences, Sierzchula (2014) surveyed the importance of factors influencing the initial decision to use BEVs<sup>3</sup>. The findings revealed that the “total ownership cost” is the only factor that discourages the adoption of BEVs. However, for organizations that choose not to increase their BEV fleet size, the lack of a “viable business model”, in terms of the financial aspect of the decision, is the primary cause, followed by the long duration of charging, the lower than expected driving range and operational capabilities (Sierzchula, 2014, p. 131). With regards to the performance of BEVs, two of the most important factors are vehicle reliability and the driving range, while the rest relate to the cost of battery replacement, maintenance, energy and infrastructure (Calstart, 2012, p. 17). The question of vehicle reliability is one, which vehicle manufacturers need to pay attention to, since early pilot projects using BEVs for freight suffered many negative complaints due to the lack of reliability (Ehrler & Hebes, 2012, Vermie, 2002), which are expected to at least match the high standards set by the ICEV. Indeed, the top two motivations for using BEVs are to save in fuel and maintenance costs (Calstart, 2012, p. 18).

The perspective taken by public authorities is much broader, since they are usually tasked with ensuring that the negative transport impacts are within reasonable limits and that the economic conditions for businesses remain vibrant. One of the more comprehensive frameworks of understanding the impacts of UFT uses the three pillars of sustainability plus a mobility dimension.

Melo (2010) integrates and summarizes the vast literature on sustainability and mobility evaluation to 54 indicators covering 16 themes. Table 2-1 shows a summary of the number of indicators in each category according to four dimensions: economic, social, environmental, and mobility. It serves as a long list for UFT in general, some of which should be suited to the aims and subject of evaluation of this study. Furthermore, there are at least several indicators

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<sup>3</sup> Note that fleet vehicles were used for commercial purposes, but not necessarily for freight movement.

or themes which are interdependent and hence though useful in “illuminating” the situation, is not methodologically good for quantitatively evaluating the system.

Table 2-1 Summary of indicators for transport sustainability (Adapted from Melo (2010))

<i>Dimension</i>	<i>Theme</i>	<i>Number of indicators</i>
Economic	Transport demand and intensity	7
	Transport costs and prices	9
	Infrastructure	3
Social	Risk and safety	2
	Health impacts	2
	Affordability	2
	Employment	1
Environmental	Transport emissions	8
	Energy efficiency	2
	Impacts on environmental resources	2
	Environmental risks and damages	2
	Renewables	3
Mobility	Mobility	5
	Service provided	3
	Organization of urban mobility	3

As previously identified, the impact of using BEVs are in the use of a different power source and in the types of vehicle, hence a shortlist of the indicators should centre around the vehicle’s investment and operating costs, tail-pipe emission, and energy consumption. These indicators are summarized in Table 2-2 and assume that the transport demand, number of vehicles used in the fleet, and mileage stays the same. If one considers the above to also change, other considerations, such as congestion and service quality would also need to be included.

Table 2-2 Relevant indicators for one-to-one swap of ICEVs with BEVs (Adapted from Melo (2010))

<i>Perspective</i>	<i>Categories</i>	<i>Indicators</i>
Freight carriers	Costs of investment Operating cost	Vehicle cost (and charger system)
		Energy/fuel cost Maintenance cost Taxation Subsidies
Local resident	Air pollution Noise	Nitrogen oxides emissions Volatile organic compounds emissions Particulate matter emissions Sulphur oxides emissions Ozone concentration Noise exposure
		Energy consumption by transport mode Fuel consumption Use of renewable energy sources Carbon dioxide emissions Nitrous oxide emissions Methane emissions

For the freight carriers, besides the operational capability of the BEV, the costs of investment and operations are of highest priority. Hence, choosing a BEV that can at least bring long term financial benefits need to be identified, particularly using the total cost of ownership approach (Taefi et al., 2015, p. 372). This point does not consider an increase in service price, which may be charged with an “eco-label”.

For the delineation between what is significant for local residents and public authorities, the difference is mainly to do with the exposure of what may be harmful. Local residents suffer due to air and noise pollution emitted from ICEV vehicles, and conversely will benefit from the use of BEVs. The public authority, however, must consider its energy security and its greenhouse gas commitments in deciding transport policy.

## **2.2. Electric mobility systems**

Land transport systems run on either road or rail, but this section focuses only on road-based systems. There are three objects in our focus: the BEV, the charging system, and the charging strategy used with the charging system.

Note that there are another class of light electric vehicles such as electric quadricycles, but are not included in this analysis. These vehicles are not included in our scope since they not considered “road-worthy”, particularly due to their low mobility, e.g. low maximum speed and acceleration. Although primarily made for intra-logistics or off-road applications, they have also found niche application for historic city centre deliveries, such as the CargoHopper in Utrecht (Eltis, 2015 [accessed 1 August 2017]).

### **2.2.1. Battery electric vehicle**

The BEV overview covers a selected range of vehicles, which have been used in one way or another in freight transport. As noted previously, any type of vehicle can function as a freight vehicle. Herein, the list is limited to only the prominent ones, within which as much technical variation is covered as possible, in terms of gross vehicle weight (GVW), driving range and battery capacity. These are summarized in Table 2-3.

The list differs starkly from that provided by Pelletier et al. (2014), which includes non-road worthy vehicles, vehicles from companies which have ceased operations, and other vehicles, which could not be verified anymore. In any case, the list provided here does not seek to be exhaustive, and also does not cover vehicles with information not available in English, such as those produced in China.

Table 2-3 Selected BEVs used for goods transport

Van or truck series	GVW ('000 kg)	Stated range (km)	Battery capacity (kWh)	By Design/ Retrofitted
Renault Kangoo ZE <sup>a</sup>	2.1	170	22	By Design
Peugeot Partner <sup>b</sup>	2.2	170	24	By Design
Nissan ENV200 <sup>c</sup>	2.2	170	24	By Design
Mercedes Vito E-Cell <sup>d</sup>	3.1	130	36	By Design
Smith EV Edison <sup>e</sup>	3.5 - 4.6	90 - 180	35 - 51	Retrofitted
Boulder DV-500 <sup>f</sup>	4.8	160	72	By Design
Boulder DT-1000 <sup>g</sup>	7.0	160	105	By Design
Smith EV Newton <sup>h</sup>	7.5 - 12.0	50 - 240	80 - 120	Retrofitted
Emiss 10, 12, 16, 18 Serie <sup>i</sup>	10.0 - 18.0	50 - 250	60 - 240	Retrofitted

a. Renault, "Pricing and specification of Kangoo ZE", <https://www.renault.co.uk/vehicles/new-vehicles/kangoo-ze/specifications.html>, (Accessed 15-07-2017)

b. Peugeot (2017), "Prices, equipment and technical specifications - Model Year 2016.75", available online at <http://business.peugeot.co.uk/media/partner-prices-and-specs-06022017.pdf>, (Accessed 15-07-2017)

c. Nissan, "The 100% electric van. E-NV200 van.", <https://www.nissan.co.uk/vehicles/new-vehicles/e-nv200.html> (Accessed 15-07-2017)

d. DPDHL (2016), "Alternative drive vehicles: Mercedes Benz Vito E-Cell", available online at [http://www.dpdhl.com/en/media\\_relations/events/carbon\\_neutral\\_delivery.html](http://www.dpdhl.com/en/media_relations/events/carbon_neutral_delivery.html), (Accessed 15-07-2017)

e. Smith Electric (2011), "Smith Edison: The world's favourite all-electric light commercial vehicle", available online at <http://www.smithelectric.com/smith-vehicles/models-and-configurations/>, (Accessed 15-07-2017)

f. Boulder Electric Vehicle (2013), "Boulder Electric Vehicle: 500 series", available online at <http://boulderev.com/models.php>, (Accessed 15-07-2017)

g. Boulder Electric Vehicle (2013), "Boulder Electric Vehicle: 1000 series", available online at <http://boulderev.com/models.php>, (Accessed 15-07-2017)

h. Smith Electric (2011), "Smith Newton: The world's best-selling all-electric truck", available online at <http://www.smithelectric.com/smith-vehicles/models-and-configurations/>, (Accessed 15-07-2017)

i. Emiss BV, "Electric trucks: the future for inner city distribution is here", <http://www.emoss.nl/en/electric-vehicles/full-electric-truck/> (Accessed 15-07-2017)

The use of retrofitting of conventional ICEVs to become BEV has played a major role in familiarizing vehicle manufacturers with electric mobility market and users with BEV vehicles, and has even spawned new forms of industry. Many of the first research projects used retrofitted vehicles, which were retrofitted by a third-party electric powertrain installation company (Vermie, 2002, TU Delft et al., 2013). One advantage of the retrofitted vehicles is the use of existing chassis and body plans of vehicles, such as Emiss. However, some companies claimed that their BEVs, which are built from ground up (i.e. by design), enable them to better optimize their BEVs, such as the Mercedes Vito E-cell.

An important and common way to optimize the BEV is to offer different battery capacity sizes. This can be seen in the Emiss and Smith Electric Vehicles in Table 2-3. This enables the vehicle manufacturers to cater to different markets, without additional customisation. This is an important option for fleet owners to ensure that the driving range they need matches the vehicle's capability. However, this option is usually only available for larger vehicles, i.e. medium duty vehicles and above, possibly since the weight of the vehicle becomes a less significant consideration than light duty vehicles – which have a maximum weight of 3.5 tonnes. This is also often a feature of retrofitting companies, since their primary product is the electric powertrain.

The light duty vehicle market is particularly vibrant. Already for passenger transport there are forecasts of the electric vehicles becoming the majority by 2030. A fairly bold goal is by DHL in introducing carbon-free transport in Bonn, Germany (and its immediate surroundings). For this reason, DHL will use electric vehicles from Renault, Mercedes, Iveco, and their self-developed Streetscooter delivery van (Deutsche Post DHL Group, 9 Dec. 2014 [accessed 5 April 2016]). Many vehicle makers have expressed their aim to develop the light duty vehicle market competitively in the coming decades. However, it is unclear whether this will extend to medium duty and larger vehicles.

Nevertheless, the ability of the industry to retrofit larger vehicles has found favour within the industry, with Emoss, Elektrofahrzeugen Schwaben, and Smith EV. Still, the future availability of BEVs for freight transport remains uncertain. For example, a ground-up BEV was designed by Modec as launched in 2006, but folded up in 2011. It was subsequently sold to Navistar (Navistar International Corporation, 2 Dec. 2009) which did not bring the vehicle development any further. Notwithstanding, recent news have surfaced about the development of fully-electrified very heavy duty trucks (Future Energy, 18 May. 2016).

However, since the question of the market of BEVs for freight has not yet been well researched, it is pointless to speculate further. In comparison, the battery, a key component in the BEV, has received a lot of attention, which is the subject of the next section.

### **2.2.2. Battery technology**

The battery pack is responsible for providing the electrical energy to the motor for movement and to power peripheral equipment, such as air-conditioning, refrigeration, information systems, and loading equipment. Besides that, the energy stored in the battery also has to supply energy to the battery management system that ensures that the battery is operated in the chosen operating environment, which may optimize battery life or performance and ensure the safety of the battery (Cluzel & Douglas, 2012). It is necessarily composed of the battery "cells, structural support, thermal management and electronic balance" (Cluzel & Douglas, 2012). The battery cell "transforms chemical energy into electrical energy; it consists of an anode and a cathode, separated by an electrolyte" (Pollet et al., 2012, p. 236).

There are many considerations in the design of a battery pack, such as the specific energy, specific power, calendar lifetime, cycle life, depth of discharge (DOD), efficiency of discharge and charge, operating temperature influence on performance, and safety (Gerssen-Gondelach & Faaij, 2012). While safety should be assumed, the other parameters affect the operational performance of the battery pack and thus significantly affect the EV. The battery must be designed or configured such that it can "store sufficient energy (kWh) and provide adequate peak power (kW) for the vehicle to have a specified acceleration performance and the capability to meet appropriate driving cycles" (Burke, 2007, p. 807), while considering the constraints of "weight, volume and cost" (Burke, 2007, p. 807). Furthermore, the battery pack

should be optimized to mitigate the degradation of battery performance, in terms of its discharge and charge efficiency, which is dependent on the calendar lifetime and cycle life. Once a level of degradation has been achieved, the battery pack must be replaced. Hence, the various operating parameters - such as "charging and discharging rates, DOD, and other conditions such as temperature" (Young et al., 2013) - must be designed to keep degradation at bay for as long as possible.

In general, the improvements to battery pack cost and properties could come through "improvement in material properties delivering higher energy densities, and the scaling up of production of large cell packs" (Cluzel & Douglas, 2012). It is important to note also that, while large scale improvements are commonly touted as revolutionary and promises to improve significantly the characteristics of the battery, actual vehicle engineering standards are very high and need to be fully met before it can venture into automotive cells (Cluzel & Douglas, 2012).

In terms of costs, the costs of lithium ion batteries can be expected to decrease by about 8% yearly based on "cell manufacturing improvements, learning rates for pack integration and capturing increasing economies of scale" (Nykvist & Nilsson, 2015). Indeed, several companies have decided to set up large scale EV battery production plants, such as Tesla and Panasonic's Gigafactory (Teslamotors, 30 Jul. 2014 [accessed 4 April 2016]) and Daimler's Deutsche ACCUMOTIVE in Germany (Deutsche ACCUMOTIVE, 1 May. 2016 [accessed 4 April 2016]).

A summary of the most common types of batteries considered for EVs are lead-acid battery, nickel-metal-hydride, lithium-ion, sodium-beta batteries, lithium metal polymer (Gerssen-Gondelach & Faaij, 2012). Other prominent experimental types in the literature include lithium-sulfur, lithium-air and zinc- air. Currently, lithium-ion batteries are the most widely used and successful types of battery chemistries (Erickson et al., 2014).

Aside from the performance and cost consideration of batteries, the environmental contributions of the batteries are also researched. A study on the environmental impact contributed by lithium-ion batteries show that it is relatively small compared to the damage attributed to the operation of the vehicle. This, however, depends on the ultimate source of the energy, i.e. the power generation units (Notter et al., 2010). The analysis by (Majeau-Bettez et al., 2011) using a lifecycle based on a functional unit of 50 MJ instead of vehicle-kilometer (Notter et al., 2010) yielded different results, which pointed to production environmental impact to be higher than that of operation. The discrepancy was due mainly to the assumptions on "vehicle design" rather than on the "battery characteristics and expected lifetime energy outputs" (Majeau-Bettez et al., 2011, p. 4552). Both studies do not include the end-of-life salvage value of the batteries and therefore can be considered worst-case-scenarios, since batteries could be used in second life applications (Castro Díaz, 2015, p. 58). In summary, the

results of the (Amarakoon et al., 2013) analysis confirmed the study of (Notter et al., 2010) and showed that in general, it is the operation stage, which is the major contributor of environmental impacts, though the “upstream materials extraction and processing and battery production are non-negligible” as contributors (Amarakoon et al., 2013).

Nevertheless, in the short to medium term, it remains a challenge to include an appropriately sized and priced battery for freight vehicles, which can accommodate the required driving range of the operations. In the next section, the methods employed to charge the batteries are described.

### **2.2.3. Charging technology**

The charging system has two main functions in this study: to ensure that the vehicle is sufficiently charged at the beginning of each vehicle cycle, and to extend the driving range of the BEV during the day, if needed. This section of the review considers only the functional part of the charging technology, i.e. the process and technical information is kept to a minimum. Hence, it focuses on the power levels, the power transfer method and the state of the vehicle while charging. There are other supporting infrastructure needed, such as payment, billing, and identification systems, which are also important, but are outside the scope of this review.

Standards for charging equipment currently exist, but they cater primarily to light-duty vehicles, for use by private individuals. Hence, standards for charging freight vehicles in industrial settings are yet to be developed. Nevertheless, using the standards for light-duty vehicles as a starting point is good for at least two reasons. The first is that these standards already account for the electrical infrastructure needed to support the charging systems. Besides ensuring that there is sufficient reserve capacity of power plants to cater for BEV charging, there is a need to ensure that power distribution networks are sufficiently capable to handle the load of charging (Habib et al., 2015, p. 210). The standards also highlight the level of upgrade needed for the power systems to ensure that BEV charging does not overload the local power distribution system. The second reason is that power level of the charging system affects the battery lifetime and rate of battery degradation. Direct current fast charging, for example, has been shown to degrade the battery capacity of BEVs faster than the alternating current Level 2 charging (Shirk & Wishart, 2015). Nevertheless, if faster charging induces quicker battery replacement, it is possible that new advances in battery technology will still make this a viable strategy, i.e. a combination of fast charge and cost-efficient battery replacement.

According to the standard SAE J1772<sup>4</sup> as reviewed by (Yilmaz & Krein, 2013), the standard levels of charging are known as Level 1, Level 2 and Level 3 charging, where the first two levels use alternating current and the third uses direct current. These are summarized in

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<sup>4</sup> Also known as "SAE Surface Vehicle Recommended Practice J1772, SAE Electric Vehicle Conductive Charge Coupler".

Table 2-4. Level 1 charging system does not require a major electrical installation and can be connected to the common household outlet. The advantage is that most passenger vehicles, with relatively small batteries (compared to electric freight vehicles), can be charged at home without the cost and effort associated with installation of Level 2 and Level 3 charging systems. In fact, Level 2 and Level 3 require a dedicated electric vehicle supply equipment (EVSE), with their own dedicated power distribution system. This are rarely found at residential homes, but are common at industrial buildings, where heavy electrical machinery are often operated.

Table 2-4 Charging system types according to power levels

Power level types	Energy supply interface	Expected power level (kW)
Level 1	Common outlet	1.4 - 1.9
Level 2	Dedicated EVSE	4 - 19.2
Level 3	Dedicated EVSE	50 -100

Another consideration when choosing the charging power levels is their efficiency of charging, which may also depend on other factors, such as total energy charged, and temperature (Sears et al., 2014). One study, which compared the different levels, show that Level 2 charging may be more efficient than Level 1 charging, up to a difference of about 5.6% (Sears et al., 2014, p. 256).

There are two broad classifications for the energy transfer methods, which are via conductive or inductive methods. Conductive charging requires direct physical (via cable) contact between the connector and the charge inlet (Yilmaz & Krein, 2013, p. 2151), whereas inductive charging occurs through electromagnetic transmission (Yilmaz & Krein, 2013, p. 2151). The conductive method is the more common type and has commercial applications for all three power levels. The inductive method (also called wireless charging) is newer, but also already has commercial application, for at least up to Level 2 power levels (Evatran, 2015 [accessed 2016]). For inductive charging, a concern is the efficiency of the energy transfer, which may easily vary depending on the distance between transmitter and receiver and even the lateral displacement (Birrell et al., 2015, pp. 721–722).

EVs can be charged, while stationary or while in motion, using static charging or dynamic charging systems. Dynamic charging systems can also charge EVs, which are stationary, but are designed for a specific vehicle speed. Here, the term en-route charging is used to denote the case where the vehicle is either in motion or only stationary for a very short interval, such as intersections. Table 2-5 shows the examples of combining the method of power transfer and the vehicle kinematic state while charging. Note that each quadrant has at least one working product available in the market, if not exactly for freight vehicles, at least for buses, which have similar needs.

Though generally inferior in terms of charging efficiency, inductive charging has two major advantages. First, in terms of convenience, since there is no need to “plug-in” the

charging cable, vehicles just need to be placed above the transmitter. This is a quick and convenient charging experience for users. The second advantage is for enabling dynamic charging. The tried and tested overhead catenary system installed on trolley buses and mining trucks are unsuitable to be used in a mixed traffic situation. Since a pantograph must be installed atop the vehicle, the variable heights of different vehicle sizes constraints the cross-compatibility between high vehicles (like heavy duty trucks) and low vehicles (like delivery vans). The problem does not arise for trolley buses or mining vehicles, since the system is designed for only one type of vehicle. Hence, there is an advantage for inductive dynamic charging, where the charging receivers are installed on the bottom of the vehicles, for which there is little variation.

Table 2-5 Major categories of charging technology

Kinematic state of the vehicle	Power transfer method	
	Conductive charging	Inductive charging
Parked vehicle	Plug-in charging <sup>1</sup>	Static wireless charging <sup>6</sup>
	- Level 1: <2 kW	
	- Level 2: <20 kW	
	- Fast Charging <sup>2</sup> :	
	- ChaDeMo (40-60 kW)	- Witricity
	- CCS Combo (50 -350kW)	- Qualcomm Halo
	- Tesla Supercharger (120 kW)	- Plugless
	Battery swapping station (BSS) <sup>3</sup>	
	- Voltia (previously Greenway) <sup>4</sup>	
En-route vehicle (either moving or stationary on road network)	Overhead catenary system <sup>5</sup>	Dynamic wireless charging <sup>8</sup>
	- E-highway by Siemens <sup>6</sup>	- Bombardier's PRIMOVE <sup>9</sup>

In en-route charging, the EV is located on the road network, and is moving or at least stopped for only very short periods of time (e.g. at an intersection). A common type of en-route charging in the city area, which is for example used in public transport, is where the trolley bus is supplied with electricity via an overhead catenary system (Neandross et al., 2012, p. 13, Gilbert, 2010, p. 59). However, as mentioned this technology is usually not considered for medium to light duty vehicles. Instead, dynamic inductive charging might be a technology that can apply to all types of goods vehicles, since the road to vehicle clearance does not vary as much. Compatibility with passenger vehicles and buses (Choi et al., 2014, p. 1) will also encourage the political decision to implement such systems within urban areas. Such systems are also being considered by England, which recently released a feasibility study on electrified roadways for main roads (Highways England Company, 2015).

The technology shows us what the system is capable of. In the next section, how charging systems can be incorporated into operations of the drivers through different charging strategies is discussed.

**2.2.4. Charging strategy**

The term charging strategy is used to denote the time and place where charging activity is conducted from the driver's or freight carrier's perspective. It is important to note that the

only one other study that has dealt with stationary charging strategies (Paffumi et al., 2014), though focused on application for passenger transport. There are three categorization criteria used in their approach. The first is, a choice between “opportunistic” or not. The absence of opportunistic charging implies that the vehicle is only charged, when the vehicle is returned to its parking location for overnight charging. Opportunistic or as Paffumi et al. (2014, p. 5) puts it “continuous”, implies that charging takes place anytime during the day, when the option for charging is available, such as when the vehicle is parked at the office. The second criterion is whether “smart charging” is enabled, either to optimize for the sake of the vehicle owner, the charging operator, or the electricity grid operator. Examples of objectives are to reduce energy cost (for vehicle owner or charging operator), instability to the grid, or simply to ensure that the vehicle battery is always full. The third criterion is the power level used, which influences the rate of energy transfer.

As for how charging strategy relates to the use in UFT, it is a less explored field. There are only two studies by Macharis et al. (2007) and van Duin et al. (2013) who considered “recharging” of the BEV once the vehicle returns to the depot in between routes. For this purpose, it might be useful to firstly look at all reasons for stopping the vehicle throughout the day, which has been more researched, particularly since it itself relates to vehicle or logistics efficiency. A comprehensive set of vehicle states during driver activities are: (1) in-transit, including traffic-related stops, (2) in-transit, but during driver rest-period, (3) being loaded or unloaded, (4) preloaded and awaiting departure, (5) stationary, in between shifts (Liedtke & Schepperle, 2004, p. 202), (Min & McKinnon, 2009, p. 645). Theoretically, each of the vehicle states (1) - (5) can possibly be used for opportunistic charging. Dynamic charging can be used while the vehicle is state (1), while static charging can be used for the rest. What is determinant is the extent of charging infrastructure rollout to the various locations and the availability of time spent in each activity.

### **2.3. Existing studies on evaluation**

In this section, selected studies which quantitatively evaluate electric vehicles for UFT according several indicators are reviewed. The studies usually present a before-after analysis, which is an “assessment of a set of scenarios and the comparison with respect to an initial situation.” (Ambrosini et al., 2013, p. 8). In these studies, the initial situation or reference scenario is often a scenario where a ICEV is used. More scenarios are developed, which are based on variations of electric mobility systems. Both the reference and the tested scenarios are usually expressed in some form of simulation or calculation of vehicle movement, according to different levels of details (e.g. distance, speed, or route). The scenarios are then evaluated according to some indicator (e.g. cost, carbon dioxide emissions) in their chosen evaluation framework (e.g. multi-criteria analysis, cost-benefit analysis).

Two stages are used as template for the review of the studies namely, (1) scenario-building of transport activity, and (2) the evaluation of scenarios according to relevant criteria. Within each stage, there are several details, which are considered here significant, and therefore have been extracted from the studies. The details are explained in the following sections.

In setting the scenarios, each scenario represents a possible real-world UFT implementation of the vehicle system (both conventional and electric). The aim of this stage is to quantitatively describe the vehicle activity, considering the constraints that the vehicle systems are under (e.g. limited driving range of a BEV). Since the ultimate goal of building the scenario is the quantitative evaluation conducted in the following stage, the units of the vehicle activity (e.g. distance travelled) must correspond to the needs of the evaluation framework.

Note also that there is an implicit condition in this stage, when the vehicle activity is being modelled. As it does not apply for all the studies, clarification is in order. The assumption is that the BEV has sufficient battery capacity to conduct the transport activity. In other words, the scenario by definition meets the operational requirements set upon the BEV and charging system. Cases, where this does not apply, are explicitly stated.

In the following section, the methodology used in the selected studies are reviewed according to the following questions, where applicable:

1. What modelling approach is used to describe the vehicle activity?
2. How are the BEV and charging system incorporated into the model?
3. If the battery capacity is insufficient, what modifications to the vehicle activity or fleet are allowed in the modelling environment?
4. How are the decision relevant indicators quantified?
5. What criteria are used in the decision making?

These questions are addressed in the following sections.

### **2.3.1. Vehicle activity model**

The vehicle activity model (VAM) depicts the movement of the vehicle in time and space, associated with the different activities carried out by the driver in the different locations, and the state of the vehicles in those locations. The level of details provided by the model enables (or disallows) complexity in how the BEV and charging system are incorporated into the model. Three distinct model types are identified from the selected studies:

1. Simple distance-based model,
2. Simple activity-based model, and
3. Operations research model.

These types are briefly discussed in the following.

### 2.3.1.1. Simple distance-based model

The simple distance-based model depicts the vehicle activity merely as the distance travelled by the vehicle in a day. The daily distance travelled is derived, according to information obtained from a survey (Davis & Figliozzi, 2013b, Gallo & Tomić, 2013) or national level statistics (Feng & Figliozzi, 2013, Lee et al., 2013). Together with the national level statistics, a whole segment of vehicles can be evaluated at a time. If there is a national distribution of average daily mileage of vehicles, the potential share of vehicles, which can be substituted with a BEV can be estimated (Lee et al. 2013). However, such a model cannot estimate the potential of opportunity charging, since information about stops are absent .

### 2.3.1.2. Simple activity-based model

The simple activity-based model adds a schedule and additional information to the simple distance-based model. The vehicle activity is properly described firstly in terms of the activity it undertakes throughout the day, such as driving, pickup, delivery, break, and charging. The driving is represented by distances travelled, which can be obtained similarly to the previous model or according to other approximation methods, such as the vehicle routing problem approximation methods

In contrast to the simple distance-based model, the daily driving distance is not fully representative of the requirement of driving range for the vehicle, since in between the routes, the vehicle could be side-tracked for charging. For example, (Macharis et al., 2007) designated a quick charge of 16 minutes in between the two routes a vehicle undertakes daily. One could also exploit the difference in vehicle weight that results after each pickup or delivery action. The difference in weight changes the power needed by the vehicle, and thus, the required battery capacity. Using this approach, (Davis & Figliozzi, 2013a) estimated the driving range of the electric vehicle more accurately, and allows the weight of the payload and the number of delivery stops to vary the capability of the vehicle.

### 2.3.1.3. Operations research models

Vehicle movement in goods transport modelling are commonly based on adaptations of operations research models, such as travelling salesman problem or vehicle routing problem (VRP). Since these "normative approaches" are originally developed to support "firm's level decisions on supply chain issues relating to inventories, shipment sizes and transport modes" (Tavasszy & Jong, 2014), they are easily adapted into the toolkit of freight transport modelling. These methods can be used to decide or "simulate" the sequence of stops (e.g. for pick-up or delivery) in a route, the distance and duration for each leg in the trip, and the number of vehicles needed.

For instance, a variant of the VRP was used by (van Duin et al., 2013), which not only determined the stop sequence of the vehicles, it calculated the optimal fleet mix and size,

choosing between two different BEVs. (Vonolfen et al., 2011) on the other hand, based on the stochastic inventory routing problem, simulated the route of a glass waste collection truck.

The main advantage of these models is that the link between the goods movement demand and the required vehicle movement is clear, which strengthens the model as a representation of the company's vehicle movement. Furthermore, operations research models provide more accurate distances between stops, and the load of the vehicle during each trip leg, instead of relying on generalized statistics. This allows a more accurate estimation of the energy consumption rate (or distance range requirement) than the simple activity-based models.

### **2.3.2. BEV and charging system model incorporation**

While the function of the BEV is to complete the task as described by the VAM, the charging system is used to ensure that the BEV has sufficient energy throughout the driving schedule. In this section, how the BEV and the charging system are integrated into the VAM is described.

The BEVs in the studies are based either on generic vehicles without an explicit link to real world vehicles (Macharis et al., 2007, Gallo & Tomić, 2013, Vonolfen et al., 2011) or models of real world vehicles (Davis & Figliozzi, 2013b, Davis & Figliozzi, 2013a, Feng & Figliozzi, 2013, Lee et al., 2013, van Duin et al., 2013). The key attributes representing the vehicles are the energy consumption rate and the battery capacity. The energy consumption rate (or the equivalent fuel consumption rate) is simply the power required by the vehicle to carry out the driving task, as described by the VAM. It is often expressed in units of kilowatt-hour per kilometre, which is the energy consumption per distance travelled. The battery capacity is the available energy that can be supplied by the battery before needing a recharge.

While the specific methods are discussed here, a physics model that simulates the vehicle dynamics and the electrical behaviour of the powertrain and battery can be used to calculate the energy consumption rate (Holdstock et al., 2012). Whether the outcome is a fixed energy consumption or if it is dynamic, the energy consumption rate represents the point of integration of the vehicle and the vehicle driving activity. Hence, it plays a pivotal part in the precision of the study.

The energy consumption and charging activity affects the energy level of the battery, which is also known as the state-of-charge (SOC). Driving activity reduces the SOC according to the energy consumption rate, while charging activity increases it according to the power rating specification of the charging system.

Most studies consider the energy consumption rate to be static, regardless of the activity of the vehicle, such that the battery capacity can be stated in terms of driving range in kilometres. But, if one considers the physics model that is behind the energy consumption rate calculation, there are several ways in which the parameters of the vehicle and driving

behaviour can affect the energy consumption. In the existing studies, the weight of the vehicle and the driving speed profile are considered.

Macharis et al. (2007) used a static energy consumption rate of the BEV, which was estimated “as a function of total vehicle weight”, which in their imprecise model, did not change, even after drop-off. Instead, Davis & Figliozzi (2013a) considered for the same vehicle, the effect of a decreasing payload after every delivery activity. The precision in their VAM, enabled this variation to be accounted for.

Any calculation of the driving range or energy consumption rate must consider some form of driving speed profile of the vehicle. The speed profile is “a fixed schedule of vehicle operation”, which specifically refers to the change of “vehicle speed and gear selection” over time, and is used originally for “an emission test to be conducted under reproducible conditions” (Barlow et al., June 2009, p. 2) on the basis of calculating the energy (or fuel) consumed in time. Even studies which used the stated driving range (as defined by manufacturers) implicitly used a speed profile. For example, most manufacturers state their driving range based on tests or calculations using the New European Driving Cycle (NEDC) as the assumed speed profile of the BEV. The studies by (Lee et al., 2013) and (Davis & Figliozzi, 2013a) explicitly used different speed profiles in their calculations to account for different traffic situations, such as the New York City Cycle and several driving speed profiles based on MOVES<sup>5</sup>, respectively. The speed profiles were chosen dependent on the vehicle type (e.g. light duty vehicle or heavy duty vehicle), road type (e.g. urban or expressway), and traffic situation (e.g. light or heavy traffic).

As for integrating a charging system into the scenario-building, none of the studies included opportunity charging activity, except for two. (Macharis et al., 2007) considered a quick charging system and (van Duin et al., 2013) considered a battery swap for the vehicles. Both exploited the time in between the first route and the second route, which coincides with the loading time for the second trip. In a quick charging system, the time interval for charging influences the amount of the increase in the energy level. However, in the battery swap, it is assumed that it is a fixed amount of time needed to replace the depleted battery with the fully-charged battery.

In summary, the electric vehicle and charging system are integrated with the VAM, when the energy demands for completing the driving tour and the potential for recharging is considered. Hence, the method used to calculate the energy consumption rate is very important for the precision of the study. If opportunity charging is included, a simple method can be used to integrate it into the model.

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<sup>5</sup> MOVES stands for Motor Vehicle Emissions Simulator.

### **2.3.3. Coping with insufficient energy capacity of the vehicle**

In developing a plausible scenario, where the BEV moves according to the VAM, the battery must have sufficient energy throughout the operation schedule. However, as previously noted, the capacity of the battery is sometimes insufficient, limiting the driving range of the vehicle. Depending on the goals of the study, one can reduce the study scope, essentially focusing only on the segment of trips that can be met by the limited driving range of BEVs. For instance, (Lee et al., 2013) and (Feng & Figliozzi, 2013) limited their analysis to a vehicle segment of the same weight class, with a statistical daily mileage within the driving range of their selected BEV. Their decisions were in line with one of their aims, which is to predict a share of BEV adoption in the country and evaluate the consequences of it.

However, if reducing the scope of the study is not permitted, one could also apply modifications to the electric mobility system, which enables the vehicle to complete the required trip. There are three real-world responses to the insufficiency of driving range, which are covered in these existing studies. The methods of modelling these responses are discussed below.

#### **2.3.3.1. Modifying the battery of the BEV**

The modification of the battery capacity (either increase or decrease) is done to align the capability of the BEV with the needs of the transport task. Besides retrofitting companies, who have the flexibility to install different battery sizes in the vehicle, vehicle production companies also offer the possibility for the different battery pack sizes, such as in the Smith Newton truck. In fact, Davis & Figliozzi (2013b, p. 8) used this exact vehicle model with the choice of a “40, 60, 80, 100, or 120 kWh battery pack size” in their study. There is naturally a trade-off, with the payload capacity of vehicle, if the battery weight is increased. Also, there is the possibility that the energy consumption rate of the vehicle increases, which is accounted for by (Macharis et al., 2007).

#### **2.3.3.2. Applying an opportunity charging activity**

Opportunity charging reduces the effective driving range (or energy capacity) requirement from the need to last the whole operation schedule, to just lasting until the next recharging activity. Both Macharis et al. (2007) and van Duin et al. (2013) exploited the opportunity in between routes, where either the vehicle was being loaded or the driver was having a break. The mode of charging used in both studies was different. For Macharis et al. (2007), the truck was charged with a 50 kW fast charging system for 16 minutes, which reduced the required battery capacity by about 13 kWh. On the other hand, van Duin et al. (2013) used a battery swap, which essentially replaced the spent 26 kWh battery with a new one, giving the vehicle another 100 km driving range for the second route of the day. However, no

information was provided as to how long it would take to replace the battery, which is a crucial factor in the operations.

#### 2.3.3.3. Varying the fleet size

In addition to enhancing the capability of the BEV, one could also increase the fleet size. If the total transport task for the fleet remains essentially the same, the distance travelled by each vehicle then reduces, thus reducing also the required battery capacity. This approach was used by Davis & Figliozzi (2013a) and van Duin et al. (2013). Changing the number of vehicles used also changes the routes and the VAM, and therefore the total distance the fleet travels. Both studies used an optimization method to find the optimal fleet size, such that the feedback effects are accounted for. van Duin et al. (2013) optimized the fleet size and mix based on the “average service level” and the “average costs per delivery”. Davis & Figliozzi (2013a) used a continuous approximation method to optimize the distance travelled by the total fleet.

In summary, the technical fit of the electrical vehicle is a prerequisite for any implementation and hence the evaluation of the concepts. If the fit is not immediately achieved, then there are several ways to adjust the system in order to do it.

#### 2.3.4. Calculation of the selected indicators

There are parallels with evaluation of sustainability and suitability. Although they may share the same indicators (and aspects or concerns) as valued by stakeholders, the evaluation criteria may be different.

The indicators represent the aspects, which are valued by the stakeholder. For example, if the stakeholder's requirement is the reduction of cost, then the indicator used must be in the measurement of cost. However, the measurement of cost could be in different terms, depending on what particular cost reduction aspect is important to the stakeholder. For example, (van Duin et al., 2013) used an “average cost per delivery” as an indicator, while other studies considered various forms of total cost of ownership calculations (Davis & Figliozzi, 2013b, Davis & Figliozzi, 2013a, Lee et al., 2013, Macharis et al., 2007). Other categories may not have that much variation among the existing studies, but certainly is an important methodological consideration. Furthermore, note also that some methods used for the VAM, especially the simple distance based models and activity-based models may not be suitable for some types of evaluations, such as “average service level”, which require more precision in the modelling. The aspects and indicators used by these studies are summarized in the Table 2-6.

Table 2-6 Evaluation aspects and indicators of existing studies

Aspects	Examples of indicators	Studies which used them
Air pollution (e.g. Hydrocarbons, Nitrous Oxides, Carbon Monoxide)	Emissions in kg	(Macharis et al., 2007) (Davis & Figliozzi, 2013b)
Greenhouse gas emissions	CO2 emissions in kg	(Macharis et al., 2007) (Davis & Figliozzi, 2013b) (van Duin et al., 2013)
	CO2 emissions per tonne-km	(Lee et al., 2013)
Energy efficiency	Energy consumption per tonne-km	(Lee et al., 2013)
Financial viability	Lifecycle costs (or total cost of ownership) in \$	(Macharis et al., 2007), (Davis & Figliozzi, 2013a) (Davis & Figliozzi, 2013b) (Feng & Figliozzi, 2013) (van Duin et al., 2013)
	Simple payback period of investment in \$	(Gallo & Tomić, 2013)
Service quality	Delivery success (%)	(Vonolfen et al., 2011)
	Average service level (%)	(van Duin et al., 2013)
Operational efficiency	Vehicle utilization (%)	(Vonolfen et al., 2011)
	Average cost per delivery in \$	(van Duin et al., 2013)

In the evaluation, these indicators may appear in an aggregated or disaggregated form. For example, (Macharis et al., 2007) aggregated the monetary and external social costs of the operations (e.g. greenhouse gas emissions and air quality) in a social cost benefit analysis framework. This aggregation allows one to see a formal “trade-off” between actual monetary costs and monetized social and health impacts. The final form of the indicators (disaggregated, aggregated or partially aggregated) depends on the perspective taken in the evaluation.

### 2.3.5. Decision rule

In this section, how the decision rules are formulated is described. But, as mentioned, not all the studies are explicitly evaluating the suitability of their scenarios. These are reflected in the decision rules applied. Some of the studies do not have any particular decision rule, and have measured the indicators for the sole purpose of exploring the consequences of using electric mobility. These studies do not involve decision making process, but simply report the results of electric mobility employment. Their analysis is relegated merely to conclusions based on undisclosed decision rules. For example, (Vonolfen et al., 2011) showed that an EV-based glass collection using a “small electric truck is possible” in their scenario. Further information about distance utilization and service quality is provided, however these indicators seem to merely provide a picture of the possible consequence of two different strategies of using EVs. Another example is (Davis & Figliozzi, 2013b), who provided the environmental benefits of an EV scenario, without a recommendation on a solution.

The other studies have implemented explicit decision rules to distinguish between a desirable and an undesirable scenario. The decision rules are classified in the following three types:

1. Measured indicators of BEVs and diesel vehicles (DV) are compared to each other, such that the better alternative, either the BEV or the DV is selected. (Macharis et al., 2007, Feng & Figliozzi, 2013, Davis & Figliozzi, 2013a, Lee et al., 2013)
2. Measured indicators of EVs are compared to external requirements, such that the EV is recommended, if the indicators meet the minimum requirements of the stakeholders. (van Duin et al., 2013)
3. Measured indicators of several EV implementations are compared with each other, such that the solution with the best "score" is recommended. (van Duin et al., 2013, Gallo & Tomić, 2013)

The first and third types are common, but the second type was only used once. It was also only used together with the third type, such that the final solution, met the minimum requirement for one indicator "average service level" and had the lowest "average costs per delivery" (van Duin et al., 2013). Indeed, if more than one indicator is used for the evaluation, each indicator could be evaluated using the same type or different types of decision rules, depending on the reasoning behind the selection. With more than one indicator used in the evaluation, how the separate decisions are combined into one decision should be considered.

With this, the main conceptual components, which have been included in previous research attempts, have been described. The next chapter deals with the joining of these components into a systematic framework that underpins the rest of the research.

### 3. Research design

The research design in this study is the set of methodological decisions, based on the adopted conceptual framework, which will be used to examine the claim of the research hypothesis. Again, the hypothesis addressed is:

*“Battery electric vehicles, when used with opportunity charging, are suitable for urban freight transport operations.”*

The chapter on the state-of-the-art discussed the relevant scientific domains and previous research in the field. Those discussions will form the basis of the research design. The key aspects of the research design to be discussed are the choice of the research sample, an overview of information needed, and the methodology overview, which includes the major stages of the methodology.

#### 3.1. Research sample

This section describes where the data, which support the outcomes of the research questions, are found. Hence, it is crucial to decide what are the actual – not just conceptual – objects researched. The study will use case studies of company operations in Singapore. Therefore, a major decision here is what cases should be studied. To inform the decision, the context of and the strategy used to select the case studies are discussed.

##### 3.1.1. Urban freight transport context in Singapore

The immediate object of the study is the UFT in Singapore city. This section will describe the context of UFT activities, which are relevant for understanding both the case studies selected and the overall research design.

Singapore is an island city-state located near the equator in the region of South-East Asia, which has tropical weather throughout the year. In comparison to OECD metropolitan areas<sup>6</sup> globally, it has one of the highest GDP per capita of about US\$71,000 and a population density of about 7,700 persons per square kilometre. Singapore’s strong economy, when measured in terms of its GDP, is predominantly based on its financial and business services, followed by its manufacturing sector (SingStat Info, 26 May. 2017 [accessed 5 August 2017]). About 8% of its GDP in 2016 was due to its transportation and storage industry. Although more detailed information is not available, one could expect that its port and the services supporting it might have been its main drivers. In 2015, the port of Singapore was the second busiest port in the world with over 30 million TEUs processed (World Shipping Council [accessed 5 August

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<sup>6</sup> The OECD provides a useful definition of metropolitan areas, based on their definition of a “functional economic unit”. Instead of considering only municipality (political) boundaries, they include the hinterland as extension of the urban area (OECD (2013)). Although the dataset does not include Hong Kong, it does include most of major urban areas in the developed world.

2017]). It also ranked 5<sup>th</sup> in the international Logistics Performance Index (World Bank [accessed 5 August 2017]).

In terms of transport sustainability, several studies provide a reasonably extensive overview of the status and policies of urban transport in Singapore, such as Chin (1996), Chin (2000), Han (2010), Rahman & Chin (2011) and Lee & Palliyani (2017). Two of the most salient aspects of Singapore's transport policy are the vehicle quota system and the vehicle emissions standards. Singapore implements a vehicle quota system by mandating that vehicle buyers must first have purchased a permit to own the vehicle. This permit is called Certificate of Entitlement (COE) and is sold twice a month during an auction. The COE is valid for a 10-year term, though it can then be extended for another 5 or 10 years. As the government adjusts the number of COEs offered per auction, the total vehicle population is controlled (Han, 2010, p. 317). Lee & Palliyani (2017, p. 123) also summarised Singapore's transport emissions policy. Since 2014, Singapore has adopted the European vehicle emissions standards: Euro 6 for petrol vehicles; Euro 3 for motorcycles and scooters; Euro V for diesel vehicles. Incentives for vehicle owners to upgrade older and more polluting diesel vehicles before the expiry of the COE are also provided in their Early Turnover Scheme. Furthermore, rebates and surcharges are provided to purchasers of vehicles with lower and higher carbon emissions, respectively, under the Carbon Emissions-based Vehicle Scheme. To date, no specific policy has been implemented specifically to incentivise electric vehicles.

Statistics on UFT in Singapore are limited to vehicle population data and highly aggregated mileage data. Singapore's freight vehicles are divided according to weight class (Land Transport Authority, 2016 [accessed 6 August 2017]):

- Light goods vehicle (LGV): not exceeding 3.5 tonnes,
- Heavy goods vehicle (HGV): between 3.5 to 16 tonnes, and
- Very heavy goods vehicle (VHGV): exceeding 16 tonnes.

Data about the number of vehicles, classified according to body type and weight, are obtained from the national vehicle registration data (summarized in Table 3-1). There is no information on the number of freight vehicles that enter from the only strongly-linked economic partner, Malaysia, via the two bridges, nor about their distance travelled in Singapore. According to Table 3-1, the dominant vehicle body type and weight class are the LGV vans, followed by LGV lorries. In 2014, the average annual mileage of all LGVs and HGVs was 30,500 km and 39,000, respectively (Land Transport Authority, 2016 [accessed 7 October 2017]). The mileage of VHGVs is undisclosed. Assuming that the mileage remains constant till 2016, it can be concluded that as a class the LGVs make larger impact in terms of distance travelled, but as individual vehicles HGVs make a larger impact.

Table 3-1 Freight vehicle population according to body type<sup>7</sup> and weight class in year 2016 (data from Land Transport Authority, 2017b [accessed 5 August 2017])

Vehicle weight class	Lorries	Vans	Goods-cum Passengers	Articulated Vehicles	Refrigerated Vehicles
LGV	34,309	59,213	2,978	-	2,091
HGV	17,901	6,926	14	-	2,705
VHGV	2,897	44	-	5,301	57

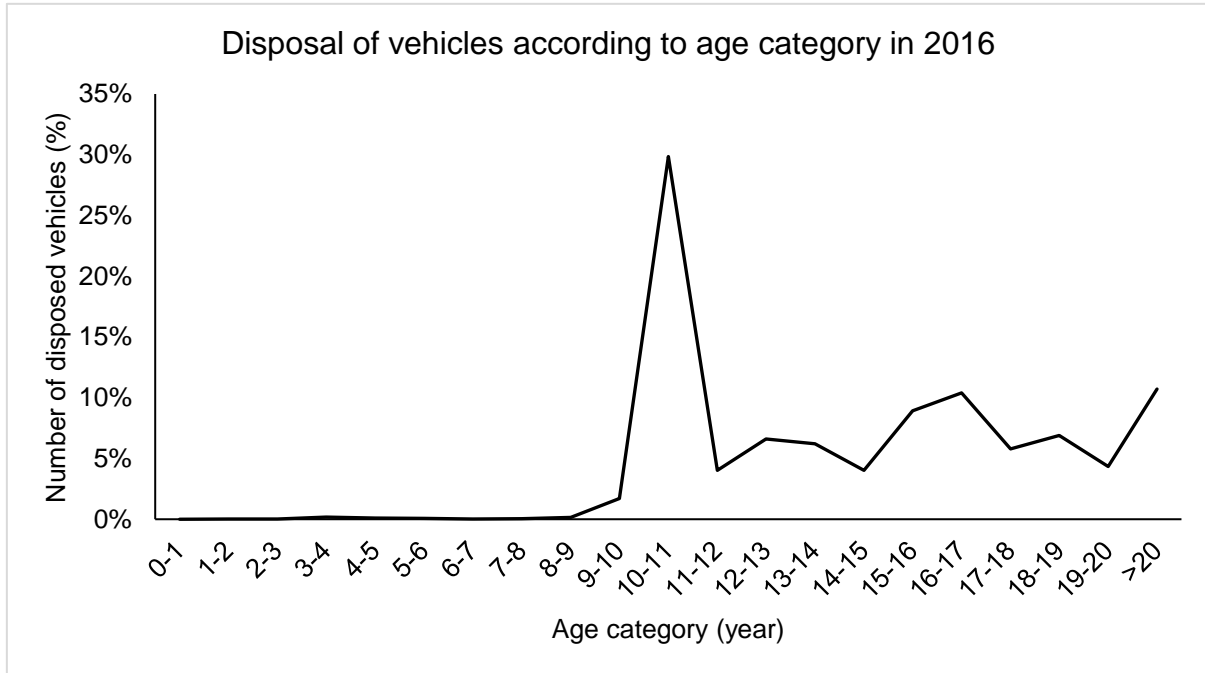


Figure 3-1 Change in freight vehicle population from 2015 to 2016 according to age category (data from Land Transport Authority (2017a))

The influence of the COE's limited term (of 10, 15 or 20 years) also affects the age distribution of the vehicles. Figure 3-1 displays the rate<sup>8</sup> of freight vehicle disposal according to their age category. In general, vehicles can be disposed for any number of reason, such as bankruptcy, severe accidents, or downsizing. Nevertheless, the drastic rate of vehicle disposal after the 10<sup>th</sup> year certainly coincides with the end of the first COE term of 10 years. The highest rate of disposal of about 30% of the total number of vehicles occurs for vehicles aged 10 to 11 years. In comparison, only about 2% of the vehicles aged less than 10 years are disposed of. The disposals per age category is on average 7% for vehicles aged more than 10 years.

Studies on freight transport traffic patterns in Singapore are difficult to find. In fact, only three studies were found, but only one was accessible. The two unaccessible ones by Oslzewski et al. (2001) and Luk et al. (2001) were summarized in a Research Bulletin of the Nanyang Technological University, Singapore (Luk et al., January 2002). Oslzewski et al. (2001) reported the results of a freight transport survey in Singapore, which covered fleet

<sup>7</sup> Vehicle body types that are related to emergency vehicles, construction vehicles, tankers, as well as articulated vehicles were not included in the table.

<sup>8</sup> This was calculated by comparing the vehicle population of each age category in 2016 with the vehicle population of the previous age category in 2015 using data obtained from Land Transport Authority (2017a).

operations, use of information technology, their support for traffic management measures, and other freight issues. Luk et al. (2001) modelled freight traffic in Singapore. One of their most significant findings was the average trip duration of 11 minutes, according to their model.

Fwa et al. (1996) conducted a detailed and city-wide traffic count of trucks at the major routes of truck traffic. They recorded their temporal characteristics, types of truck, lane use, and road class. The study found some of the major traffic generators of that time – the ports, the bridges between Malaysia and Singapore, and the industrial area. Also, it found that peak for truck traffic was less pronounced compared to the peak for cars, and that the distribution of truck usage throughout the day was flatter and more constant. It also confirmed the dominance of trucks on the slow lanes of all road types. However, one limitation of their method was that the counts and truck characteristics were recorded by “sight”. Therefore, it could only account for the size of the truck and the number of axles; estimation of weight class would be difficult. The study data is about 20 years old, which casts doubts on the current validity of the observed traffic patterns.

In conclusion, there are no contemporary studies about Singapore’s UFT, which could help to shed light on traffic patterns, although there is sufficient statistics about the vehicle population. Furthermore, to date there are no studies on the breakdown of travel according to company-specific categories.

### **3.1.2. Case study selection strategy**

For the purpose of the present study, which explores use of a new vehicle system, it would be ideal to base the selection of case studies on data about how the vehicles are currently used. However, too little is known about individual vehicle movement (e.g. based on number of stops, or mileage). Hence, the case study selection needs to depend on other criteria, at least initially.

There are two important aims for the case study selection. First, the case studies should be relevant to evaluate the hypothesis. For this reason, the case studies do not need to create a representative sample, but should be sufficiently diverse. In this regard, diverse refers to the variety of UFT vehicle movement types. In Section 2.1, the case was built that there is a complex relation (based on decisions made by autonomous individuals, e.g. logistics planners and drivers) between the characteristics of the firms involved, their product characteristics, and the vehicle movement. Because of this, aiming for a variety of UFT vehicle movement types in the case study selection is an unachievable goal; it cannot be determined *a priori*, rather it can be reasoned *a posteriori*. Based on this aim, the initial selection criteria will be on the diverse set of qualitative characteristics of the firm and its products. A second selection can be used to select on the actual vehicle movement types.

The second aim for the selection is to isolate causal factors: the attributes that influence the outcome of the hypothesis evaluation. Ideally, the selection of cases then should be on the

“basis of similarities on many attributes but a few potentially very important differences” (6 & Bellamy, 2012, p. 126). The presumption is that the differences in the outcome of the suitability evaluation are *caused* by the differences in characteristics of the UFT.

Table 3-2 List of companies contacted for the study

Company type	Search for the company	Date of primary communication	Response
Fine-dining restaurant	Via personal network	Met: 26th September 2012	Request denied
E-grocery	Website	Met: 3rd October 2014	Request denied
Supermarket chain	Website	Email: 15 <sup>th</sup> April 2015	Request denied
Beverage manufacturer	Website	Email: 30 <sup>th</sup> June 2015	No response
Construction logistics	Website	Email: 30 <sup>th</sup> June 2015	No response
Office supplies	Website	Email: 30 <sup>th</sup> June 2015	No response
Case study C: Fast food chain	Via personal network	Met: 8 <sup>th</sup> September 2015	One case study. Survey form
Spare parts distributor	University site visit on 3 <sup>rd</sup> August 2015	Email: 8th September 2015	Request denied
Supermarket logistics	Website	Phone: 7 <sup>th</sup> October 2015	Request denied
Supermarket chain	Website	Phone: 7 <sup>th</sup> October 2015	Request denied
Supermarket chain	Website	Phone: 7 <sup>th</sup> October 2015	Request denied
Bakery	Website	Met: 20th October 2015	Request denied
Case study E and F: Furniture retailer	Via networking event at Green Freight Asia Forum 2 <sup>nd</sup> November 2015	Met 15 <sup>th</sup> January 2016	Two case studies. Survey form.
Case study D: Ice-cream distributor	Website	Met: 26 <sup>th</sup> January 2016	One case study. Survey form and additional fleet data.
CEP	Website	Email: 29 <sup>th</sup> March 2016 Phone: 4 <sup>th</sup> April 2016.	No response
CEP	Via professional network	Filled in survey form by email.	Some data shared, but could not get data on vehicle fleet.
Case study A: CEP	Via professional network	Met: 11 <sup>th</sup> April 2016	One case study. Survey form and additional data.
Case study B: CEP	Via personal network	Met: 12 <sup>th</sup> April 2016	One case study. Survey form

The main approaches used to solicit participation in the study were via personal or professional networks, networking events, phone, and email. In total 18 companies were contacted, some via several methods. Seven decided to collaborate, but in the end only six case studies were selected. The seventh did not provide adequate data and in addition represented the courier-express-parcel services (CEP) type of logistics, which was sufficiently covered by the other cases. Therefore, the case was not included. For confidentiality reasons, the names of the companies who participated in the study are kept anonymous. The other companies, which were contacted are listed in Table 3-2.

Most of the firms that were approached without having prior contact or referral from someone else did not want to participate in the project, except for the firm from Case D. Professional networking had the best results, particularly because the participants had already “self-selected” for openness to collaboration.

The final list of cases is shown in Table 3-3. The similarities and differences among cases are at this stage sufficiently represented by the industry sector, the type of products, and the tour structure. For instance, cases A and B have the first two characteristics similar, but differ in their tour structure. Cases C and D deal with replenishment of food from a single

depot, but with different refrigeration requirements. Cases E and F feature different types of furniture delivery: home delivery and store replenishment, respectively. The tour structure of case E is one-to-many, whereas the tour structure of case F is full-container-load (FCL).

Table 3-3 Qualitative attributes of case studies

Cases	Industry sector	Product type	Tour structure
Case A	Courier-Express-Parcel	Mail, parcels	1 depot (with many cross-docking locations) to many addresses (delivery & collection)
Case B	Courier-Express-Parcel	Mail, parcels	3 depots to many addresses (delivery & collection)
Case C	Fast food chain	Refrigerated food, beverage	1 depot to many stores (replenishment)
Case D	Ice cream distributor	Frozen ice cream	1 depot to many stores (replenishment)
Case E	Furniture retail chain	Furniture	2 depots to several addresses (home delivery)
Case F	Furniture retail chain	Containerized furniture	1 depot to 2 stores (replenishment)

The types of cases selected fulfil the two selection aims: each case is different, but there are sufficient similarities between some sets of cases, which can be used to highlight causal factors.

### 3.2. Overview of information needed

The research relies on three key types of information. The first is the values of indicators that measure the suitability of the BEV in consideration for each case study. It is presumed that these are not readily available. Hence, other data must be provided for each case in order to calculate these indicators. The bulk of the work in this study is dedicated to calculating these indicators.

The second key type of information is the set of values with which the suitability indicators are compared with. The type of decision rule (see Section 2.3.5 for a description) determines the source of the value to be used. In this study, the value is obtained from stakeholder’s threshold values, which are based on literature review and reasoning. Using these values and the calculated indicator value, the research hypothesis can be evaluated.

The third key type of information is contextual data that enables the cross-comparison between the cases. Table 3-3 already shows some information that may be important for identifying the causal factors of suitability. Besides qualitative descriptors, quantitative descriptions may also be adequate causal factors (when properly interpreted). Some of this information may overlap with the information used to calculate the suitability indicators.

### **3.3. Research design overview**

The research design is composed of three stages. The stages correspond to the information needed for the research. The first two stages are to build up the cases and to evaluate the research hypothesis. The third aims at discovering causal factors of BEV suitability by a comparative-case analysis. The stages are:

1. Scenario-building of each case
2. Suitability evaluation of each case
3. Comparative-case analysis

Stages one and two are also obtained from the methodological framework of similar studies in the past (see Section 2.3). The third stage aims to develop a better understanding of the factors that affect the suitability of BEVs for UFT. The next three sections explain the rationale behind the stages and the key elements of the research methodology.

### **3.4. Scenario-building**

A scenario in the study is defined by the type of vehicle, opportunity charging strategy and charging technology. For each case study, the vehicle activity is kept constant. The number of scenarios created per case study depends on the number of combinations of charging technology and strategies, which are applicable to the case.

There are three major steps in this stage, which are discussed in the subsequent sections. The first is the data collection to obtain “a deep understanding of each case” (Goodrick, 2014, p. 4), in order to obtain the key types of information for the case as described in section 3.2. The second and third steps deal with the three modelling decisions highlighted in section 2.3. Specifically, the second step develops the VAM, which is necessary to define the operational requirements of the vehicle. The third step is the vehicle system parameterization, which calculates the specifications of the vehicles and the charging system of each scenario to accommodate the operation requirements.

#### **3.4.1. Data collection approach**

The data collected is used to develop a realistic VAM and to describe the existing fleet of the company of each case study. The semi-structured interview is chosen as the primary method to collect data based on the following reasons. First, the small number of case studies (only 6) permits to conduct interviews as intensively and in as much depth as necessary (or as constrained by interviewee). Second, the semi-structured approach allows the interviewer to flexibly deal with the data that interviewees prefer to keep confidential by perhaps asking for proxy data, estimates or averages of the data.

Third, the interviewees of the case studies have different roles in their companies, such as transport manager or distribution manager. Thus, the semi-structured approach allows the

interviewees to describe in their words their perception of how the transport operations work in their company. Based on their narrative, the operational decisions of the company can be clarified with more detailed questions with regard to, for example, driver work schedules and time windows. In some cases, the information may not be available, but the experience of the interviewee could be used to circumvent the lack of knowledge of that particular point.

Fourth, as there is a dearth of publicly available information on UFT in the selected case study location, it is difficult to imagine what kind of transport operations a company runs. Each company deals with its unique set of resources and constraints, which is difficult to ascertain from the outside. The flexibility of the semi-structured approach allows the interviewer to therefore change the questions to suit each transport operation type.

In case suitable information is unavailable for a particular case, literature or website information, if available, is used. These instances are indicated in Chapter 5 for each individual case study.

### **3.4.2. Vehicle activity model**

The VAM depicts the movement of the vehicle in time and space, associated with the different activities carried out by the driver in the different locations and the state of the vehicles in those locations. In the absence of vehicle GPS-tracking data, the movement can be simulated. Recall that there are three approaches to model vehicle's movement and activity in existing studies (see Section 2.3.1). In terms of the desired output, which is the schedule of the vehicle with precise vehicle routes and changes of the vehicle weight, the approach using operations research (OR) models is the most appropriate. Generally, OR models aim to optimize the activity of their drivers considering the constraints that can be included in the models. However, optimality can neither be achieved here, nor is it necessarily required. Optimality remains out of reach considering the type of OR model used for the routing of the vehicles, the Vehicle Routing Problem, which is an NP-Hard problem (Jansen, 1993, p. 166), and the large problem size. The reliance on well-established heuristics is the best that one can achieve here. Moreover, it is also not necessary to obtain the globally optimal route for the vehicle for two reasons. First, the simulated route is a simplification of the external environment and the constraints faced by the company and drivers. Second, the global optimum precludes decision making of the drivers and other ad-hoc or unplanned activities. Hence, even reasonable locally optimal results of these normative models should be treated as idealized situation. With regards to the evaluation of methodology, the optimality of the solution will not be considered. Instead, the study defers to the reputation of the software used in the optimization.

Two complementary OR models are used. The first optimizes the routes for the transport operators given the constraints of payload capacity and route duration. The second assigns the routes to individual vehicles in the fleet given the constraints of the total operation

duration, with an objective to balance the workload of each vehicle in terms of operation duration. These are treated as separate and sequential decisions. The assignment of the routes creates a schedule for each vehicle since the routes are carried out sequentially in time. Note that the routes are assigned to the vehicles, not to the drivers. Since a vehicle might be driven by different drivers in a day (in case of multiple work shifts), the activity schedule of the vehicle should be treated separately. Nevertheless, the information about the driver's work schedule is used to construct the vehicle cycle, which is bounded by the start of the work shift of the earliest driver of the vehicle and the end of the work shift of the last driver of the vehicle. In between, the planned breaks and shift changes of the drivers also demarcate the operational activities of the vehicle. The schedule of other activities - driving, loading and unloading - are determined based on the routing and route assignment procedures. How the driver uses the vehicle can be understood from a generic vehicle cycle for deliveries depicted in Figure 3-2.

The first activity for the driver is to drive the vehicle to the loading bay (A1), where the vehicle is loaded with shipments for the current delivery tour (A2). Then, the vehicle is driven to the customer's unloading bay (A3), where it unloads and delivers the relevant shipment (A4) to the customer. This is repeated until there are no more deliveries to be made according to the current itinerary (D2). The tour may also be interrupted, if it is the break time of the driver (D1). If the tour is complete (D2), the driver determines if there is another tour assigned (D3). If there is, the driver returns to the loading bay (A1) and starts the new tour. If it is the end of the driver's shift (D4), the vehicle is either used by another driver for the next shift (A6) or it is driven to the parking lot (A7) and parked (A8).

The VAM, as needed in the study, also models intensity of the activities in the vehicle cycle. For example, the intensity of the driving activities can be characterised by the distance travelled, the type of road driven, the vehicle speed (as a time profile or averaged), and other indicators. Most activities in the vehicle cycle, such as loading or unloading, are primarily conducted by the driver, while the vehicle stands stationary. Hence, in the VAM, the types of activities (conducted by the driver), the sequence of these activities, and the energy-relevant intensity of each activity, are combined.

The verification of the routes and schedules is a difficult task, as is obtaining other data from the interviews. The approach taken is to ask the interviewees their opinions regarding the route maps and the several key descriptive statistics of the routes, such as average distance travelled.

Note that the usual limitations of electric vehicles (such as driving range) are not included as a constraint in this procedure. Instead, it is assumed that the electric mobility system should adapt to operational requirements, and not to adapt the operations to the limitations of the electric mobility system. Hence, for each case study, only one VAM is created, even though several vehicle systems are tested.



Figure 3-2 UML activity diagram of a generic vehicle cycle

### 3.4.3. Vehicle system parameterization

The vehicle system is a sociotechnical system defined as the combination of the type of vehicle, charging system, and charging strategy. This section describes the approach to determine the kind of vehicle system that is needed to fulfil the operational requirements of the VAM. The type of BEV modelled is a mass-produced truck fitted with an electric powertrain. The battery size needs to be calculated to match the energy requirement of the VAM. The procedure to do so follows sections 2.3.2 and 2.3.3 and is devised in two steps. First step considers how the BEV and the charging system interfaces with the VAM. The second step adjusts the electric mobility system to the VAM.

The integration of the BEV model in the VAM occurs at the battery energy level, i.e. the SOC. The use of electrical components for movement or refrigeration reduces the SOC, while

the charging activity increases the SOC. The reduction of the SOC follows the energy consumption rate of the particular vehicle activity. For driving activity, this rate varies according to the weight of the vehicle. For this study, other parameters that affect the energy consumption rate are held constant. This includes regenerative braking. Charging activity increases the SOC based on duration spent charging and the power level of the charging system. Hence, it is important to discuss when and for how long the BEV is charged, under different opportunity charging scenarios.

Diesel vehicles do not need to be adjusted according to the energy requirements, as it is assumed that the fuel tank always provides sufficient energy for the VAM. Nevertheless, for the calculation of the suitability indicators, it is necessary to calculate the fuel consumption, which is the key cause of the negative traffic impacts. The fuel consumption is calculated based on a fuel consumption rate, which varies according to the weight of the vehicle.

To adjust the energy requirement demands to vehicle system, two methods are used: the opportunity charging and the sizing of the battery. The charging scenarios are composed of the decisions (made by the freight carrier) to use opportunity charging and to use conductive or inductive charging systems. The battery is sized for each scenario to ensure that sufficient capacity is available to operate the vehicle for its whole vehicle cycle, while considering the energy consumed in the various activities and the opportunity charging activities. The battery is calculated to be the minimum needed for all the vehicles in the fleet under those considerations.

The interaction between the battery sizing and the scenario is depicted in Figure 3-3. The interactions are either in the same direction denoted by “s”, for example, an increase in vehicle activity will increase the daily energy requirement, or in the opposite direction denoted by “o”, for example, an increase in amount of opportunity charging will decrease the battery capacity.

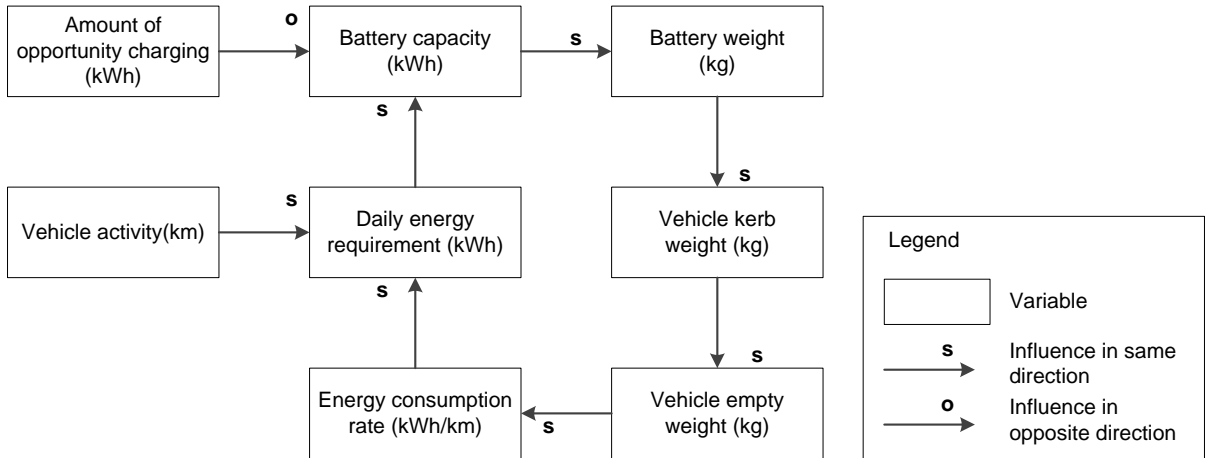


Figure 3-3 Conceptual model for interactions between vehicle activity, charging activity, and vehicle parameters

The two exogenous influences are the vehicle activity and the amount of opportunity charging. The vehicle activity is an outcome of the VAM. Note that the diagram only focuses

on energy required for the vehicle movement, and not for the other equipment. The amount of opportunity charging depends on the time available and the power of the charger.

The energy required is dependent on the energy consumption rate and the intensity of the vehicle activity (such as distance travelled). The energy consumption rate is dynamic and depends on the vehicle weight, which varies after every collection or delivery activity. The factors that influence the energy consumption rate have been discussed in detail in Chapter 2.

The amount of energy required for the task needs to be provided by the energy capacity of the vehicle system, which is roughly equivalent to the battery capacity plus the amount of opportunity charging. This in turn depends on the charging technology and strategy used, as well as its fit with the activity schedule of the vehicle. Note that the effectiveness of the charging technology and strategy affects the needed battery capacity. Hence, a detailed schedule of activities is needed to see how different charging strategies can influence the required battery capacity.

The battery capacity has a direct relation to the weight of the battery. The entire Figure 3-3 shows the “mass compounding effect” for the weight of the other components in the vehicle (Malen & Reddy 2007). For example, due to the additional weight, the chassis needs to be stronger and hence heavier (barring any changes to design or materials). A full loop is made, since the vehicle weight is factored in to energy consumption rate calculation. The minimum battery capacity is considered because (as it has been previously discussed) the battery is one of the most significant cost factors.

In summary, the VAM is developed based on the description of the transport operations by the interviewees for each case study. Then, scenarios characterized by the vehicle type and charging strategy and technology are developed. These scenarios include the parameterization of the vehicle system in terms of vehicle weight, battery capacity (if applicable), energy consumption, and other attributes that define the usage of the vehicle system in the UFT case study.

### **3.5. Suitability evaluation**

The evaluation aims at assessing the suitability of the electric mobility system in each scenario. First, the indicators are calculated to represent each scenario; then, each scenario is evaluated based on the indicators and a predetermined decision rule. Therefore, the key methodological questions are the selection of suitability indicators and the choice of the decision rule.

#### **3.5.1. Selection of suitability indicators**

Suitability indicators are selected considering the requirements of key stakeholders, their relevance when comparing diesel and electric vehicles, and their measurability.

With regard to the requirements of key decision makers and stakeholders, the discussion on transport system requirements in Chapter 2 compiles and discusses the set of relevant indicators (see Table 2-2). The reasons for some of these indicators to be used in the suitability evaluation are added in Table 3-4. Among the reasons are the scale of the impact (individual, local, national, or global), the relevance to both vehicle types (ICEV and BEV), and the related main input variable. With regards to the relevance, it is clear that air pollutants (e.g. nitrogen oxides, volatile organic compounds, particulate matter, sulphur oxides and ozone) are caused by diesel vehicles. Electric vehicles indirectly cause air pollutants, but the effect occurs at the power plant, which is usually located outside urban areas. Therefore, including the indicator would give an unfair or at least obvious advantage to the BEV, which does not produce local air pollutants. If this is set as a requirement, the BEV will definitely meet it. Hence, the requirement will not serve to evaluate the suitability of the BEV.

Table 3-4 Indicator relevance to ICEV and BEVs, in terms of its source and influence

Categories	Indicators	Impact scale	ICEV	BEV	Main input variable
Costs incurred to vehicle driver	Vehicle cost (and charger system)	Individual	Yes	Yes	Fleet size
	Energy/fuel cost	Individual	Yes	Yes	Energy used
	Maintenance cost	Individual	Yes	Yes	Distance travelled
	Taxation	Individual	Yes	Yes	Fleet size
	Subsidies	Individual	Yes	Yes	Fleet size
Air and noise pollution	Nitrogen oxides emissions	Local	Yes	No	Energy used
	Volatile organic compounds emissions	Local	Yes	No	Energy used
	Particulate matter emissions	Local	Yes	No	Energy used
	Sulphur oxides emissions	Local	Yes	No	Energy used
	Ozone concentration	Local	Yes	No	Energy used
	Noise exposure	Local	Yes	Yes	Vehicle speed in sensitive area
Energy security and climate change	Efficiency of energy consumption	National	Yes	Yes	Energy used and power mix
	Efficiency of vehicle fuel consumption	National	Yes	Yes	Energy used
	Use of renewable energy sources	Global	No	Yes	Power mix
	Carbon dioxide emissions	Global	Yes	Yes	Energy used and power mix
	Nitrous oxide emissions	Global	Yes	Yes	Energy used and power mix
	Methane emissions	Global	Yes	Yes	Energy used and power mix

Furthermore, the indicator “noise exposure” will also not be evaluated, although it is an important benefit of BEVs (Kloth et al., 2013, Marbjerg, 2013). The main reason for this dismissal is the difficulty to measure noise exposure using the methods and resources

available in this study. Specifically, the simulation of noise exposure requires that the full traffic context of that local area is included, which is not supported by the used simulation method.

The calculations for the category “costs incurred to vehicle driver” are already conducted using the lifecycle-cost analysis. A discussion of the approach is provided in the chapter on methods. This indicator will be used to represent “financial suitability”.

Finally, it should be avoided that any of the indicators are redundant or overlap. There is overlap among the indicators in the category “energy security and climate change”, because it includes both the reduction of consumption of fossil fuel and use of renewable energy. To resolve this, the dominant of the two types of indicators, which represents the impact of transport on climate change using greenhouse gas emissions (carbon dioxide, nitrous oxide, methane) is kept. This indicator will be used to represent “environmental suitability”.

### **3.5.2. Decision rule**

This section describes the use of indicators to evaluate the suitability of each scenario. There are two sets, and two levels, of decision rules. The first evaluates the individual indicators. The second assesses the scenario considering all the indicators.

As per the definition of suitability, the electric mobility system should meet each requirement placed upon it. Note also that for both groups of suitability indicators, a lower value indicates a better performance.

This leads to the first decision rule concerning each requirement category:

*A scenario is considered suitable, according to this particular requirement, if the value of the indicator is lesser than the threshold value.*

The threshold value is a requirement placed upon the system by the relevant stakeholders. Critical questions are what value it should be and on what basis it should be set. In this research, this will be based on literature or surveys. Otherwise, it should be determined as a political decision.

The definition of suitability implies that the scenario needs to satisfy all requirements. This translates into the following decision rule:

*A scenario is considered suitable, if it is suitable according to all imposed requirements.*

This type of decision rule is also called a conjunctive decision rule (Gilbride & Allenby, 2004); it is non-compensatory, since the failure of one attribute to meet its requirement cannot be *compensated* by an overperformance in another attribute. In contrast, compensatory models, which are very commonly used as decision making frameworks, such as the social cost-benefit analysis, cost-effectiveness analysis, or the multi-criteria analysis, allow for “trade-offs” between the utility (or cost) of the different indicators, such that a “poor” performance in one category can be offset by a “good” performance in another category. Such decision rule is

more appropriate for selecting the optimal approach among several suitable (or acceptable) proposals, which is however not the goal of this research.

### **3.6. Comparative-case analysis**

The principles for the comparative-case analysis (CCA) are described by 6 & Bellamy (2012). The fundamental presumption of CCA is that differences and similarities in outcomes among “relevantly similar cases” imply differences and similarities in causal forces, respectively (6 & Bellamy, 2012, p. 122). Hence, it is the aim that by comparing the case studies in this work, one can identify causal factors of scenarios, where electric mobility is considered suitable for UFT, according to the suitability indicators or the aggregated indicators. Two categories of causal factors are considered: the attributes of UFT and the attributes of the electric mobility system. This harkens to the fundamental axiom behind the design of sociotechnical systems that “organizational objectives are best met not by the optimization of the technical system and the adaptation of a social system to it, but by the joint optimization of the technical and the social aspects” (Cherns, 2016, p. 784).

This study is considered a small-n study, which refers to the few number of cases studies. In contrast, existing studies usually fall into one of two categories: a single-n study or a large-n study. While the single-n study develops a rich-detailed case, it lacks explanatory power beyond the case described. Conversely, the large-n study has a good ability to represent the “whole population”, but it usually describes its sample population with broad strokes (using statistical approaches). CCA sits in the middle, and is able to integrate “intensive data collection and analysis” and “a deep understanding of each case” (Goodrick, 2014, p. 4), but with limited general explanatory power.

The key, however, is the selection of case studies in the sample, which depends on “what we want to know” (6 & Bellamy, 2012, p. 122). Both “what we want to know” and other potential causal factors need to be included in the set of variables in the CCA. The next sections outline the variables of the CCA and the framework for interpreting the results.

#### **3.6.1. Descriptors of the scenarios**

This section describes the variables that characterize the causal factors, i.e., the independent variables. The first category contains the attributes of the case studies, which describe the UFT context and activity. The second category includes attributes of the vehicle system: the type of vehicle, the charging system and the charging strategy.

The case study can be described at two different levels. The first is the qualitative level, which lists the categories of industry sector, product type, and tour structure, which characterizes the transport operations of the company. The second is the quantitative level, where the freight transport demand and fleet movement in time and space is described. The

quantitative data in this study include the transport order data, the VAM, the required payload capacity and the fleet size.

For CCA, qualitative descriptors are usually used to explain differences in outcome. However, the relationship between the qualitative and quantitative descriptors is complex and difficult to specify. It is therefore more useful to treat both types of descriptors as independent in the CCA.

The qualitative vehicle-system descriptors are available from scenario definitions. At the quantitative level, the types of vehicle system are adapted to the quantitative case study descriptors, resulting in quantitative attributes of the vehicle system. These are used as causal factors, although they are not fully independent from the qualitative causal factors. A summary of the scenario descriptors available in the study is given in Table 3-5.

Table 3-5 Case study and vehicle system descriptors of scenarios

<b>Case study descriptors</b>	<b>Vehicle system descriptors</b>
<b>Qualitative level</b>	<b>Qualitative level</b>
Industry sector	Vehicle type
Product type	Charging technology
Tour structure	Charging strategy
<b>Quantitative level</b>	<b>Quantitative level</b>
Transport order data	Battery capacity
Vehicle activity model	Vehicle weight
Required payload capacity	Opportunity charging power
Fleet size	Overnight charging power

**3.6.2. Interpretation of results**

The results are interpreted using the scenario descriptors and the suitability indicators. The scheme in Table 3-6 shows four situations (I-IV) that combinations of the case studies might exhibit. The case combinations should be selected such that situations I and IV are to be avoided. In other words, for the case combinations, either the dependent or independent variables must be different, but not both. As a minimum, there should be two cases in each combination. Several combinations are used in order to look at different aspects or causal factors.

Situations II and III are useful. Situation II points to different sets of factors that lead to same outcome (either suitable or unsuitable). However, the majority of the combinations belong to situation III. Situation III refers to a control of some (but not all) independent variables, which leads to different outcomes. Hence, the variables that are not controlled cause the different outcomes.

Table 3-6 Scheme for comparison (Adapted from 6 & Bellamy, 2012, p. 131)

<b>Comparison cases exhibiting:</b>	<b>Same values on scenario descriptors</b>	<b>Different values on scenario descriptors</b>
<b>Same values on the suitability indicators</b>	I: Sample may lack sufficient diversity to test for causal relationship	II: May be sufficient to examine a hypothesis about equifinality
<b>Different values on the suitability indicators</b>	III: May be sufficient to examine a hypothesis about divergent or branching causation	IV: Sample may exhibit too much diversity to enable control

In the final analysis, the results are interpreted discursively. In other words, statistical methods are not used due to the small sample size. The sets of case studies selected for comparison depend primarily on the descriptors.

### **3.7. Chapter summary**

This chapter has described and argued about the main methodological decisions in this work. The study uses six cases of UFT from Singapore. The study proceeds with a description of cases, a forecast of potential electrification transport, a scenario-based suitability evaluation, and a cross-comparison of cases to isolate suitability factors. The next chapter describes the methods used in each step of the research design.

# 4. Methods

In the previous chapter, the overall methodology, which includes the major stages of the research design and the rationale for its organization is described. Nevertheless, a lot of the details have been left out, for the sake of clarity in giving the overall picture. In this section, the methods are described in more detail, and at this level the rationale for including the specific methods are provided.

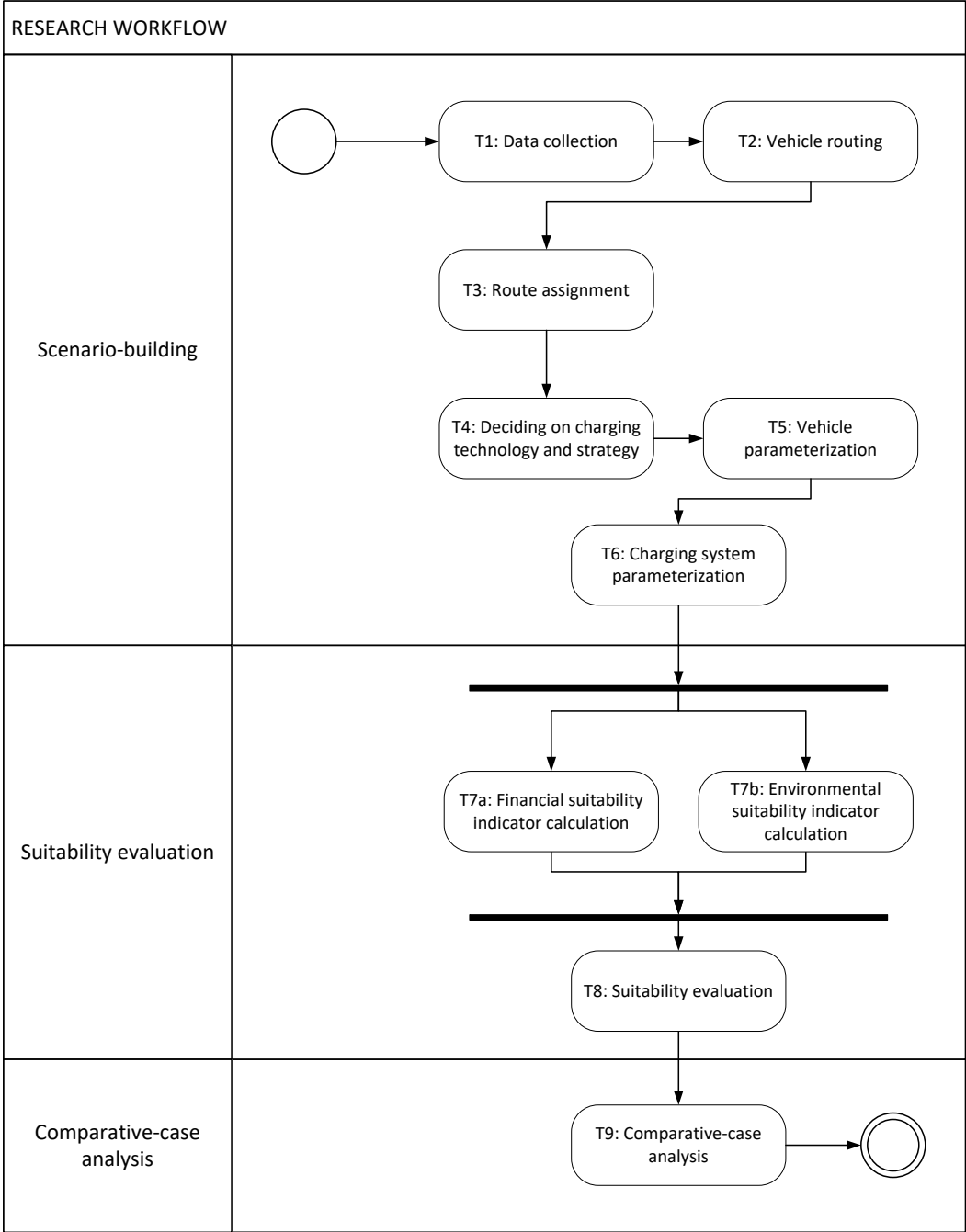


Figure 4-1 Research workflow

The main steps in the research workflow are presented in Figure 4-1. The three stages are “scenario-building”, “suitability evaluation”, and “comparative-case analysis”. To make the chapter more readable, most of the section headings follow the titles used in the diagram.

However, in some cases the larger sub-tasks are made into individual sections. The “4.2 Synthesis of shipment orders” is a pre-processing step for “Vehicle routing”. The “Energy consumption model” is general calculation module for various other steps. The “Vehicle parameterization” step (see Figure 4-1) is composed of “Battery sizing and “Electric motor sizing”.

#### **4.1. Data collection**

The data collection step is specifically for providing enough case-specific information to build the UFT operation scenarios. There are two main sources of information: the semi-structured interview and secondary sources, such as websites or research literature. While it is necessary to detail the exact steps taken, it is more prudent (and clearer) if the description of the data collection methods is provided with the next step in the research design, namely the “synthesis of shipment orders”. This is because though there is a common logic behind the steps, there are several necessarily ad-hoc steps, which are taken to accommodate the data available or lack thereof.

The semi-structured interview was used to gather primary information from the companies of interest. The outline is provided in Appendix A. While the aim was to gather enough data such that a representative VAM can be built, it is acknowledged that attempts to elicit confidential information from companies would be challenging. In other words, companies may not be so willing or capable to provide the data that are desired.

The interviewee is asked to give a general description of what their business activity is, especially in terms of what is being transported and for what purpose. This is an attempt to describe the qualitative attributes of the UFT activity.

Ideally, the information provided should include all the shipment orders of one day categorized according to each vehicle in the fleet. Each order would include shipment volume, location of origin and destination, time window, and the vehicle identity. Additionally, the vehicle payload capacity, fleet size and activity schedule information are needed, which are the overall planning activities for the company. With this level of information, the route and schedule of each vehicle in the fleet can be simulated quite precisely.

However, in the absence of these data, the semi-structured interview approach is flexible enough to circumvent the lack of data, by asking for statistical values or rough approximations. It is assumed that the approximations by someone intimately tied to the operations of the company would serve as a credible source of information. The vehicle model used are also found out, which can then be combined with secondary sources to find out about payload capacity. The company’s website also provides some information, especially on the locations of origin and destination of some of the cases. The information needed for research design is summarised in Table 4-1.

Table 4-1 Information needed for research design

Ideal information (Interview)	Proxy information (Interview)	Supplementary data
Shipment weight (Order specific)	Average shipment weight (Destination type specific)	Product density
Location of origin	Geographical region; Type of building	Addresses according to website, public map
Location of destinations	Distribution of stops according to region, area; Service area definition	Addresses according to website, public map
Time windows	General activity schedule	-
Vehicle payload capacity	Vehicle model	Specifications according to vehicle model on manufacturer's website or vehicle registration office
Fleet size	-	-
Activity schedule	-	-

## 4.2. Synthesis of shipment orders

The inputs used to simulate the vehicle activity (both route and schedule) are either taken-as-is or synthesized using multiple sources of information. Essentially, it involves creating a list of shipment orders, which in the ideal case, could be obtained from the interviewee. However, since that is a rare case, it would require at least two steps, besides data collection, to create a synthetic list of shipment orders. The first is to create a “customer” list with location information. The second is to assign each “customer” with a shipment order size. In the absence of specific time window data, it is simply assumed that the orders are not time sensitive on the delivery side. The alternative, in the absence of data, is to arbitrarily assign time window restrictions to each customer. However, it was deemed that this would not increase the value of the current study.

### 4.2.1. Destination list synthesis

If precise locations of the destinations are not known, then the addresses within a given pre-defined area are “randomly” selected using a GIS programme, QGIS. The programme allows a chosen number of addresses to be randomly selected using a spatial query function. In other words, one can randomly select the probable number of customers (for a single day) within any one pre-defined area, such as a planning region or postal code area. The numbers of customers are chosen, such that the number of customers in the destinations list always “exceeds” the capacity of the vehicle to serve the area. Hence, within the routing procedure, there is always an excess number of customers that cannot be served by the vehicle either due to payload restrictions or route duration restrictions. This is an attempt to ensure that the vehicle is “maximally utilized”.

#### **4.2.2. Shipment size assignment**

With the list of customers, the amount of shipment is then attributed randomly to each customer using MS Excel. This of course depends on the types of customers in the list, such that large customers are given larger shipments. For this to be done, the proportion of the customers with the different shipment sizes need to be known, which can be inferred from the interviews or assumed explicitly. The details are provided when each individual case study is discussed. With both steps completed, the missing data of daily shipment orders have been filled.

#### **4.3. Vehicle routing**

The single depot capacitated vehicle routing problem (CVRP) is chosen as the underlying model to describe the movements of the vehicles in the fleet to deliver to (or collect from) each customer according to the shipment orders. If there are multiple depots, the procedure is repeated for each depot. The solver used is a commercial software XCargo (LOCOM, 2016 [accessed 8 April 2016]), which uses proprietary algorithms to produce the solutions. Though the exact algorithms or heuristics used in the software are not made public, the general problem model for solving the CVRP is described in the following.

In general, the procedure of VRPs is to design the “pick-up or delivery routes from one or more central depots to a set of geographically scattered customers” (Crainic & Laporte, 1997, p. 425) at the least total cost. For each route, the distance between each stop is known. Assuming a speed profile allows one to also calculate the driving duration between any two stops. The routes provide a detailed space-time model how each vehicle is moving in the road network to satisfy the transport demand. This can be supplemented by providing also the stop time at each stop used for different activities.

The term “capacitated” in CVRP refers to the payload capacity of the vehicle in carrying the shipments. In addition to the payload capacity, XCargo also allows constraints on the route distance and duration, and the number of routes. The payload capacity is a necessary constraint in XCargo. If the number of routes is unconstrained, the solver will find the minimum number of routes needed to fulfil all shipment orders. Besides that, to maintain compliance with the activity schedule, the route duration can be constrained to match the typical route duration for each case.

While the actual algorithm used in XCargo will not be presented, VRP models are commonly solved using heuristics, such as the savings method and the sweep heuristic (Crainic & Laporte, 1997, p. 426). The CVRP model can be formulated in many ways, as seen in Laporte (1992). One of the formulations is presented and explained below. The format is as follows: the objective function is presented in (4.1) and the constraints are provided in (4.2) - (4.5).

$$\text{Minimize} \quad \sum_{i \neq j} c_{ij} x_{ij}, \quad (4.1)$$

$$\text{subject to,} \quad \sum_{j=0}^n x_{ij} = 1 \quad (i = 1, \dots, n), \quad (4.2)$$

$$\sum_{i=0}^n x_{ij} = 1 \quad (j = 1, \dots, n), \quad (4.3)$$

$$\sum_{i,j \in \mathbb{S}} x_{ij} \leq |\mathbb{S}| - v(\mathbb{S}) \quad \left( \mathbb{S} \subset V \setminus \{0\}; |\mathbb{S}| \geq 2; v(\mathbb{S}) = \left\lceil \frac{\sum_{i \in \mathbb{S}} d_i}{D} \right\rceil \right), \quad (4.4)$$

$$x_{ij} \in \{0,1\} \quad (i, j = 0, 1, \dots, n; i \neq j) \quad (4.5)$$

$i, j$  are nodes of departure and arrival, respectively.

$x_{ij}$  describes whether edge  $i$  to  $j$  is used.

$c_{ij}$  is the cost for using the edge  $i$  to  $j$ .

$\mathbb{S}$  is a set of vertices in a subtour.

$V$  is the set of all vertices.

$v(\mathbb{S})$  is the minimum number of routes necessary to serve the demand  $d_i$ .

$d_i$  is the amount of demand to be delivered to node  $i$ .

$D$  is the capacity of the vehicle.

The network, which connects depot and customers, is defined with vertices  $V$  and edges  $E$ . The depot is at vertex 0, and customers are located on vertices 1 to  $n$ .  $x_{ij}$  is a binary variable (see (4.5)) and is equal to 1, if  $e_{ij}$  (edge from  $i$  to  $j$ ) is part of the final solution. Hence, the cost  $c_{ij}$  associated with that particular arc is incurred. The optimal solution is that which minimizes the total cost, as shown in (4.1). Constraints (4.2) and (4.3), respectively, limit each customer to be departed from and to be visited exactly once. Constraint (4.4) is a “subtour elimination constraint”, which ensures that all routes satisfy the payload capacity restrictions and that “no subtour [is] disconnected from the depot” (Laporte, 1992, p. 347).  $\mathbb{S}$  represents the set of vertices in the subtour and  $v(\mathbb{S})$  is defined as the minimum number of routes necessary to serve the demand  $d_i$ . The payload capacity of the vehicle is represented with  $D$ .

Finally, the outcome of the routing procedure is a set of routes, which are then to be assigned the vehicles in the fleet. The duration of travel between each stop in the route solution set can be calculated assuming the speed of the vehicle in each edge or leg. XCargo also provides a function for that.

#### 4.4. Route assignment

The aim of the route assignment procedure is to equally distribute the routes created in the previous step to vehicles in the fleet. If each vehicle is only to drive on one route in a day, this step is skipped. There are two main constraints included in this procedure. The first

is the fleet size and the second is the available daily operating time of the vehicle. They are interdependent; if one is fixed, the other is allowed to vary. The procedure presented in this section holds the available operating time of the vehicle to be fixed, hence the fleet size will vary.

In the routing procedure, the routes can be organized in the following way. Each route  $j^9$  is composed of a series of route legs  $i$ , such that the duration of the route is the sum of the duration of a route legs (4.6)). The activities of loading and unloading are modelled as one of the activities performed in each route leg. Thus, the duration of each route leg  $i$  is the sum of the duration of the driving activity in leg  $i$ , and the duration of loading and unloading (4.7). Note that  $D_i^{Load}$  is non-zero only if in leg  $i$ , the vehicle departs from depot to the first stop in the route. Conversely,  $D_i^{Unload}$  is zero only when in leg  $i$ , the vehicle returns to the depot from the last customer stop in the route. The total operational time for the fleet  $D_{fleet}$  is the sum of the duration of each route, as in (4.8).

$$D_j^{route} = \sum_{i \in \mathbb{I}_j} D_i^{leg} \quad (4.6)$$

$$D_i^{leg} = D_i^{Driving} + D_i^{Load} + D_i^{Unload} \quad (4.7)$$

$$D^{Fleet} = \sum_{j \in \mathbb{J}} D_j^{route} \quad (4.8)$$

$i, j$  are indices for route leg, and route, respectively.

$\mathbb{I}_j$  is the set of route legs for route  $j$ .

$\mathbb{J}$  is the full set of routes considered in the case.

$D_i^{leg}, D_j^{route}$  are the duration of route leg  $i$  and route  $j$ , respectively.

$D_i^{Driving}, D_i^{Load}, D_i^{Unload}$  are the duration of driving, loading, and unloading activity in leg  $i$ , respectively.

$D^{Fleet}$  is the total duration of all routes in the fleet.

Each route  $j$  and each vehicle  $k$  is an element in the set of all routes  $\mathbb{J}$  and in the set of all vehicles  $\mathbb{K}$ , respectively. The set of routes, which are assigned to vehicle  $k$  is set  $\mathbb{J}_k$ . The initial size of  $\mathbb{K}$  is first estimated using (4.9), which divides the total route duration by the daily available operating time of the vehicle,  $D^{Available}$ . Note that  $D^{Available}$  differs from the work duration of the driver in the case of multiple driver shifts per day. Each vehicle in a case is assigned the same available operating time.

$$K = |\mathbb{K}| = \left\lceil \frac{D^{Fleet}}{D^{Available}} \right\rceil \quad (4.9)$$

$\mathbb{K}$  is the initial set of all vehicles in the fleet.

$K$  is the initially estimated number of vehicles in the fleet.

$D^{Available}$  is the total time each day the vehicle is available to be used.

<sup>9</sup> Note that the indices  $i$  and  $j$  here have a different meaning than in the previous section.

The procedure aims to equally distribute the total operation time to each vehicle. To do this, each route  $j$  is ranked according to its duration in descending order (i.e. the longest duration route is given the rank 1). In the initial assignment, each of the longest  $K$  routes are assigned to each vehicle in set  $\mathbb{K}$ . The operational time of vehicle  $k$ ,  $D_k^{vehicle}$  is defined by (4.10), which is the sum of the route duration of routes assigned to vehicle  $k$ .

$$D_k^{vehicle} = \sum_{j \in \mathbb{J}_k} D_j^{route} \quad (4.10)$$

$j, k$  are the indices of routes and vehicles, respectively.

$\mathbb{J}_k$  is the set of routes assigned to vehicle  $k$ .

$D_j^{route}$  and  $D_k^{vehicle}$  are the duration of route  $j$  and routes assigned to vehicle  $k$ , respectively.

Next, the vehicle with the *shortest* operational time and the next *longest* unassigned route are identified with (4.11) and (4.12), respectively. The intention is to add the longest remaining route to the route set with the currently shortest operational duration.

$$k_{short} = \{k_{short} \in \mathbb{K} : D_{k_{short}}^{vehicle} = \min_{k \in \mathbb{K}} D_k^{vehicle}\} \quad (4.11)$$

$$j_{next} = \{j_{next} \in \mathbb{J} : D_{j_{next}}^{route} = \max_{j \in \mathbb{J} - \mathbb{J}_{k,k} \cup \mathbb{K}} D_j^{route}\} \quad (4.12)$$

$j, k$  are the indices of routes and vehicles, respectively.

$j_{next}$  is the next longest duration route in set  $\mathbb{J}$ , yet to be assigned to a vehicle.

$k_{short}$  is the vehicle with the shortest total duration of routes assigned to it.

$D_j^{route}$  and  $D_k^{vehicle}$  are the duration of route  $j$  and vehicle  $k$ , respectively.

$\mathbb{J}$  is the set of routes in the fleet.

$\mathbb{J}_k$  is the set of routes assigned to vehicle  $k$ .

$\mathbb{K}$  is the set of vehicles in the fleet.

This route  $j_{next}$  is added to the route set of vehicle  $k_{short}$ , if the available operational time of the vehicle is not exceeded. The check uses the condition in (4.13), which constrains the operational time of each vehicle according to the available operational time of the vehicle. If it exceeds  $D_{available}$ , a vehicle is added to set  $\mathbb{K}$  and the route  $j_{next}$  is added to the route set of the new vehicle (see (4.14)). Otherwise, the route  $j_{next}$  is added to the route set of the identified vehicle  $k_{short}$  as in (4.15).

$$\text{If } D_{k_{short}}^{vehicle} + D_{j_{next}}^{route} > D_{Available} \quad (4.13)$$

$$\text{Then } \mathbb{K} = \mathbb{K} \cup \{|\mathbb{K}| + 1\} \quad (4.14)$$

$$\text{Else } \mathbb{J}_{k_{short}} = \{j_{next}\} \cup \mathbb{J}_{k_{short}} \quad (4.15)$$

$D_{k_{short}}^{vehicle}$ ,  $D_{j_{next}}^{route}$  are the duration for vehicle  $k_{short}$  and route  $j_{next}$ , respectively.

$\mathbb{K}$  is the set of vehicles.

$\mathbb{J}_{|\mathbb{K}|}$  is the set of routes for the last vehicle in set  $\mathbb{K}$ .

$j_{next}$  is the longest unassigned route in  $\mathbb{J}$ .

$\mathbb{J}_{k_{short}}$  is the set of routes assigned to vehicle  $k_{short}$ .

The procedure using (4.10) - (4.15) is repeated until all routes in  $\mathbb{J}$  have been assigned (see (4.16)).

Terminating condition: 
$$\mathbb{J} - \bigcup_k \mathbb{J}_k = \emptyset \quad (4.16)$$

$\mathbb{J}$  is the set of all routes to be assigned to the vehicles in the case.  
 $\mathbb{J}_k$  is the set of all routes assigned to vehicle  $k$ .

The outcome of the procedure is the minimum size of the fleet needed to undertake the transport task and the set of routes assigned to each vehicle. Additionally, since each route has a defined duration, distance and load of the vehicle, a full description of the vehicle activity has been modelled.

## 4.5. Deciding on charging technology and strategy

The battery capacity of the BEV must be configured such that there is sufficient energy capacity in the vehicle system to completely fulfil the operational requirements. Before the battery capacity is calculated, the type of charging technology and strategies to be used for each scenario are first discussed. This relation is illustrated in Figure 3-3 in the effect of the “Amount of opportunity charging (kWh)” to “Battery capacity (kWh).”

The charging technology, which will be considered are conductive and inductive charging systems for parked vehicles (i.e. static charging) and inductive charging for moving or en route vehicles (i.e. dynamic charging). The power level will be initially set to 100 kW, which is considered fast charging. This will be adjusted upwards, if necessary.

Opportunities for charging can be identified by looking the activities, and downtime of the vehicle. A generic model for the activities driver during operation of the vehicle is shown in Figure 3-2. For each case, the type of activities, where opportunity charging can take place, needs to be determined.

For static charging, the three main times, when opportunity charging could take place is during the loading and the unloading of the vehicle, and when there is a break or shift change. During these times, the vehicle is essential stationary at the loading and unloading bays, at a break area or the depot and may be charged. For this study, three static opportunity charging strategies were defined. Both conductive and inductive charging systems are used.

The first is while the driver is having a break during lunch time or during a driver shift change. The strategy to charge during either of these times is termed break time charging. Naturally, not every case will have a shift change, but most would have at least a short break during the day. The actual period can be determined via interview. The location for charging can be anywhere, such as at the depot or along the way, and depends on the driver behaviour. The exact location is assumed to be unimportant in this study.

The next reason for a vehicle being stationary is while it is being loaded with goods at the depot (or origin location). The third reason is while the goods are being unloaded from the vehicle. The strategy to charge during both times is loading time charging and unloading time charging, respectively. Both strategies can be very effective, especially for vehicles that make many delivery or collection stops.

For dynamic charging, it was assumed that the charging only occurs on the highway or expressway in the city. The decision was taken for two reasons. The first is that existing research and government interest has been towards implementing highway charging above any other forms of dynamic charging. This makes it a more likely candidate for such a possible future scheme and is therefore more relevant. The second reason, which may be related to the first reason, is that the traffic volume on highways is significantly larger than on other road types, which then helps to justify the investment. Nevertheless, it is an acknowledged limitation of the study that other types of dynamic charging locations are excluded. Furthermore, as to the transfer technology, only the inductive method is used, since as discussed in Section 2.2.3, it is the only type to show cross-compatibility for vehicles of different sizes, and thus more probable that it may be added into the future planning scenario of a city. The various charging scenarios are summarised in Table 4-2 and each given a scenario ID.

Table 4-2 Scenarios investigated in the study composed of vehicle type, charging strategy and charging technology

Scenario ID	Scenario	Vehicle type	Charging strategy	Charging Technology
S0	Diesel vehicle	DV	-	-
S1	Overnight conductive charging	BEV	Overnight not opportunity charging	Conductive
S2	Overnight inductive charging			Inductive
S3	Break time conductive charging		During break and shift change	Conductive
S4	Break time inductive charging			Inductive
S5	Loading time conductive charging		During loading of vehicle	Conductive
S6	Loading time inductive charging			Inductive
S7	Unloading time conductive charging		During unloading of vehicle	Conductive
S8	Unloading time inductive charging			Inductive
S9	Highway inductive charging			Driving on highway

**4.6. Energy consumption model**

There are three parts to the energy consumption model. The first is dependent on the distance travelled which represents the energy needed to move the vehicle as well as “comfort” accessories, such as air conditioning and the radio. This is termed the driving energy consumption (DEC). The next is dependent on the duration of the operation, either while moving or stationary, and is the energy needed to power refrigeration (if applicable). This is termed refrigeration energy consumption (REC). The third is the idle energy consumption (IEC) which occurs while the vehicle is parked, but the engine is switched on “idling”. These three are described in later sections.

The DEC rate varies according to the payload, and thus should be calculated for each leg  $i$  in the route. The overall calculation of energy consumption for each leg  $E_i^{leg}$  is shown in (4.17). The respective rate of DEC, REC, and IEC, are multiplied by the relevant leg attributes developed in the VAM, such as the length and duration of the leg, and the duration of stationary activities. The energy used during the break times are calculated according to (4.18).

$$E_i^{leg} = ER_i^{DEC} * l_i^{leg} + ER^{REC} * D_i^{leg} + ER^{IEC} * (D_i^{Load} + D_i^{Unload}) \quad (4.17)$$

$$E_q^{break} = (ER^{REC} + ER^{IEC}) * D_q^{break} \quad (4.18)$$

$i, q$  are the indices for route leg and break session, respectively.

$l_i^{leg}$  is the length in km. of route leg  $i$ .

$D_i^{leg}, D_i^{Load}, D_i^{Unload}$  are the duration of route leg  $i$ , the loading and unloading activity, respectively.

$E_i^{leg}$  is the total energy consumed by the vehicle for route leg  $i$ .

$ER_i^{DEC}$  is the energy consumption rate for vehicle during driving in route leg  $i$ .

$ER^{REC}$  is the energy consumption rate for refrigeration.

$ER^{IEC}$  is the energy consumption rate for vehicle while idle.

$D_q^{break}$  is the duration of break session  $q$ .

$E_q^{break}$  is the energy consumed during the break session  $q$ .

Before presenting the method to estimate the rate of DEC, REC and IEC, an estimation model for the kerb weight of a synthetic vehicle fleet is presented.

#### 4.6.1. Regression model for weight dimensions for the vehicle

The existing BEV market is very limited. In this section, a method to estimate the parameters of a realistic BEV is developed. The first step is to develop a kerb weight estimation model, because it serves as an input for the energy consumption rate model described in the next section. Vehicle dimensions follow general design principles but can vary depending on customer preferences and vehicle technology.

The basis of the estimation model is a database of GVW, kerb weight, vehicle frontal area, wheelbase and engine power of 80 conventional vehicles, as presented in manufacturer's specification sheets. Table 4-3 shows the variety of vehicle makes and models used. Many of the vehicles can be considered "variants" of the same model, which will contribute to differences among vehicle dimensions, such as kerb weight and length.

Table 4-3 Range of vehicles used in the database

GVW range (kg)	No. of vehicles	Manufacturers
2,000-2,999	3	Hiace, Nissan
3,000-3,999	24	Nissan, Mitsubishi, Hiace, Isuzu
4,000-4,999	6	Nissan
5,000-5,999	1	Isuzu
6,000-6,999	4	Mitsubishi, Isuzu
7,000-7,999	18	Mitsubishi, Isuzu, MAN
8,000-8,999	5	Mitsubishi
10,000-10,999	6	MAN
11,000-12,000	13	Isuzu, MAN

A model for estimating kerb weight based on the GVW of a vehicle is based on a regression analysis of the averaged values of kerb weight and GVW of the vehicles in the database. The values of 7 vehicles first need to be adjusted because they were of the van body type. The other vehicle models were dropside (only 1 out of 23) and chassis-cab types.

The weight of just the van body could be estimated for two variants of two vehicle models. The variants had both the chassis-cab type and the van type of body. Subtracting the kerb weight of both variants of each vehicle model provides an estimate of just the weight of the van body,  $W_{VB}$ . A ratio  $r_{KW/VW}$  of the differences between the weight of the van body  $\Delta W_{VB}$  to the kerb weight  $\Delta W_{KW,VAN}$  was calculated for the two sets of vehicles using (4.19). The ratio  $r_{KW/VW}$  was found to be 0.188. Then, the kerb weight of the other van type vehicles was calculated using (4.20) and the new values were substituted in the database.

$$r_{KW/VW} = \frac{\Delta W_{VB}}{\Delta W_{KW,VAN}} = \text{---} \quad (4.19)$$

$$W_{KW} = (1 - r_{KW/VW}) * W_{KW,VAN} \quad (4.20)$$

$r_{KW/VW}$  is the ratio of the weight of the van body over the kerb weight.

$\Delta W_{VB}$  is the difference between the weights of the van body for the two vehicle models.

$\Delta W_{KW,VAN}$  is the difference between the kerb weights of the van variants for the two vehicle models.

$W_{KW,VAN}$  is the kerb weight of the van variant.

$W_{KW}$  is the estimated kerb weight of the van without the van body.

The values are plotted in Figure 4-2.

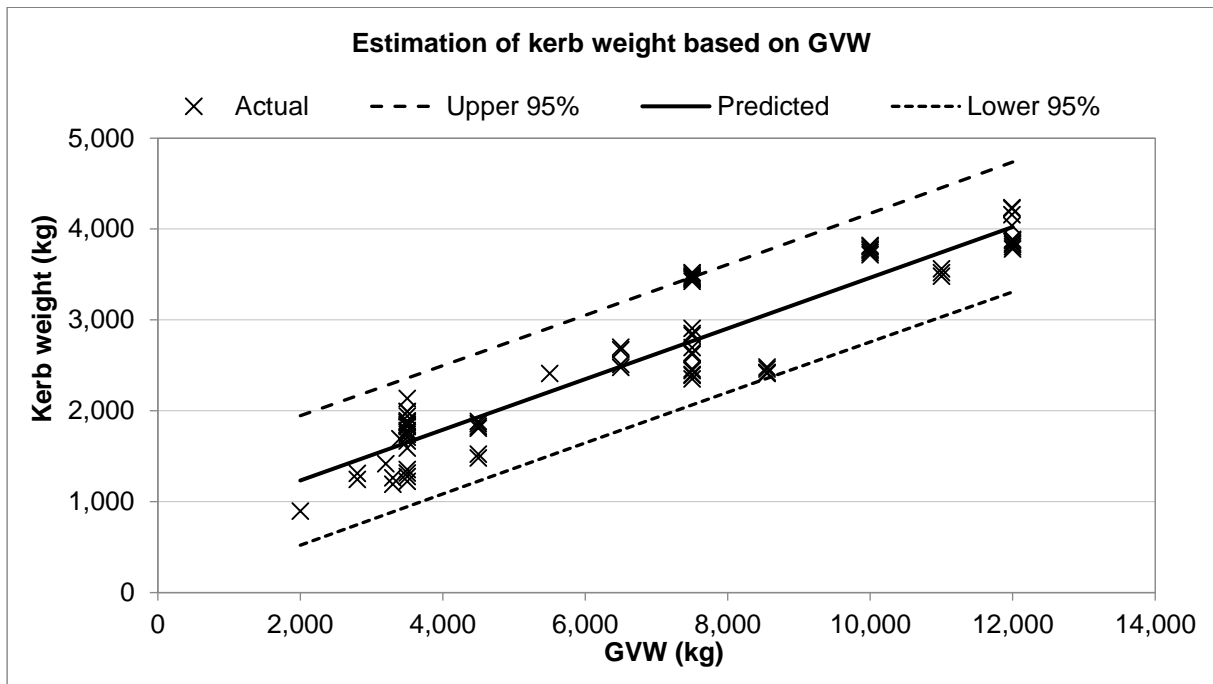


Figure 4-2 Estimation model for kerb weight based on vehicle model database with 95% confidence interval

A linear regression model was calculated based on the final set of values yielding (4.21) and the regression values in

Table 4.4.

$$W^{kerb} = a^W * W^{gvw} + b^W \quad (4.21)$$

$W^{kerb}$  is the estimated kerb weight of the vehicle.

$W^{gvw}$  is the GVW of the vehicle.

$a^W, b^W$  are the regression coefficients.

Table 4.4 Kerb weight estimation model summary

Regression statistics	R-squared	0.861
	Standard Error of Regression [kg]	351
	Sample size	80
Coefficient estimates (P-values)	$a^W$ [-]	0.279 (0.000)
	$b^W$ [kg]	676 (0.000)

The model sufficiently fits the data, with an R-squared value of 0.861 and a relatively low standard error of regression of 351 kg. The coefficients chosen are significant with p-values less than 0.001. Also, the model matches the expectation that with a higher GVW, the kerb weight also increases. But, the model does not account for other physical dimensions of the chassis, such as the width or length, which may vary even if the GVW remains the same for market or regulatory reasons.

#### 4.6.2. Driving energy consumption

By design, for a given vehicle (defined by a fixed GVW, kerb weight and payload capacity), the DEC rate only changes in response to the payload weight. Hence, an increase

in the payload weight, increases the DEC rate, and vice versa. The first step is to calculate the DEC rate for the vehicles collected in the database, assuming both powertrain vehicle types are used, namely electric vehicles and diesel vehicles. Based on this, a regression model is used to create an empirical model for DEC rate with weight as the dependent variable.

In general, the calculation of DEC rate of a vehicle model is based on the calculation of energy consumption of the vehicle model over a fixed driving speed profile using FASTSIM (NREL, 2014 [accessed 13 April 2016]). FASTSIM is an excel-based simulation tool that incorporates factors such as “speed vs time simulation, powertrain components, regenerative braking, energy management strategies” in its energy consumption model (NREL, 2014 [accessed 13 April 2016]). The weight, vehicle frontal area, wheelbase, and the engine power are taken from the vehicle database and set as inputs in the model. However, instead of using the kerb weight of the original vehicle specifications in the vehicle database, the kerb weight is calculated for each of the vehicles using the regression model (4.21). Using this reduces the number of variables in the final form of the DEC model.

In this study, the Heavy Duty Urban Dynamometer Driving Schedule (HDUDDS) was used as a driving speed profile. Ideally, a speed profile created in Singapore for urban goods vehicles should be used, however research in this field is currently non-existent in Singapore. Also, often the energy consumption or carbon dioxide emissions are calculated using the NEDC speed profile. However, the NEDC is an idealized speed profile and is inappropriate for estimating real-world vehicle usage. Figure 4-3 shows how the HDUDDS and NEDC speed profiles differ.

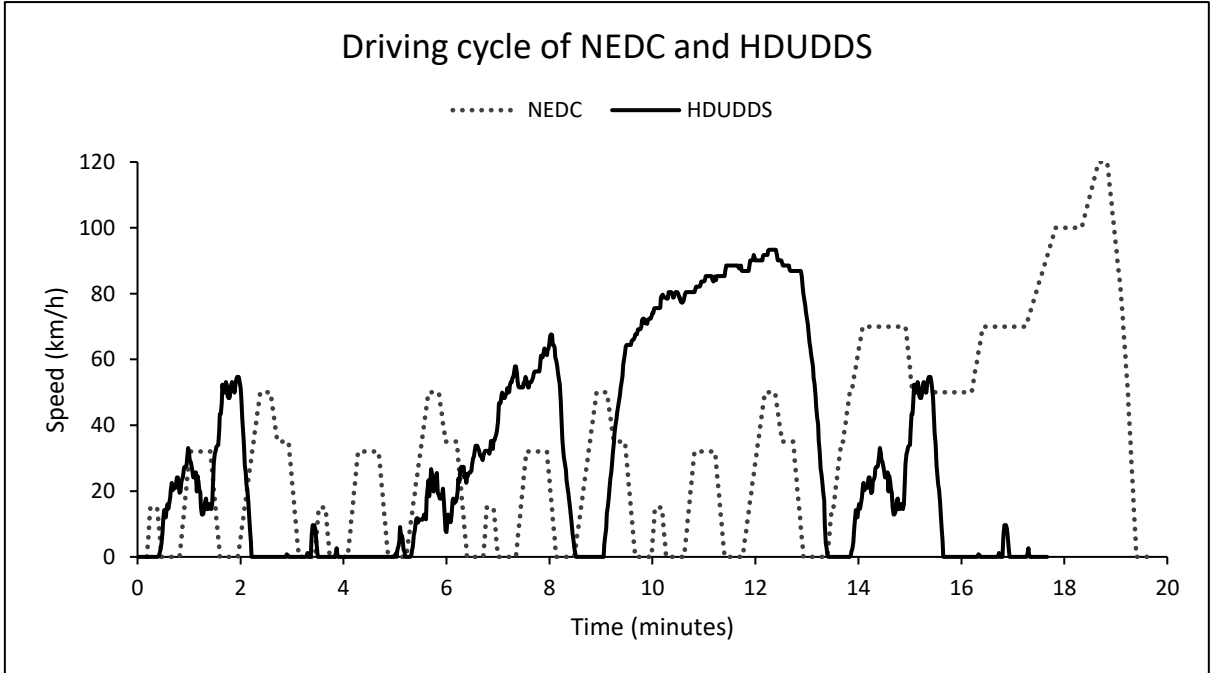


Figure 4-3 Speed profile of HDUDDS in km/h

The most glaring disadvantage of the HDUDDS speed profile is this: the driving speed profile exceeds 90 km/h, which exceeds the maximum speed of goods vehicles allowed in

Singapore of between 50 to 70 km/h – depending on the road and size of vehicle. Despite this mismatch, the HDUDDS is still used, due to lack of a better alternative to represent the different speed stages of heavy goods vehicles in the urban setting. The energy consumption rate is calculated by dividing the total energy consumed in kilowatt-hours for the duration of the driving speed profile by the distance travelled in the driving profile in kilometres.

The calculation method for the DEC rate at each leg  $i$  for vehicle type  $V$  is based on a linear interpolation of the DEC rate of an empty and a fully loaded vehicle (see (4.22)). The weight parameters are the weight of the vehicle in the leg, the empty weight of the vehicle and fully loaded vehicle weight. The models for estimating the DEC rate of empty and fully loaded coefficients are presented in (4.23) and (4.24), respectively. The coefficients of these models are different for electric and diesel vehicles (

Table 4-4).

$$ER_i^{DEC} = \left( \frac{W_i^{leg} - W^{kerb}}{W^{gvw} - W^{kerb}} \right) * (EC^{DEC,empty} - EC^{DEC,full}) + EC^{DEC,empty} \quad (4.22)$$

$$EC^{DEC,empty} = a^{DEC,empty} * W^{gvw} + b^{DEC,empty} \quad (4.23)$$

$$EC^{DEC,full} = a^{DEC,full} * W^{gvw} + b^{DEC,full} \quad (4.24)$$

$ER_i^{DEC}$  is the driving energy consumption rate in kWh/km for the vehicle in route leg  $i$ .

$EC^{DEC,empty}$  and  $EC^{DEC,full}$  are the driving energy consumption rates in kWh/km for the vehicle at kerb weight and GVW, respectively.

$W_i^{leg}$  is the weight of the vehicle in kg in route leg  $i$ .

$W^{kerb}$  and  $W^{gvw}$  are the weights of the vehicle in kg for the vehicle at kerb weight and GVW, respectively.

Table 4-4 Parameter values for linear regression models used in driving energy consumption rate calculation

Variable		BEV		DV	
		At kerb weight	At GVW	At kerb weight	At GVW
		$ER_{MOV,empty,EV}$	$ER_{MOV,full,EV}$	$ER_{MOV,empty,DV}$	$ER_{MOV,full,DV}$
Regression statistics	R-squared	0.803	0.985	0.817	0.991
	Standard Error of Regression [kWh/km]	0.039	0.027	0.125	0.082
	Sample size	80	80	80	80
Coefficient estimates (P-values)	$a$ [kWh/(km.kg)]	0.0000253 (0.000)	0.0000691 (0.000)	0.0000841 (0.000)	0.0002665 (0.000)
	$b$ [kWh/km]	0.277 (0.000)	0.228 (0.000)	0.825 (0.000)	0.580 (0.000)

The linear model for both the empty and full BEV is compared with the stated energy consumption rate of twenty real-world BEVs (see Table 2-3) in Figure 4-4). The stated energy consumption rate is calculated by dividing the battery capacity by the stated driving range.

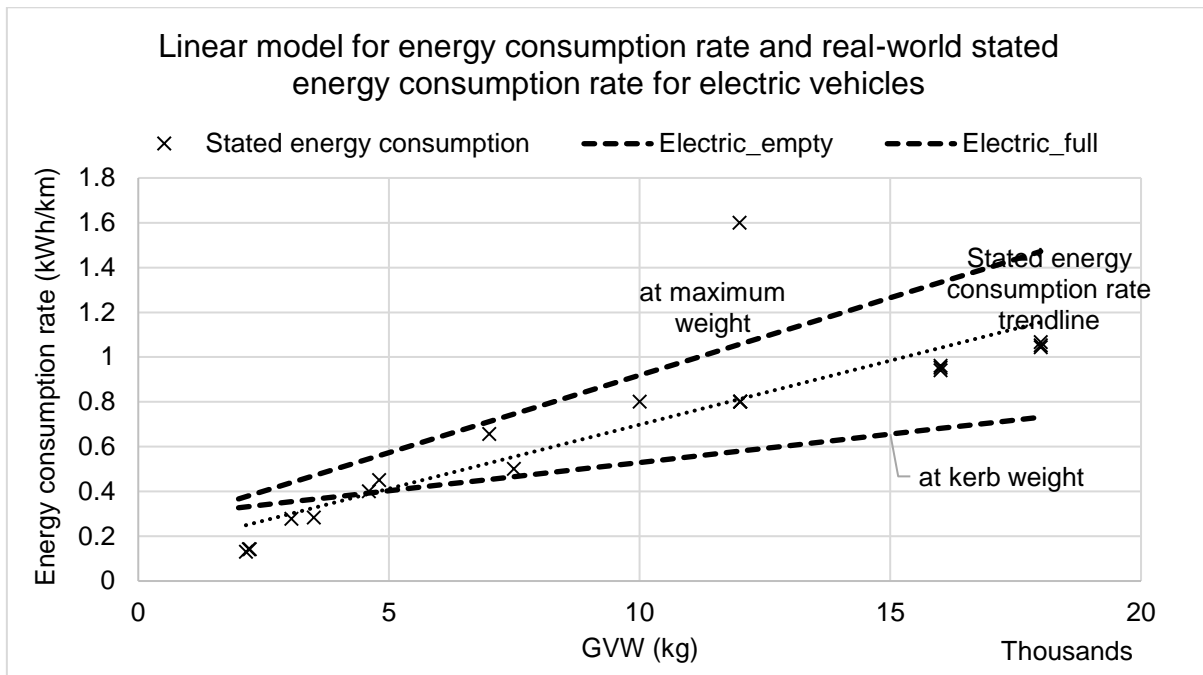


Figure 4-4 Estimation model for energy consumption rate of BEVs with comparison to stated energy consumption rate of real-world BEVs

The values for GVW larger than 4,800 kg (except for one point) fall below the linear model for empty and full vehicles. Hence, one can expect that the model overestimates for vehicles lighter than 4,800 kg. But, since the stated driving range are not real-world values, but are typically calculated by manufacturers using the NEDC driving cycle, the comparison serves as a general indication and not a validation step of the model.

In Figure 4-5, the linear model for the diesel vehicle is compared with real-world energy consumption rates obtained from Transportation Research Board & National Research Council (2010). The values were the lower and higher limits of averaged mileage per gallons of diesel fuel for vehicle weight classes. The upper and lower bounds compare reasonably with the estimation model for the DV at maximum weight and at kerb weight, though it might also be an underestimation of the values.

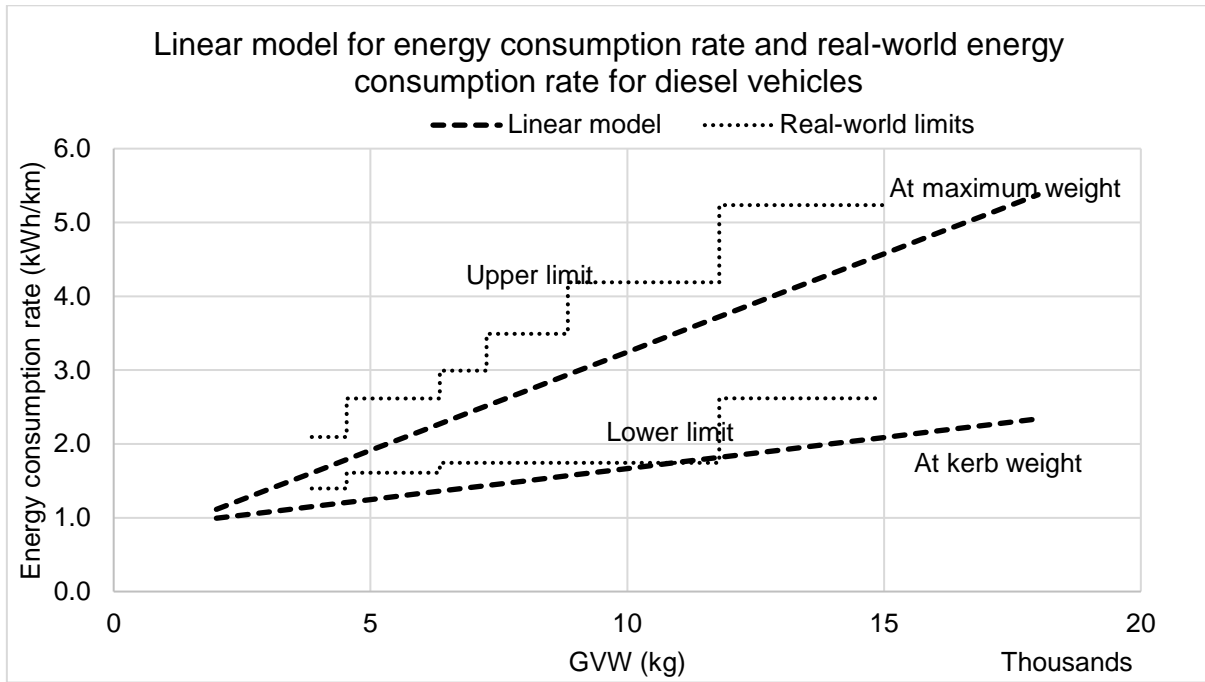


Figure 4-5 Estimation model for energy consumption rate of DVs with comparison to real-world energy consumption rate limits (data on real-world values from (Transportation Research Board & National Research Council, 2010)

#### 4.6.3. Energy consumption for refrigeration

In case refrigeration is necessary, it is assumed that the refrigeration unit consumes energy at a fixed rate throughout the operational hours of the vehicle. The rate is designed to vary depending on the volumetric capacity of the cargo box, which is fixed in each case. The REC rate is calculated based on the estimated rate of 3.6 kW per volume of 20-foot containers (Gesamtverband der Deutschen Versicherungswirtschaft, 2003 [accessed 12 April 2016]). This yields a required power rate  $a_{ECR}$  of 0.0923 kW/m<sup>3</sup>. An efficiency factor,  $\gamma_V$ , is applied depending on the source of energy: 100% for electric vehicles and 40% for diesel vehicles. This represents the average efficiency fuel conversion, which can be achieved by diesel vehicles. The calculation is represented by (4.25).

$$ER_V^{REC} = \frac{a^{REC}}{\gamma_V} * VolBox \quad (4.25)$$

$ER_V^{REC}$  is the energy consumption rate for refrigeration in kW for vehicle  $V$ .  
 $a^{REC}$  is the ratio for required power for refrigeration per cargo box volume in kW/m<sup>3</sup>.

$\gamma_V$  is energy efficiency factor based on vehicle type.

$VolBox$  is the volume of the cargo box.

#### 4.6.4. Energy consumption while idle

It is common for diesel vehicles to be kept “idling”, even though the vehicle is parked, such as during loading or unloading activities, or while the driver is on a break. In this state, the engine of the vehicle remains switched on, but at a low (or “idling”) revolutions-per-minute. Thus, the diesel vehicle continues to consume fuel, although stationary. This state may also

occur during short stops on the road, such as at red lights, but this is accounted for by the driving speed profile (see the zero-speed moments in Figure 4-3). The electric vehicle does not have a comparable energy consumption state. Hence, for this study it is assumed that for any reason the vehicle is parked, during operational hours, there is zero “idling” energy consumption. To support this assumption, it is noted that it is an offense, which carries a fine in Singapore, to “leave the engine of a motor vehicle running when it is stationary for reasons other than traffic conditions”, except in certain cases, which include the operation of on-board machinery, such as refrigeration (National Environment Agency, 2016 [accessed 27 May 2018]). It is assumed that drivers aim to avoid the risk of a fine and the excessive use of fuel.

Nevertheless, in the case of refrigeration (or for any other valid and legal reason), the diesel engine is assumed to consume fuel at a base rate of 0.44 gallons per hour (Khan et al., 2009), in addition to the energy needed to drive the refrigeration unit. Hence, the rate of IEC  $ER_{IEC}$  is fixed at 16.67 kilowatt-hour per hour.

#### 4.7. Battery sizing

The most important design parameter of the BEV is the size of the battery, in terms of its energy capacity in kilowatt-hours and its weight in kilogrammes. Without the use of opportunity charging, the battery capacity needs to exceed the maximum daily energy consumed by a vehicle in the fleet. When an opportunity charging strategy is in play, this battery capacity can be significantly reduced.

As noted previously, the weight of the battery, which can be a significant fraction of the total weight of the vehicle, affects also the DEC rate. Hence, the weight of the vehicle, the battery capacity, and the resulting energy consumption need to be determined simultaneously. In this study, this process is performed iteratively, by increasing the total weight of the vehicle in steps of 100 kg (usually from the total weight used in the diesel vehicle scenario). On one hand, the total weight increase also increases the energy consumption of the vehicle, which in turn increases the required battery capacity. On the other hand, the available battery capacity also increases, since the vehicle has more weight capacity to carry a heavier (and thus higher capacity) battery. The process is stopped once the available battery capacity just reaches above the required battery capacity.

To understand how the increase in total weight of the vehicle causes the changes to both the required and available battery capacity, the following weight calculation models are presented. First, note that the payload capacity  $W^{cap}$  and the special load  $W^{special}$  are given as constants for each case study. The payload capacity is determined by the current vehicle used by the company. The special load refers to any other significant weight which must be carried by the vehicle, besides the freight, such as additional equipment or refrigeration units. As previously introduced (see (4.21)), the kerb weight of the vehicle varies depending on the

GVW of the vehicle. The GVW is a legal limit, which cannot be exceeded. Hence, the addition of the kerb weight, the available weight of the battery, the special load, and the payload capacity should be equal to the GVW. Re-formulating of this definition to calculate the available weight for the battery, produces (4.26). Calculation of the available battery capacity, by using the specific energy of the battery in units of kilowatt-hour per kg, is shown in (4.27).

$$W^{BT} = W^{gvw} - W^{empty} - W^{cap} - W^{special} \quad (4.26)$$

$$E^{BT,available} = \delta^{BT} * W^{BT} \quad (4.27)$$

$W^{BT}$  is the weight of the battery in kg.

$W^{gvw}$  is the GVW in kg.

$W^{cap}$  is the available payload capacity in kg.

$W^{empty}$  is the estimated kerb weight in kg.

$W^{special}$  is any special additional weight that the vehicle must carry in kg.

$E^{BT,available}$  is the battery capacity in kWh.

$\delta^{BT}$  is the specific energy of the battery in kWh/kg.

The following equations are needed to incorporate the varying kerb weight and battery weight of the vehicles in the calculation of energy consumption of the vehicles for each leg within a route throughout the day. To calculate the energy requirement for the vehicle, the energy consumption rate for each leg is calculated using (4.22). (4.28) is used to calculate the weight of the vehicle at each leg  $i$ , which varies according to the current payload in leg  $i$  and the other fixed weight components of the vehicle.

$$W_i^{leg} = W_i^{pay} + W^{BT} + W^{empty} + W^{special} \quad (4.28)$$

$W_i^{leg}$  is the weight of the vehicle in route leg  $i$

$W_i^{pay}$  is the weight of the payload in route leg  $i$

$W^{empty}$  is the estimated kerb weight in kg

$W^{BT}$  is the weight of the battery in kg

$W^{special}$  is any special additional weight that the vehicle must carry in kg

Using (4.17) and (4.18), the energy consumed during each leg and during break time is calculated. This energy consumed per leg is aggregated into energy per route and energy per vehicle using (4.29) and (4.30), respectively.

$$E_j^{route} = \sum_{i,i \in \mathbb{I}_j} E_i^{leg} \quad (4.29)$$

$$E_k^{vehicle} = \sum_{j,j \in \mathbb{J}_k} E_j^{route} + \sum_q E_q^{break} \quad (4.30)$$

$E_j^{route}$  is the energy consumed in route  $j$ .

$E_i^{leg}$  is the energy consumed in route leg  $i$ .

$E_q^{break}$  is energy consumed during the break  $q$ .

$E_k^{vehicle}$  is the energy consumed in the day by vehicle  $k$ .

#### 4.7.1. Battery size for overnight charging only (S1 and S2)

Without an opportunity charging strategy, the battery must last from the beginning of the shift till the end of the shift. The required battery capacity is easily calculated using (4.31)

and accounts for the vehicle with the highest energy consumption in that day. For each strategy, the remaining energy in the battery must not fall below 20%, which gives the DOD of 80%. The available battery capacity must exceed the required battery capacity.

$$E^{BT,req} = \left( \max_{k=1,\dots,K} E_k^{vehicle} \right) / DOD \quad (4.31)$$

$E^{BT,req}$  is the required battery capacity.

$E_k^{vehicle}$  is the energy consumed by vehicle  $k$ .

$DOD$  is the depth of discharge in percentage.

#### 4.7.2. Battery size for break time charging (S3 and S4)

In this strategy, each vehicle is allowed to charge itself for the duration of the break or shift change using a fast charger according to the times determined by the operating schedule of each case study. For a single-break schedule, the first segment ( $s=1$ ) occurs before the break ( $b=1$ ), while the second segment ( $s=2$ ) occurs after the break ( $b=1$ ). For double-break schedule, there are three segments, and are named accordingly. The SOC must be calculated for each vehicle and segment. The SOC for each segment must exceed 20% of the available battery capacity, to maintain a maximum DOD of 80% (see (4.32)). Since during the breaks, energy may also be consumed, the net charged energy during the break must take that into account. The net energy transferred during each fast charging for each break session is calculated in (4.33).

$$E_s^{SOC,BR} > 20\% * E^{BT} \quad (4.32)$$

$$E_q^{CG,BR} = P^{CG,BR} * D_q^{break} - E_q^{break} \quad (4.33)$$

$E_s^{SOC,BR}$  is the SOC of the BEV at the end of segment  $s$  in kWh.

$E^{BT}$  is available battery capacity in kWh.

$E_q^{CG,BR}$  is the amount of energy charged during the break  $q$  in kWh.

$D_q^{break}$  is the duration of break  $b$  in h.

$P^{CG,BR}$  is the charging power in kW.

$E_q^{break}$  is the energy consumed during break  $q$ .

The energy consumed in each segment is calculated using (4.34). It simply takes the operational energy consumed by the vehicle proportional to the duration of the segment. In the final segment, the rest of the operational energy consumed by the vehicle is used. The SOC of the battery in each segment is calculated by (4.35). For the first segment, the SOC is simply the full battery capacity minus the energy consumed in the first segment. The next segments account for the energy charged during the previous break but limited by the total battery capacity.

$$E_s^{session} = \begin{cases} \frac{D_s^{session}}{D_k^{vehicle}} * (E_k^{vehicle} - \sum_{s=1}^{s_{max}} E_s^{break}) & s \geq 1 \\ E_k^{vehicle} - \sum_{s=1}^{s_{max}} E_s^{break} - \sum_{s=1}^{s-1} E_s^{session} & s = s_{max} \end{cases} \quad (4.34)$$

$$E_s^{SOC,BR} = \begin{cases} \min(E_{s-1}^{SOC,BR} + E_s^{CG,BR}, E^{BT}) - E_s^{session} & s > 1 \\ E^{BT} - E_s^{session} & s = 1 \end{cases} \quad (4.35)$$

$E_s^{session}$  is the energy consumed during session  $s$ .

$D_s^{session}$  is the duration of session  $s$ .

$D_k^{vehicle}$  is the duration of operation of vehicle  $k$ .

$E_k^{vehicle}$  is the energy consumed by vehicle  $k$ .

$E_s^{break}$  is the energy consumed during break after session  $s$ .

$s$  is the index for each session.

#### 4.7.3. Battery size for loading time charging (S5 and S6)

When the vehicle is being loaded, charging can take place for that duration. For this strategy, the GVW is increased until the SOC of the battery exceed 20% of the available battery capacity, as shown in (4.36). As the loading time is assumed constant throughout the day, the maximum energy transferred throughout the day is also constant. It is calculated in (4.37). The SOC of the battery is the amount of charge available in the battery after each route and is calculated using (4.38). The energy consumption should also include the energy consumed during any breaks that happen during the route  $E_j^{break,route}$ . For the first route ( $j=1$ ), the SOC is simply the battery capacity minus the energy consumed in the first route and during the breaks that occur in the first route. For subsequent routes, the amount of energy that be charged is limited by the battery capacity.

$$E_j^{SOC,LD} > 20\% * E^{BT} \quad (4.36)$$

$$E_j^{CG,LD} = D_j^{Load} * P^{CG,LD} \quad (4.37)$$

$$E_j^{SOC,LD} = \begin{cases} \min(E_{j-1}^{SOC,LD} + E_j^{CG,LD}, E^{BT}) - E_j^{route} - E_j^{break,route} & j > 1 \\ E^{BT} - E_j^{route} - E_j^{break,route} & j = 1 \end{cases} \quad (4.38)$$

$E_j^{SOC,LD}$  is the SOC of the BEV after route  $j$  in kWh.

$E^{BT}$  is the battery capacity in kWh.

$E_j^{CG,LD}$  is the energy charged during the loading time in kWh.

$D_j^{Load}$  is the duration of loading activity in h in route  $j$ .

$P^{CG,LD}$  is the charging power in kW.

$E_j^{route}$  is the energy consumed in route  $j$ .

$E_j^{break,route}$  is the energy consumed during the break that occurs in route  $j$ .

#### 4.7.4. Battery size for unloading time charging (S7 and S8)

While the goods are being unloaded from the vehicle, charging can take place for that duration. The minimum GVW is found that fulfils (4.39), which ensures the SOC in each leg exceeds 20% of the battery capacity. The energy charged during the time varies according to the duration of unloading and is calculated using (4.40). For the SOC during each leg, the

energy used in the leg is subtracted from the previous SOC, which for the first leg, is the battery capacity. This is reflected in (4.41).

$$E_i^{SOC,UL} > 20\% * E^{BT} \quad (4.39)$$

$$E_i^{CG,UL} = D_i^{Unload} * P^{CG,UL} \quad (4.40)$$

$$E_{j,i}^{SOC,UL} = \begin{cases} E^{BT} - E_{j,i}^{leg} - E_{j,i}^{break,leg} & j = 1, i = 1 \\ \min(E_{j,i-1}^{SOC,UL} + E_{j,i-1}^{CG,UL}, E^{BT}) - E_{j,i}^{leg} - E_{j,i}^{break,leg} & \forall j, i > 1 \\ \min(E_{j-1,i}^{SOC,UL}, E^{BT}) - E_{j,i}^{leg} - E_{j,i}^{break,leg} & j > 1, i = 1 \end{cases} \quad (4.41)$$

$E_i^{SOC,UL}$  is the SOC at the end of route leg  $i$ , before charging takes place.

$E^{BT}$  is the battery capacity in kWh.

$E_i^{CG,UL}$  is the energy charged during unloading activity in route leg  $i$ .

$D_i^{Unload}$  is the duration of unloading activity in route leg  $i$ .

$P^{CG,UL}$  is the charging power in kW.

$E_{j,i}^{leg}$  is the energy consumed in route leg  $i$ .

$E_{j,i}^{break,leg}$  is the energy consumed in break in route leg  $i$ .

$i_j^{max}$  is the index for the last leg in route  $j$ .

#### 4.7.5. Battery size for highway charging (S9)

For highway charging, the vehicle is assumed to start charging for the duration spent on the highway in that leg. The VRP solver can calculate the duration spent on highway type links. In this calculation, the urban segment of the road is always assumed to be travelled on first before the highway segment. The critical segment of the leg is the urban part, since the charging occurs on the highway segment. Hence, the condition for the right GVW is such that the SOC on the urban segment of the leg is greater than 20% of the battery capacity. This condition is reflected in (4.42). The energy consumption attributed to the urban segment is based on the proportion of time not spent on the highway and the energy consumed on any breaks occurring during that leg, as in (4.43).

$$E_i^{SOC,urban} > 20\% * E^{BT} \quad (4.42)$$

$$E_i^{leg,urban} = E_i^{leg} \left( 1 - \frac{D_i^{leg,highway}}{D_i^{leg}} \right) - \quad (4.43)$$

$E_i^{SOC,urban}$  is the SOC of the BEV after driving on urban road of route leg  $i$

$E^{BT}$  is the battery capacity.

$E_i^{leg,urban}$  is the energy consumed in urban road of route leg  $i$

$E_i^{leg}$  is total energy consumed in route leg  $i$

$D_i^{leg,highway}$  is the duration of driving on the highway in route leg  $i$

$D_i^{leg}$  is the duration of route leg  $i$

$E_i^{break}$  is the energy consumed during the break in route leg  $i$

Since the vehicle will still consume energy on the highway, while it is being charged, the effective charge is reduced. The maximum effective charge is calculated by (4.44). The SOC for the urban segment of each leg is calculated using (4.45). This accounts for the SOC of the previous urban segment, the power charged on the highway segment, and the energy

consumed on the current urban segment. Naturally, for the first leg, the full battery capacity is used as the starting SOC.

$$E_i^{CG,HW} = P^{CG,HW} * D_i^{leg,highway} - E_i^{leg} * \frac{D_i^{leg,highway}}{D_i^{leg}} \quad (4.44)$$

$$E_i^{SOC,urban} = \begin{cases} \min(E_{i-1}^{SOC,urban} + E_{i-1}^{CG,HW}, E^{BT}) - E_i^{leg,urban} & i > 1 \\ E^{BT} - E_i^{leg,urban} & i = 1 \end{cases} \quad (4.45)$$

$E_i^{CG,HW}$  is the net energy increase during the highway part of route leg  $i$ .

$P^{CG,HW}$  is the charging power in kW.

$D_i^{leg,highway}$  is the duration spent on highway in route leg  $i$ .

## 4.8. Electric motor sizing

The electric motor needs to be sized according to the GVW of the vehicle to provide sufficient power for acceleration. A linear regression model was created using the engine power of the vehicles in the database (see Section 4.6.1). The result is (4.46) with parameters summarized in

Table 4-5.

$$P^{MT} = a^{MT} * W^{gvw} + b^{MT} \quad (4.46)$$

Table 4-5 Regression results for electric motor power (standard deviations from mean)

Regression statistics	R-squared	0.369
	Standard Error of Regression [kW]	20
	Sample size	80
Coefficient estimates (P-values)	$a^{MT}$ [kW/kg]	0.00484 (0.000)
	$b^{MT}$ [kW]	86 (0.000)

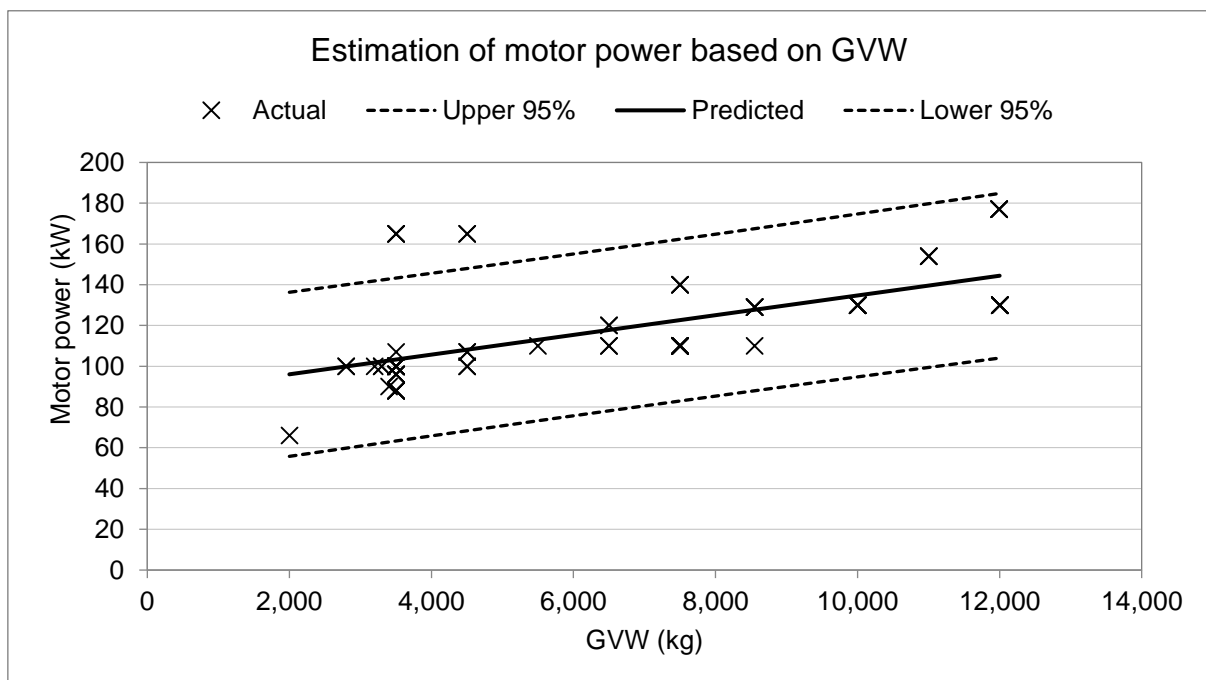


Figure 4-6 Estimation of motor power based on GVW

With the battery and electric motor sized, all the key design parameters for the electric vehicle can be estimated. Next, the required power rating for the overnight charger is determined.

#### 4.9. Charger system parameterization

Each electric vehicle regardless of opportunity charging strategy is charged using an overnight charger, where the vehicle is parked. The charger is to be purchased by the company together with the vehicle. The required power rating is dependent on the battery capacity and the duration the vehicle is parked (see (4.47)).

$$P^{CG,OC} = E^{BT} \div D^{CG,OC} \quad (4.47)$$

$P^{CG,OC}$  is the power rating for the overnight charger in kW.

$E^{BT}$  is the battery capacity in kWh.

$D^{CG,OC}$  is the duration of overnight charging in h.

#### 4.10. Lifecycle cost calculation

In comparison to the diesel vehicle, the BEV is said to have at least two notable financial impacts: a higher purchasing price for the vehicles and charging equipment, and lower operating costs. A total cost of ownership approach is suited to account for this trade-off for “improved purchasing decision making” (Ellram, 1994). In particular, the approach aims to capture all costs associated with “the acquisition, possession, use and subsequent disposition of a good” (Ellram, 1995). The variant used in this study is the lifecycle-cost (LCC) analysis, which “focuses primarily on capital or fixed assets”, emphasizes “purchase price of the asset”, and the costs “to use, maintain and dispose of that asset during its lifetime” (Ellram, 1995, p. 5). This specific variant does not account for ambiguous and difficult-to-measure costs like opportunity costs or pre-purchasing costs and puts the electric and diesel vehicles on a comparable stage.

The assets in question are the vehicles and the overnight charging system. The lifetime of the vehicles refers to the duration in which the vehicles are in service with the company. Since the calculation of LCC is based in the Singaporean context, the vehicles are used for either 10, 15, or 20 years, depending on the individual decisions of the company. These numbers are based on the typical COE duration, which is a temporally limited permit to own a vehicle in Singapore. The initial COE is always 10 years, with a possibility to extend in the tenth year for another 5 or 10 years.

An overview of the costs is presented in Figure 4-7 and shows how the costs are distributed over the lifetime of the vehicle. There are also recurring costs, such as the annual operating costs and the battery replacement cost, which is incurred in fixed intervals dependent on the cycle life of the battery. The resale of the vehicle happens at the end of the lifetime of the vehicle.

### Overview of costs calculated in the lifecycle cost analysis

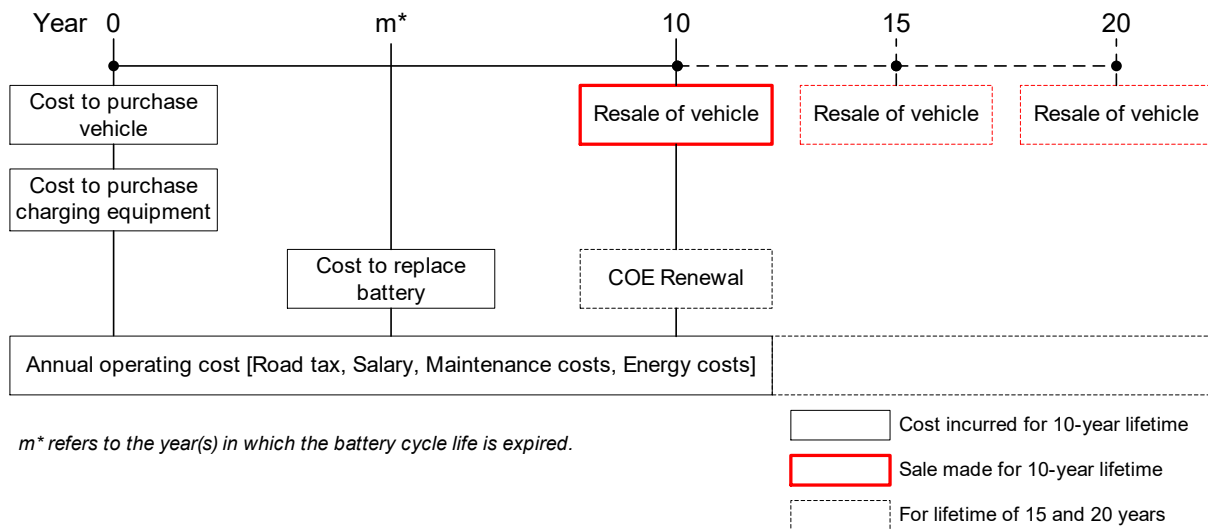


Figure 4-7 Overview of costs calculated in the lifecycle cost analysis

In a calculation of future costs incurred, one must take into account “the preference for receiving cash flow sooner rather later” (Tomic & Gallo, 2012, p. 2). To achieve this, the net present value (NPV) is used as the method to aggregate the financial cash flow associated with the vehicle system to the current year. At the end of this section, the method used to calculate NPV is given. But first, the cost components accounted for in this study are described, starting with the purchasing cost of the vehicle.

#### 4.10.1. Purchasing a vehicle in Singapore

The vehicle purchasing cost accounts for all the costs that are incurred to purchase a vehicle. In addition to the retail price of the vehicle, the following fees are payable for each vehicle in Singapore: registration fees, additional registration fees (ARF) and COE (Land Transport Authority, 2016 [accessed 14 April 2016]). The additional registration fee is payable for diesel vehicles only and is a form of disincentive for polluting vehicles. The costs of the fees are straightforward and are found on the website of the Land Transport Authority (Land Transport Authority, 2016 [accessed 14 April 2016]), but the purchase prices of the vehicles are not.

Previously, it is mentioned that the vehicles are sized according to the payload and the battery weight. Hence, a parametric method capable of estimating the purchase price of vehicles in Singapore is needed. The method to estimate the purchase price of the diesel vehicle is based on a regression analysis of vehicle prices in an online second-hand vehicle marketplace (sgCarMart, 2016 [accessed 14 April 2016]). The purchase price of the electric vehicle is then estimated based on the differences between diesel and electric vehicles, in terms of the types and prices of their components, such as the battery and electric motor. This method has been used in several studies and reports, such as by Cuenca et al. (1999) and Den Boer et al. (July 2013).

#### 4.10.2. Purchase price of the diesel vehicle

The online second-hand vehicle marketplace “sgCarMart” lists goods vehicles, with information on the vehicle model, age, and offered price (sgCarMart, 2016 [accessed 14 April 2016]). This information is combined with GVW of the vehicle obtained from manufacturer specification. The information from the website was accessed on 24<sup>th</sup> July 2015.

The database yielded 152 unique data points after filtering out listings with incomplete information, and duplicates of the vehicles in the same year band. Tractors were excluded. The vehicles used in the analysis were also limited to vehicles aged 9 years and less, due to an observed significant drop between the prices after the ninth year. This can be attributed to the need for a renewed COE that affects the offered price of the vehicle. The listing prices in the analysis include the price of the COE, which is assumed to be S\$50,000. The regression analysis yields (4.48). The regression coefficients  $m^{gvw}$  and  $m^{age}$  have units S\$/kg and S\$/year, respectively. The parameter values are presented in Table 4-6.

$$Y = m^{gvw} * GVW + m^{age} * AGE + b^Y \quad (4.48)$$

Table 4-6 Regression results for vehicle prices

Regression statistics	R-squared	0.853
	Standard Error of Regression [S\$]	12621
	Sample size	152
Coefficient estimates (P-values)	$m^{gvw}$ [S\$/kg]	3.238 (0.000)
	$m^{age}$ [S\$/year]	-9042.5 (0.000)
	$b^Y$	89377 (0.000)

Since the aim is to find an estimation model for the purchase of a new vehicle, the AGE variable is eliminated (or set to zero). Furthermore, the regression constant  $b$  is reduced by S\$ 50,000 to account for the cost of the COE. Hence, this results in an equation that estimates the price of a new diesel vehicle dependent only on the GVW of the vehicle, as presented in (4.49), with parameters in Table 4-7.

$$price_{DV}^{vehicle} = a^{price} * W^{gvw} + b^{price} \quad (4.49)$$

Table 4-7 Coefficients to calculate price of diesel vehicles

$a^{price}$ [S\$/kg]	3.238
$b^{price}$	39,376

#### 4.10.3. Purchase price of the electric vehicle

The purchase price of the electric vehicle is estimated by accounting for the price discrepancy between the main components of the diesel and electric vehicles. According to

Cuenca et al (1999), a diesel vehicle without its powertrain costs about 85%<sup>10</sup> of the retail price. This ratio is used to estimate the price of the electric vehicle without its powertrain, based on the price of the diesel vehicle with an identical GVW. Replacing the diesel powertrain are the battery pack, the motor and controller, and the inductive power receiver (if applicable), which yields (4.50) to estimate the price of the electric vehicle. The prices of the individual components - battery pack, motor and inductive power receiver - are calculated using (4.51), (4.52) and (4.53), respectively.

$$price_{EV}^{vehicle} = 85\% * price_{DV}^{vehicle} + price^{BT} + price^{MT} + price^{IR} \quad (4.50)$$

$$price^{BT} = a^{BT} * E^{BT} \quad (4.51)$$

$$price^{MT} = a^{MT} * P^{MT} \quad (4.52)$$

$$price^{IR} = a^{IR} * P^{IR} \quad (4.53)$$

$price_{EV}^{vehicle}$  is the purchase price of the BEV in S\$.

$price_{DV}^{vehicle}$  is the purchase price of the DV in S\$.

$price^{BT}$  is the cost of the battery in S\$.

$price^{MT}$  is the cost of the motor in S\$.

$price^{IR}$  is the cost of the inductive power receiver in S\$.

$E^{BT}$  is the battery capacity in kWh.

$P^{MT}$  is the power of electric motor in kW.

$P^{IR}$  is the power rating of the inductive power receiver in kW.

The battery capacity, the power rating of the motor, and the power rating of the inductive receiver are determined in the vehicle sizing section. The literature (Nykqvist & Nilsson, 2015, Cuenca et al., 1999, Bångtsson & Alaküla, 2016) provides estimates for the cost coefficients  $a^{BT}$ ,  $a^{MT}$ , and  $a^{IR}$ , and are presented in Table 4-8.

Table 4-8 Coefficients to calculate price of battery pack, electric motor and controller, and inductive power receiver

$a^{BT}$ [S\$/kWh]	400
$a^{MT}$ [S\$/kW]	36
$a^{IR}$ [S\$/kW]	48

#### 4.10.4. Cost to purchase a vehicle

In addition to the purchase prices, the COE cost, registration cost and ARF are also charged when purchasing the vehicles (see Table 4-9). The COE in practice is the product of an auction and therefore varies at every bidding period. The COE value used in this study is an approximate based on values of historical COE prices of Category C vehicles. The registration and ARF values are obtained from the LTA website (Land Transport Authority, 2016 [accessed 14 April 2016]). ARF is charged only to diesel vehicles, depending on the price of the diesel vehicle (see (4.54)). Combining the purchase prices with the fees incurred by the government, yields (4.55).

<sup>10</sup> According to Cuenca et al (1999), the percentage of the manufacturing cost of components, which could be subtracted is 21.53% for the engine, 5.03% for transmission, exhaust system 3.01% and fuel system 0.36% (Cuenca et al., 1999, p. 8). The manufacturing costs itself is 50% of the Manufacturer Suggested Retail Price (Cuenca et al., 1999, p. 6), which yields 15% for the powertrain compared to the retail price.

$$arf_V = \begin{cases} a^{arf} * price_{DV}^{vehicle} & \text{for } V = \{DV\} \\ 0 & \text{for } V = \{EV\} \end{cases} \quad (4.54)$$

$$cost_V^{vehicle} = price_V^{vehicle} + coe + reg + arf_V \quad V = \{EV, DV\} \quad (4.55)$$

$arf_V$  is the ARF payable for the vehicle in S\$.

$a^{arf}$  is the rate of the ARF in %.

$price_{DV}^{vehicle}$  is the price of the DV in S\$.

$cost_V^{vehicle}$  is the final cost of purchasing the vehicle in S\$.

$price_V^{vehicle}$  is the price of the vehicle (either DV or BEV) in S\$.

$coe$  is the cost of the COE in S\$.

$reg$  is the registration cost of the vehicle in S\$.

Table 4-9 Prices for COE, registration and the ARF ratio

$coe$ [S\$]	50,000
$reg$ [S\$]	140.00
$a_{arf}$ [%]	5

#### 4.10.5. Cost to purchase charging equipment

In contrast to the diesel vehicle, which may depend on an external refuelling station, the BEV generally requires a charger located at the parking area of the vehicle for each vehicle. Depending on the size of the battery and the time allowed to charge overnight, the power level of the charger is determined. There are at least three standard power levels (see Table 4-10). For Level 2 and Level 3, additional electrical systems need to be installed to provide the required high voltage and current. The electrical system can be shared by several chargers, which makes the subsequent purchases of the charging equipment less than the first purchase. However, this reduction is not considered for this cost model. The estimates of the cost are developed based on estimates of the charging station equipment, electrician materials, labour and mobilization, and permits for installation in the US (Agenbrood & Holland, 2014 [accessed 14 April 2016]). For the inductive charger, 75% of the equipment cost is added. This assumption is made since existing quotes do not yet exist.

This total cost for purchase and installation is only included in the LCC for the overnight charging chargers. Opportunity charging is treated as a service; hence the purchase and installation costs are not explicitly considered. However, it is accounted for by a premium on top of the energy costs calculation. This is discussed in a later section on the energy cost calculation.

Table 4-10 Equipment cost and total cost for the charging system for three levels of power

Charger type	Range of power, $P_{CGOC}$ (kW)	Equipment cost (S\$)		Total cost, $cost_{CG}$ (S\$)	
		Conductive	Inductive	Conductive	Inductive
Level 1	$\leq 2$ kW	960	1,700	1,600	2,400
Level 2	$\leq 20$ kW	2,700	4,700	7,300	9,400
Level 3	$> 20$ kW	32,000	56,000	80,000	104,000

#### 4.10.6. Vehicle resale value

The resale of a vehicle depends on the market and condition of the vehicle. However, it is necessary to be able to estimate this value, if it is to be included in the LCC. Using the second-hand vehicle database, one can estimate the loss in value over time. The estimated prices of new vehicles are used (based on model developed in Section 4.10.2) is combined with the selling prices of the vehicles in the second-hand vehicle database to generate the percentage of the resale price to the estimated price of the new vehicle over the lifetime of the vehicles. This can be seen in Figure 4-8.

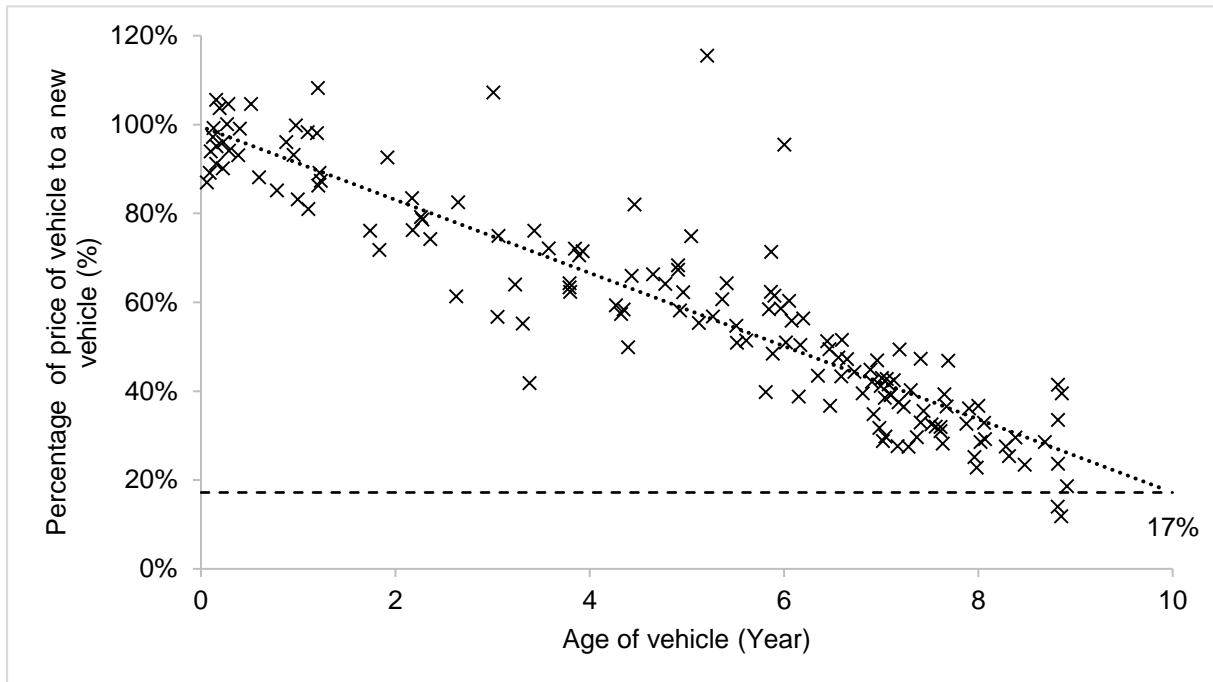


Figure 4-8 Resale value of an aged vehicle compared to a new vehicle in percentage

A linear regression analysis yields (4.56), with regression parameters in

Table 4-11 .

$$\frac{res}{price} \% = m^{dep} * YEAR + b^{dep} \quad (4.56)$$

Table 4-11 Regression results for vehicle resale value ratio (standard deviations from mean)

Regression statistics	R-squared	0.831
	Standard Error of Regression [S\$]	0.103
	Sample size	152
Coefficient estimates (P-values)	$m^{dep}$ [S\$/year]	-0.082 (0.000)
	$b^{dep}$ [%]	0.995 (0.000)

Figure 4-8 also shows that the vehicles in general depreciates by about 83% of their initial value after the tenth year in service. In this study, the resale value of the vehicle is assumed to be 17% of the purchase price of a new vehicle for all service lifetimes (10, 15, and

20 years). The values obtained from the database only support this value for the service lifetime of 10 years. It can be expected that the vehicle simply depreciates further for service lifetimes of 15 and 20 years. However, this is not considered in the study for two reasons. First, there is not enough information to determine the percentage of depreciation for 15- and 20-year old vehicles. In the absence of more precise data, the study instead acknowledges the deficiency in the calculation model. The second reason is that the significance of the resale value in the 15<sup>th</sup> and 20<sup>th</sup> years is much reduced due to the presence of the discount factor used in the calculation model of the NPV. Hence, the resale value of the vehicle  $res$  is calculated using (4.57).

$$res = 17\% * price^{vehicle} \quad (4.57)$$

$res$  is the resale value of the vehicle.

$price^{vehicle}$  is the original purchase price of the vehicle.

Note that other purchases are not assumed to be resold. This includes charging equipment; whose depreciation behaviour is unknown. Also, the model does not account for the value of newly replaced batteries or any other major spare parts replacement.

#### 4.10.7. Battery replacement cost

The battery replacement cost is incurred once the average lifetime of the battery is reached, which may happen more than once in the lifetime of the vehicle. This average lifetime is calculated based on the average charges made per year  $cycle_{average}$  and the battery charge cycle lifetime specification  $cycle_{BT}$ . The cycle lifetime  $cycle_{BT}$  is taken to be 3,000 (Burke, 2007, p. 808). The year(s) that the battery is replaced  $t_{rep}$  is calculated using (4.58).

$$t_m^{rep} = \left\lceil \frac{cycle_{average}}{cycle_{BT}} \right\rceil * m \quad t_m^{rep} < t^{life}, \quad m = 1, \dots, M \quad (4.58)$$

$t_m^{rep}$  is the year in which the battery must be replaced.

$cycle_{average}$  is average charges made per year.

$cycle_{BT}$  is the lifetime of the battery in terms of charge cycles.

$m$  is an index representing the number of times the battery is replaced during the lifetime.

$t^{life}$  is the assumed service lifetime for the LCC.

The cost to replace the battery uses a similar linear relation as in (4.51), except that the cost parameter is expected to decrease yearly by a percentage. Though Nykvist & Nilsson (2015, p. 330) suggests a value of 8%, this study assumes a more conservative estimate, a yearly decrease of 3%, which better reflects the estimates their analysis was based on. The calculation of the battery replacement cost is presented in (4.59).

$$cost^{BT,rep}(t_m^{rep}) = price^{BT} * (1 - a^{BT,rep})^{t_m^{rep}} \quad (4.59)$$

$cost^{BT,rep}(t_m^{rep})$  is the cost of the replacement battery at the year  $t_m^{rep}$ .

$a^{BT,rep}$  is yearly percentage decrease of the battery cost.

$price^{BT}$  is the price of the battery when the vehicle was purchased.

#### 4.10.8. Renewal of the COE

The initial COE lasts for the first 10 years. After this period, the owner may extend it once for 5 or 10 years, which would cost either half or the full price of the COE, respectively. The cost for the extension is presented in (4.60), with the service lifetime. This cost is incurred once in the tenth year, in case the calculation is for service lifetime 15 or 20 years.

$$coe^{ext} = \frac{t^{life} - 10}{10} * coe \quad (4.60)$$

$coe^{ext}$  is the cost for extending the COE for either five or ten years.  
 $t^{life}$  is the service lifetime for the LCC.

#### 4.10.9. Annual operating cost

The operating costs are incurred regularly and are composed of the road tax, salary, insurance premiums, maintenance costs and energy costs. (4.61) is used to calculate the cost for the entire fleet. The annual road tax, salary and insurance premiums can be calculated for each vehicle, then multiplied by the size of the fleet. The maintenance and energy costs can be calculated for the fleet directly.

$$cost^{op}(t) = (roadtax(t) + salary + insurance) * K + maintenance + cost^E \quad (4.61)$$

$cost^{op}(t)$  is the operating cost for year  $t$ .

$roadtax(t)$  is the roadtax to be paid for year  $t$ .

$salary$  is the annual salary of the driver.

$insurance$  is the annual insurance premium .

$K$  is the size of the fleet.

$maintenance$  is the maintenance cost for vehicles and charging systems.

$cost^E$  is the energy cost.

#### 4.10.10. Road tax

Road taxes in Singapore are categorized by GVW, propulsion type and age. Table 4-12 presents the road tax incurred for diesel and electric goods vehicles according to LTA (Land Transport Authority, 2016 [accessed 14 April 2016]).

Table 4-12 Road tax incurred for diesel and electric goods vehicles

GVW range (kg)	Annual road tax for vehicles, $a_{roadtax_{gvw}}$ (S\$)	
	Electric	Diesel
0<GVW≤3,500	340	426
3,500<GVW≤7,000	524	656
7,000<GVW≤11,000	578	724
11,000<GVW≤16,000	782	978
16,000<GVW≤20,000	1,122	1,403
20,000<GVW	1,224	1,530

Once the vehicle exceeds 10 years of age, the vehicle is also charged a surcharge on the road tax. This is calculated according to (4.62), with the values of the surcharge presented in

Table 4-13.

$$roadtax(t) = a^{roadtax}(W^{gvw}) * surcharge(t) \quad (4.62)$$

$roadtax(t)$  is the roadtax payable in year  $t$ .  
 $a^{roadtax}(W^{gvw})$  is base annual road tax dependent of GVW.  
 $surcharge(t)$  is the surcharge percentage for vehicles over 10 years old.

Table 4-13 Road tax surcharge according to the age of the vehicle

Age of vehicle, $t$ (year)	Road tax surcharge, $surcharge(t)$
$0 < t \leq 10$	100%
$10 < t \leq 11$	110%
$11 < t \leq 12$	120%
$12 < t \leq 13$	130%
$13 < t \leq 14$	140%
$t < 14$	150%

#### 4.10.11. Driver salary

The salary value used in the study is taken from the government statistics on median wages for a van driver, lorry driver and a trailer-truck driver (MOM, June 2014). This is assumed to correspond to the GVW classification of the light, medium, and heavy duty truck, respectively. The annual salary is taken as 13 times the monthly salary to account for other bonuses or expenses that might be included in the compensation package. The salary is presented in Table 4-14.

Table 4-14 Median monthly salary and yearly salary according to GVW of vehicle

GVW range (kg)	Median monthly wage (S\$)	Yearly salary, $salary$ (S\$)
$GVW \leq 3,500$	2,079	27,027
$3,500 < GVW \leq 12,000$	2,337	30,381
$GVW > 12,000$	2,621	34,073

#### 4.10.12. Vehicle insurance premiums

Annual insurance premiums are taken to be 4% of the purchase of the vehicle (own calculations based on Cuellar (26 Aug. 2014)) and is calculated using (4.63).

$$insurance = 4\% * price^{vehicle} \quad (4.63)$$

$insurance$  is the annual cost for insurance.  
 $price^{vehicle}$  is the purchase price of the vehicle.

#### 4.10.13. Vehicle and charging equipment maintenance cost

Both the vehicle and the charging infrastructure need to be maintained. The maintenance cost of the vehicle depends on the mileage travelled by the vehicle annually and differs depending on the vehicle's GVW (see Table 4-15). Larger vehicles are expected to have higher maintenance costs. The values for the maintenance cost rate for diesel vehicles are taken from Sinha & Labi (2007). Since electric vehicles are expected to have significantly less maintenance costs than diesel vehicles, the maintenance cost rates for electric vehicles are assumed to be approximately half (Davis & Figliozzi, 2013a).

Table 4-15 Maintenance cost coefficient for DV and BEV

GVW range	Maintenance cost coefficient, $a_{maintenance_V}$ , S\$/km)	
	Diesel vehicle	Electric vehicle
GVW ≤ 3,500	0.09	0.05
3,500 < GVW ≤ 12,000	0.19	0.10
12,000 < GVW	0.35	0.18

The average annual maintenance cost of the charger is assumed to be 5% of the equipment costs (own calculations based on Miller et al. (December 2013)). This gives the total annual maintenance cost for the chargers as presented in Table 4-16.

Table 4-16 Annual maintenance cost of the overnight charging system

Power level	Annual maintenance cost of chargers, $maintenance_{CG}$ , (S\$)	
	Conductive	Inductive
Level 1	48	85
Level 2	135	235
Level 3	1,600	2,800

The annual total maintenance costs are calculated using (4.64).

$$maintenance = a_{V,gvw}^{maintenance} * l^{fleet} * Days + maintenance^{CG} * K \quad (4.64)$$

$maintenance$  is the annual maintenance cost for vehicles and charging systems.

$a_{V,gvw}^{maintenance}$  is the rate of maintenance cost for the vehicle in S\$/km depending on GVW.

$l^{fleet}$  is the total mileage of the fleet in an operational day.

$Days$  is the number of operation days per year

$maintenance^{CG}$  is the cost of maintenance for an overnight charger.

$K$  is the size of the vehicle fleet.

#### 4.10.14. Energy cost

The energy cost depends on the cost for diesel for the diesel vehicle and on the cost of electricity for the electric vehicle. The unit of calculation of energy used by the vehicles are in kWh. The prices are quoted in S\$ per kWh. Depending on the method and technology for charging, the electricity cost per unit kilowatt-hour, and the amount of electricity chargeable in kilowatt-hour may vary. As mentioned previously, the opportunity charging is considered a service, which affects the cost the service provider might charge. Additionally, for each type of charging technology, there is a different rate of charging efficiency.

$$cost^E = Days * \sum_e price_e^E * \frac{E_e}{\gamma_e} \quad (4.65)$$

$cost^E$  is the cost of electricity used per year.

$Days$  is the number of operation days per year.

$price_e^E$  is the price per unit of energy per energy type in S\$/kWh.

$E_e$  is the amount of energy used per type in kWh.

$\gamma_e$  is the efficiency of charging in %.

$e$  is the index for type of charging system used.

(4.65) is used to calculate the annual energy costs for the fleet. In the case of opportunity charging, the energy cost incurred for the overnight charging and the opportunity charging is different. This is segmented according to index  $e$ . The amount of energy charged during each segment (overnight or opportunity charging) is represented by variable

The unit energy price depends on the type of energy, and method for charging. This is presented in Table 4-7. The diesel price is based on a single rate of S\$0.90 per litre, which is a discounted value for bulk purchases, discovered during an interview with one of the logistics managers. Using the net calorific value and density of diesel fuel, the amount of energy which a litre of diesel is equivalent to is 10.01 kWh (Department for Environment, Food & Rural Affairs, 2013 [accessed 5 August 2017]). This yields a unit price of 0.09 S\$/kWh for at tank-to-wheel cost. The electricity costs is S\$0.15 per kWh (source: own estimate based on published tariffs for month of January 2016 (Energy Market Authority, 2017 [accessed 25 February 2017])). Additionally, in order to finance opportunity charging facilities (both on and off-site), a premium on the energy cost is levied (Borden & Boske, 2013, p. 21). Only Level 3 charging systems are assumed to be used for on operation charging. Hence, assuming a usage of 12 hours a weekday and an amortization in 7 years (Snyder et al., 2012) for a 100-kW charger, an additional charge of 5 and 6 cents (own calculation) is levied, for conductive and inductive charging systems, respectively. Assumptions on the additional energy cost for electrified roadways is unavailable (Highways England Company, 2015), so an increase of 20% of the Level 3 static inductive charging cost is assumed. The prices per kWh are summarized in Table 4-17.

Table 4-17 Energy prices per kWh for diesel, overnight and on operation charging

Energy supply	Rate of energy price, $price_{E_e}$ (S\$/kWh)	
Diesel	0.09	
Overnight charging	0.15	
On operation Level 3 charging	Conductive	0.20
	Inductive	0.21
	Dynamic inductive	0.23

The efficiency of electricity (or fuel) transfer to the vehicle is dependent on the type of charging system used. The electric vehicle is supplied electricity by the charger, which has an efficiency, depending on the power level and the type of charger. The efficiency of refuelling is

assumed to be 100%. Since not all efficiency values are available, some assumptions were made. The efficiency values for conductive charging for Level 1 and Level 2 were calculated based on the experimental results of Sears et al. (2014), specifically for charging above 4 kWh. For Level 3, the experimental results of INL (2014) was used. Efficiency values for Level 2 inductive charging were taken from INL (2015). Other values were not available, so an estimation of the values was used instead. The difference between Level 2 conductive and inductive charging was used to represent the loss of efficiency by using the different technology. This difference is then applied to Level 1 and Level 3 inductive charging. This reduced the efficiency by 7.9%. The values are summarized in Table 4-18.

Table 4-18 Efficiency of charging

Charging type, $e$	Efficiency of charging, $\gamma_e$ , (%)	
	Conductive	Inductive
Static Level 1	85.8%	78.4%
Static Level 2	90.2%	82.3%
Static Level 3	88.7%	81.0%
Dynamic Level 3	-	75.0%

**4.10.15. Aggregation of costs to the NPV**

With the cost components, and the year the costs are incurred, the NPV of the lifecycle cost of all the fleets can be calculated. Costs which are incurred in the future are adjusted using a discount factor  $df$  to a “present value” (Tomic & Gallo, 2012, p. 2). This value is based on a discount rate assumed to be 5% though other studies have used values ranging from 5% to 15% (Macharis et al., 2007, p. 320, Feng & Figliozzi, 2013, p. 139, Davis & Figliozzi, 2013a, p. 18, Lee et al., 2013, p. 8027, van Duin et al., 2013, p. 14). This calculation is shown in (4.66).

$$df = \frac{1}{(1 + discount\ rate)} \tag{4.66}$$

$df$  is the discount factor.  
 $discount\ rate$  is the discount rate assumed for the study.

The NPV is used for the LCC calculation and sums up all the (present adjusted) costs incurred throughout the service lifetime of the vehicle (see (4.67)). This calculation is done for service lifetimes of 10, 15, and 20 years.

$$NPV(t^{life}) = \left( cost^{vehicle} + cost^{CG} - res * df^{t^{life}+1} + coe^{ext} * df^{10} \right. \\ \left. + \sum_{\forall t_{rep}} cost^{BT,rep}(t^{rep}) * df^{t^{rep}} \right) * K + \sum_t^{t^{life}} cost^{op}(t) * df^t \quad (4.67)$$

$NPV(t^{life})$  is the net present value for the LCC for service lifetime  $t_{life}$ .

$cost^{vehicle}$  is the cost for the purchase of the vehicle.

$cost^{CG}$  is the cost for purchase of the overnight charger.

$res$  is the resale value of the vehicle.

$coe^{ext}$  is the cost for extending the COE, if applicable.

$cost^{BT,rep}(t^{rep})$  is the cost for battery replacement in year  $t_{rep}$ .

$K$  is the fleet size

$cost^{op}(t)$  is the operating cost in year  $t$ .

#### 4.11. Carbon dioxide emissions calculation

The calculation of carbon dioxide (CO<sub>2</sub>) is based only on a fixed average rate for CO<sub>2</sub> production depending on the energy source. For the diesel vehicle, the emission factor  $\varepsilon_{CO_2,DV}$  of 0.2677 kgCO<sub>2</sub>/kWh is used (Department for Environment, Food & Rural Affairs, 2013 [accessed 5 August 2017]). For the electric vehicle, the fuel is burned at the power plant with an emission factor  $\varepsilon_{CO_2}$  of 0.4332 kgCO<sub>2</sub>/kWh (Energy Market Authority Singapore, 7 Apr. 2016 [accessed 11 April 2016]). There is also an efficiency loss due to the transmission of electricity in the grid (Gabriel et al., 2014, p. 234). The transmission loss factor of 1.0383 is obtained from one of service providers in Singapore (Mypower, 31-Mar-16 [accessed 11 April 2016]). The equations for CO<sub>2</sub> emissions for a day for diesel and electric vehicles, are (4.68) and (4.69), respectively. Note that for the electric vehicles, the type of charging used affects the amount of electricity used because of the efficiency (see Table 4-18)

$$CO2_{DV} = 0.2677 * E^{fleet} \quad (4.68)$$

$$CO2_{EV} = 0.4332 * 1.0383 * \sum_e \frac{E_e}{\gamma_e} \quad (4.69)$$

$CO2_{DV}$  is the amount of CO<sub>2</sub> emitted per day by the DV fleet in kg

$CO2_{EV}$  is the amount of CO<sub>2</sub> emitted per day by the BEV fleet in kg

$E_e$  is the energy transferred to the vehicle during the charging process using charger  $e$  in kWh

$\gamma_e$  is the efficiency of charging in %

$e$  is the type of charger used

#### 4.12. Suitability evaluation

For the suitability analysis, indicators for financial suitability and environmental suitability are compared separately to the requirements it is subject to. The suitability indicators are then calculated as the percentage change of the NPV and the CO<sub>2</sub> emissions compared

to the values calculated for the diesel vehicle scenario. The financial suitability indicator  $FSI$  and the environmental suitability indicator  $ESI$  are calculated using (4.70) and (4.71), respectively.

$$FSI = \left( \frac{NPV(t^{life})_{EV}}{NPV(t^{life})_{DV}} - 1 \right) * 100\% \quad (4.70)$$

$$ESI = \left( \frac{CO2_{EV}}{CO2_{DV}} - 1 \right) * 100\% \quad (4.71)$$

$FSI$  is the financial suitability indicator

$ESI$  is the environmental suitability indicator

$NPV(t^{life})_{EV}$  and  $NPV(t^{life})_{DV}$  are the NPV for the LCC of the BEV and DV for service lifetime  $t_{life}$ , respectively

$CO2_{EV}$  and  $CO2_{DV}$  is the amount of CO2 emitted by the BEV and DV, respectively

Financial suitability is a requirement set by profit-seeking firms, which unless coerced would not willingly adopt BEVs. The condition for financial suitability is simply that the lifecycle cost for the electric vehicle scenario does not exceed the lifecycle cost of the diesel vehicle scenario. This would mean that the firm at the very least, would not suffer any financial loss from using BEVs. This translates into the following condition:

*“If  $FSI \leq 0$ , then EV scenario is financially suitable.”*

The environmental suitability requirement is set by the government, which is responsible for setting policy objectives. In the evaluation of environmental suitability, the threshold value was based on the Singapore’s Intended Nationally Determined Contribution (INDC) at the Paris COP21 World Climate Change Conference 2015. The Singapore Government in the INDC set a target of reducing its overall “emission intensity by 36% from 2005 levels by 2030” (Singapore Government, 2015 [accessed 11 April 2016], p. 1). Assuming that the emissions intensity of the transport operations of the company using the diesel vehicle remained roughly the same from 2005 till now and will remain the same till 2030, the only real change would be if an electric vehicle was used. This translates into the following condition:

*“If  $ESI \leq -36\%$ , then EV scenario is environmentally suitable”.*

Naturally, the setting of these conditions may be controversial. However, it will not be dealt with in the study, since it would anyway be a matter of policy, as to the percentage level of the difference the EV is expected to bring.

As previously discussed, the overall suitability of the EV scenario is determined by the meeting both conditions. In other words, the suitability condition is stated in the following statement:

*“If the EV scenario is both financially and environmentally suitable, the EV scenario is suitable.”*

With the clear methods used for evaluating the suitability of an EV scenario, the following section deals with the derivation of higher order conclusions based on the conclusions of single cases.

### 4.13. Comparative analysis

The comparative analysis aims to establish causal relations between the different factors exemplified in the different cases (and scenarios) and the suitability indicators. It is desirable, as much as possible, to compare between the results of scenarios which differ only slightly (i.e. by as few variables as possible). In this study, there are two broad categories, which “guide” the selection of differentiation in the comparative analysis: the factors relevant to the vehicle usage and the attributes of the electric vehicle and charging concept. The specific variations are specified in Chapter 6.

As a tool for analysis, the cost components for the NPV are grouped into categories, such as “Major purchases”, “Operating costs”, and “Energy costs”. This may be done, for some of the analyses, to clarify in which way the costs change. The presentations of the changes are still done in comparison to the costs of the diesel vehicle. This is done using (4.72), which can be modified for any level of the cost component, such as from “Vehicle purchase price” to “Major purchases”, which additionally includes the cost for the charging system.

$$CPC_i = \left( \frac{CC_{EV,i} - CC_{DV,i}}{NPV_{DV}} \right) * 100\% \quad (4.72)$$

$CPC_i$  is the calculated component percentage change

$CC_{EV,i}$  and  $CC_{DV,i}$  are the cost components for the BEV and DV, respectively

$NPV_{DV}$  is the NPV for the LCC of the DV

The calculated component percentage change  $CPC_i$ , where  $i$  refers to the type of cost component in analysis, is relative to the  $NPV_{DV}$ , such that the summation of  $CPC_i$  for all  $i$  yields the  $FSI$ . The cost component for electric and diesel vehicles over the particular service lifetime are denoted  $CC_{EV,i}$  and  $CC_{DV,i}$ . Using this tool enables the research to identify the strength of the factors to influence the suitability indicators.

## **5. Case study results**

Each case study is to be treated individually before combination for the CCA. Hence, according to the overall research design, the results for the scenario-building and suitability evaluation are presented in this chapter. There are two goals in this chapter. Firstly, to show the development of the case study and the scenarios. Some modelling decisions are ad hoc in order to deal with the available data as well as the nuances of the particular transport operations to be modelled. In order to display the full richness of the case studies, while still maintaining methodological integrity, it is vital to show the particular ad hoc decisions taken. This is especially the case for the step “synthesis of the transport task”, such as creating the shipment orders – destination addresses and shipment sizes. The second goal is to present the calculation of low level independent, intermediate and dependent variables. This is an important step to carry out the CCA. The CCA compares the causal factors (independent and intermediate variables) and the outcomes (dependent variables), in the analysis.

Each case study is presented in four sections. The first describes selected information from the interview covering the shipper’s business activity relevant to their transport operations and transport operational parameters. The second describes the methodological assumptions and the steps taken to develop the representative shipment orders. In particular, it focuses on the data not available from interviews, which must be obtained from external sources. Route and schedule specific statistical descriptors are provided, as well as relevant graphics, to describe the simulated VAM. The third section presents the intermediate (electric mobility specifications) variables. The various charging schemes are conditions for different electric mobility specifications, especially in terms of battery capacity. The fourth section presents the results of the suitability indicators and the verdict on suitability of the scenarios.

### **5.1. Case A: Courier, express and parcel service**

Company A was interviewed in March 2016 and is the first of two CEP companies to be interviewed in Singapore. It is a global company with a large vehicle fleet in Singapore. The interviewee is the Country Operations Director overseeing the operations in Singapore from the headquarters in Singapore. Coincidentally, the interviewee also had access to their delivery and collection data. A sampling of these data were provided and used in this case study, as well as for Case B, which is also a CEP case study.

#### **5.1.1. Interview results**

The CEP business is fairly well-described in the literature. Company A does not provide any service deviating from the ordinary. They have a single distribution centre in Singapore. They provide both delivery and collection services, which are simultaneously optimized for the

vehicle delivery routes and pickup routes. Both services are time-sensitive. The senders expect their deliveries to reach the receivers on schedule, as depending on selected service package, which usually means that it is day-sensitive (arrival during the day). Collection services are also pressing, since there is often a time cut-off point for receiving the packages at the consolidation centres for redistribution. The items shipped are documents or parcels usually of high monetary value or time-sensitivity, since the service is more expensive than normal postal services. The receivers are predominantly individuals or entities in the commercial sector, but increasingly also private residential individuals.

The fleet size is 64 delivery vans, excluding spares, each serving a single service area. Some delivery is conducted on foot, especially in congested areas with inaccessible (or inconvenient) parking, such as in the central business district area. On foot deliveries are outside the scope of this study. The vehicles depart from a single distribution centre (DC) for their first delivery routes to their allotted service areas and return to it after their last route. For subsequent routes, new delivery shipments are loaded on the delivery vehicles at a cross-docking site within each service area. The replenishment routes are served by a milk-run from the depot to each cross-docking site. Items collected by the delivery vehicles are also transferred to the milk-run vehicles at the same time. The cross-docking points are not pre-arranged, hence the milk-run vehicle drivers must contact the delivery vehicle drivers to set up a meeting time and place. The milk-run trips are not modelled in this study.

As mentioned, the interviewee provided precise data on a sample of delivery and collection data for a day. For each delivery record, the delivery time, address, shipment weight and volume, and designated service area was provided. Similar information was provided for each collection record. From the interview, the first shift time starts at 7:30 am and ends at 6:00 pm with a one-hour break from 12:00 noon to 1:00 pm. The night shift runs from 7:30 pm to 11:00 pm. This splits the day into at least three time groups. The operations are conducted 7 days a week. From the data sample, it would seem that the work shift is loosely organised, which is expected since there are many uncertainties in real-world operations and conditions.

### **5.1.2. Vehicle activity model**

With sample data, there are only a few things, which need to be assumed or estimated to create a VAM. Herein, there is a break with the usual method of routing and scheduling. The first step is to create a stop sequence for each route. This involves meshing the delivery and collection data in such a way that a coherent route is formed, starting from the depot (or cross-docking point) and ending at the depot (or next cross-docking point). The cross-docking locations are set as the last stop made in the previous route.

The sample data are not taken directly to describe the vehicle activity, since there are some inconsistencies and data loss in the original data obtained. Hence, a pre-processing stage is required to use the data (see Figure 5-1). Firstly, the time stamp of each record is

used to decide the time group it is serving – either morning, afternoon or evening. Each route is composed of the stops in a time group in a service area, but the sequence is undetermined as yet. The sequence is calculated using the scheduling function of XCargo, which rearranges the stop sequence to reduce the distance travelled. The simulated time is then calculated by taking into account the duration of driving in each leg and the time spent for loading or unloading activities. The loading duration is 30 minutes, while the unloading duration is 5 minutes.

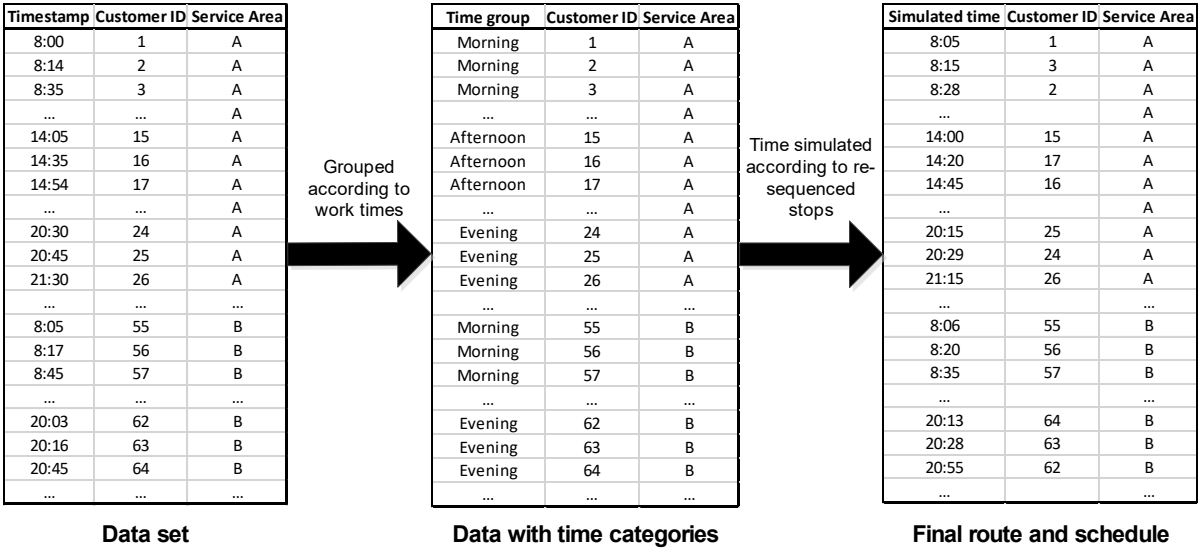


Figure 5-1 Process from data sample to final route and schedule

As is usually the case, CEP transport operations are characterised by high stop frequencies, but low distance travelled. Table 5-1 shows a summary of selected indicators. One notes that the vehicle usage is quite imbalanced as indicated by the high discrepancy between the average and maximum distance travelled and the reduced number of routes in the evening shift.

Table 5-1 Route statistics according to time group for Case A

Time group	Number of routes (-)	Average number of stops (-)	Average (Maximum) distance (km)	Average duration (h)
Morning	60	23.8	30.7 (61.0)	3.8
Afternoon	62	28.3	39.2 (62.0)	4.5
Evening	15	3.9	27.2 (29.0)	2.0

The routes are visualised in Figure 5-2. One can appreciate the route imbalance in the different sessions (morning, afternoon, evening), especially that the evening routes are quite few.

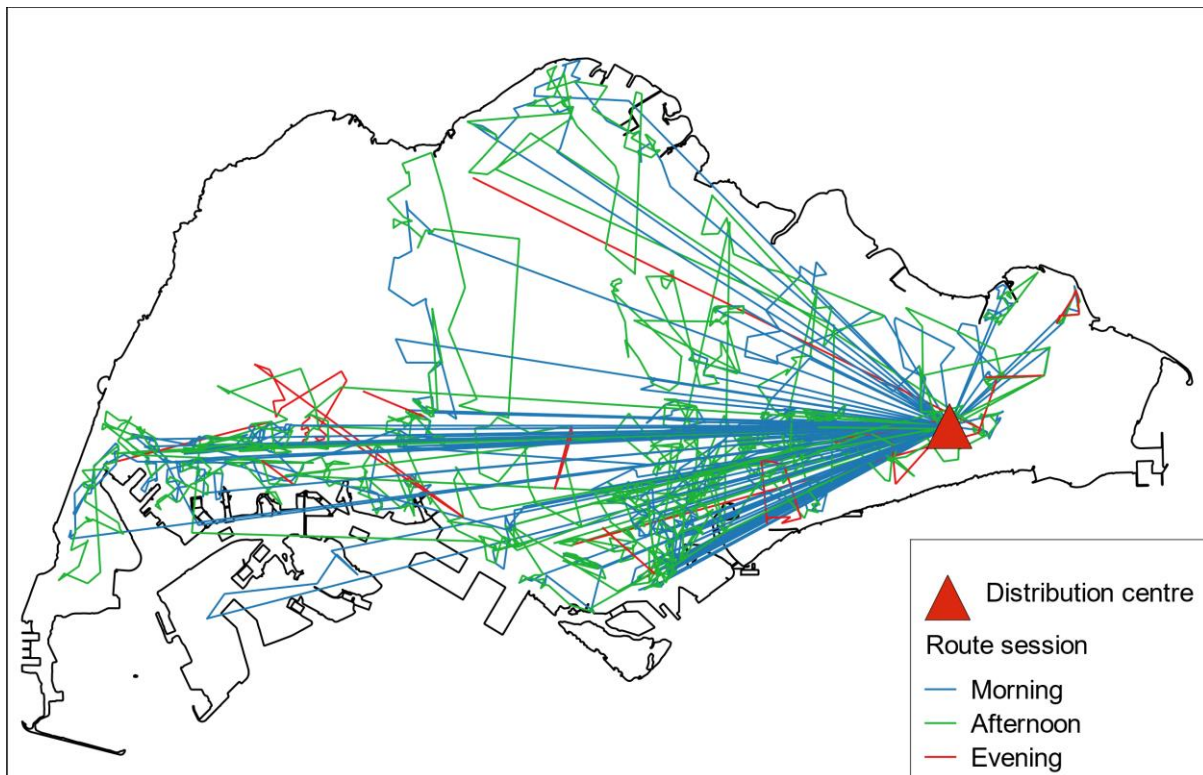


Figure 5-2 Visualised routes of case A

### 5.1.3. Vehicle system specification

For Case A, all four opportunity charging strategies can potentially be used. Hence, the battery capacity and total vehicle weight for five BEVs – one for each charging strategy, including “no opportunity charging” – and one diesel vehicle must be determined. The two parameters are presented in Table 5-2, as well the power level of the overnight charging. Without opportunity charging, the BEV will require a battery capacity of 78 kWh, which increases the GVW by 700 kg in comparison with diesel vehicle. With opportunity charging strategies, the battery capacity reduces to between 27 and 58 kWh. The battery capacity of for scenarios S3 to S6 are equal, while the battery capacity for S7 to S9 are equal, which means that the efficacy of the opportunity charging strategies

The efficacy of the opportunity charging strategies to reduce the battery needed are similar between break time charging and loading time charging, and between unloading time charging and highway charging. In comparison to the overnight charging scenarios, S3 to S6 reduces the battery capacity required by 20 kWh (a 26% reduction), while S7 to S9 reduces it by 51 kWh (a 65% reduction). The vehicles for S7 to S9 are only 200 kg more than the diesel vehicle. All BEV scenarios require Level 2 charging.

Table 5-2 Vehicle parameters and changes of weight and battery capacity for Case A

Scenario ID	Scenario	GVW (kg)	Battery capacity (kWh)	Overnight charging level
S0	Diesel vehicle	2,400	-	-
S1	Overnight conductive charging	3,100	78	Level 2
S2	Overnight inductive charging			
S3	Break time conductive charging	2,900	58	Level 2
S4	Break time inductive charging			
S5	Loading time conductive charging	2,900	58	Level 2
S6	Loading time inductive charging			
S7	Unloading time conductive charging	2,600	27	Level 2
S8	Unloading time inductive charging			
S9	Highway inductive charging	2,600	27	Level 2

#### 5.1.4. Suitability evaluation

The results of the FSI and ESI are presented in Table 5-3. None of the scenarios in any of service lifetimes meet the financial suitability requirement ( $FSI \leq 0$ ). The best performing scenario in terms of FSI is S7. Also, only S7 meets the environmental suitability requirement ( $ESI \leq -36\%$ ). This means that none of the scenarios are considered suitable, even if the BEVs were used for up to 20 years.

Table 5-3 Summary of suitability indicators for Case A

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	7.7%	5.8%	4.9%	-31.0%
S2	9.0%	6.9%	5.9%	-24.4%
S3	5.5%	4.1%	3.3%	-32.6%
S4	8.4%	6.6%	5.7%	-26.2%
S5	5.3%	3.8%	3.1%	-32.8%
S6	8.1%	6.3%	5.4%	-26.4%
S7	2.4%	1.2%	1.0%	-36.0%
S8	5.2%	3.7%	3.4%	-29.9%
S9	6.0%	4.5%	4.2%	-25.4%

Greyed out boxes meet the suitability thresholds

Note also that opportunity charging, when controlled for the type of charging technology used, improves both the FSI and the ESI. And as mentioned, opportunity charging during the unloading times is the best for Case A. This could be the case because of the high number of stops made by the vehicles for a courier service.

Besides this result and observations, there are two general trends, which can be noted for further discussion. First, increasing the service lifetime reduces the FSI significantly. Second, the use of inductive charging instead of conductive charging increases the FSI and ESI. Both trends are important and will be discussed in Chapter 6.

## **5.2. Case B: Courier, express and parcel service**

Case B also evaluates the electric mobility system for a CEP service provider. The company was also interviewed in March 2016. Similar to Company A, Company B is a global CEP service provider with a large vehicle fleet in Singapore. The type of service provided (i.e. customer types, service products) are expected to be the same, except that the scale is larger. In other words, Company B (by interviewee in Company A's own admission) is a larger and more established company in Singapore. The interviewee is an Industrial Engineer in Operations. The standard methods are used to develop the case study and build the scenarios.

### **5.2.1. Interview results**

As mentioned, Company B is a CEP service provider similar to Company A, except in the scale. One big difference is in the urban distribution channel structure. While Company A uses a single DC and a multi-location cross-docking feature, Company B uses three regional DCs to reduce the total distance travelled by the fleet. Case B only focuses on the distribution from the regional DCs to the receiver addresses. There are no other notable differences in terms of the business model or tour structure.

The fleet size is 53 delivery vans, excluding spares, each serving a single service area. Each DC (i.e. DC1, DC2, and DC3) has a set number of vehicles, from which the vehicles depart and return after each route. The vehicles are parked after the last shift at their respective DCs. The areas served by each DC are as follows: DC1 serves the Central and East regions<sup>11</sup>; DC2 serves the North and North-East regions; and DC3 serves the West region. The vehicles at each DC are as follows: DC1 has 23 vehicles; DC2 has 17; and DC3 has 13.

Unlike Case A, the interviewee only provided averaged values from which to derive the customer list. Hence, the transport orders are to be synthesized. Similar to Case A, the first shift time starts at 7:30 am and ends at 6:00 pm with a one-hour break from 12:00 noon to 1:00 pm. The night shift runs from 7:30 pm to 11:00 pm. This splits the day into at least three time groups. The operations are conducted 7 days a week. For each route, the numbers of delivery (or collection) stops are about 40, the number of pieces delivered are about 45, with a weight per piece of less than 20 kg. In a day, on average each vehicle travels about 150 km.

### **5.2.2. Vehicle activity model**

Since the customer data (i.e. location and shipment size, at least) have to be synthesized, there are two major assumptions here. The first is that the numbers of customers served by each DC are proportional to the fleet size at each DC. The locations of the customers can then easily be assigned using the random selection procedure of addresses according to the DC and the time group (i.e. morning, afternoon and evening). The second assumption

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<sup>11</sup> The urban area of Singapore (which excludes the islands) is divided into 5 major planning regions.

deals with the assignment of the weight of each order for each customer. It is assumed that the distribution of weight of each piece follows the distribution of the weight of each piece of Case A. This is then randomly assigned to the customer list in Case B. Figure 5-3 shows the aggregated frequency of shipment weights distribution for the weight of order assignment procedure.

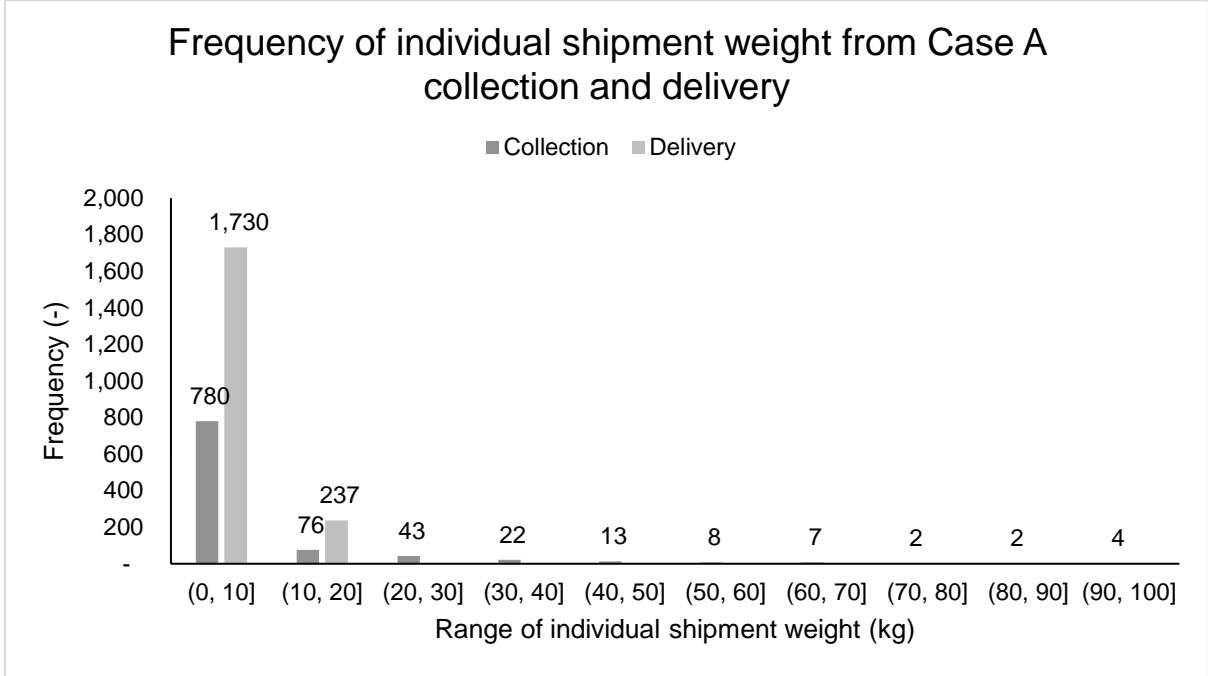


Figure 5-3 Probability of weight distribution for distribution and collection activities

The loading and unloading duration is similar to Case A: 30 and 5 minutes, respectively. The standard vehicle routing procedure is used, but the route assignment step is unnecessary, since this is integrated into the customer list synthesis step. A summary of the statistics are displayed in Table 5-4. Note that the average numbers of stops and distance travelled are much lower than the average values obtained from the interview. Though the maximum distance travelled cannot be explained, except to assume that the 150 km average distance travelled is somewhat an exaggerated approximation by the interviewee, the average number of stops might be explained, by adjusting the definition of a stop. For example, it could be the case that each “stop” as simulated by the model, actually refers to several customers at the same address. At least this is the situation in Case A, where at some addresses, different customers are visited. In any case, the difference is considered insignificant.

Table 5-4 Route statistics according to time group for Case B

Time group	Number of routes (-)	Average number of stops (-)	Average (Maximum) distance (km)	Average duration (h)
Morning	53	23.4	36.4 (64.9)	4.1
Afternoon	53	23.0	37.7 (71.9)	4.1
Evening	29	18.6	44.8 (87.6)	4.0

Figure 5-4 shows the visualised routes for Case B according to the different DCs. One notices the stark imbalance of the routes that need to be served by each DC.

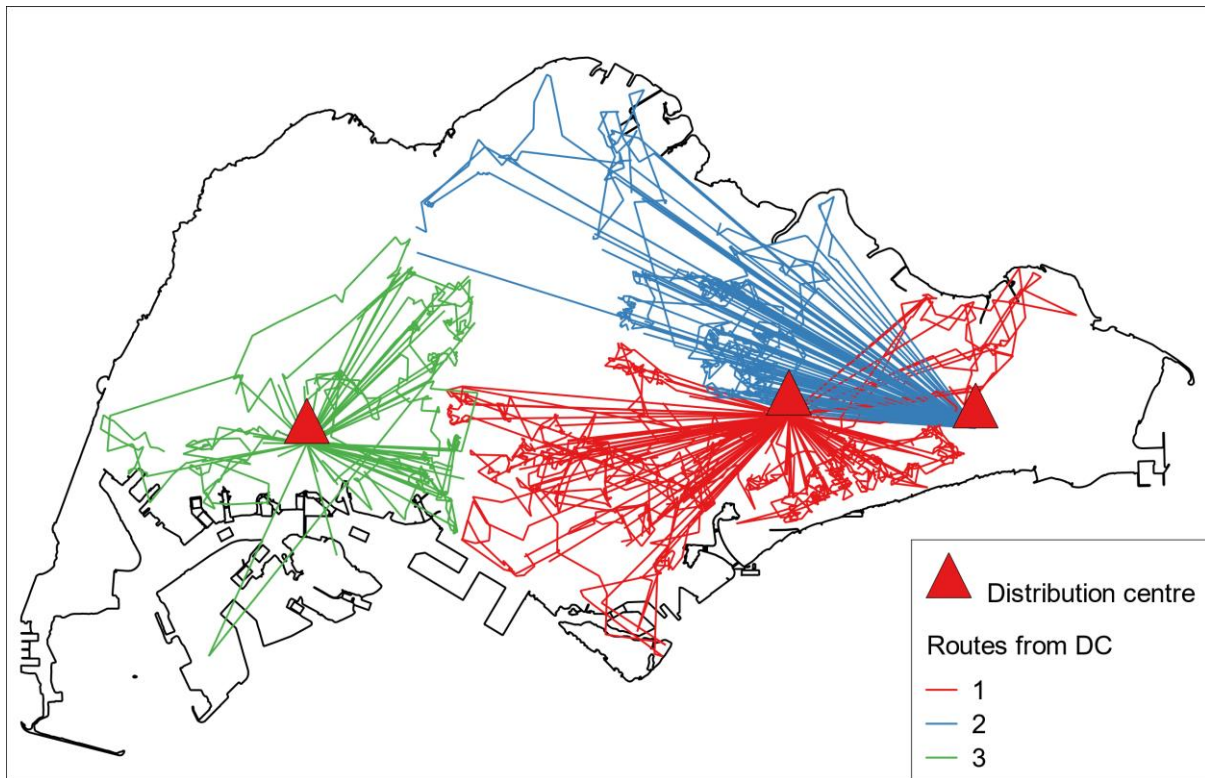


Figure 5-4 Visualised routes according to the DCs in Case B

### 5.2.3. Vehicle system specification

For Case B, all four opportunity charging strategies can potentially be used. The battery capacity and total vehicle weight are presented in Table 5-5. Without opportunity charging, the BEV weighs 800 kg more than the DV because of the 88 kWh battery. The BEVs in the scenario with unloading time charging has the lowest battery requirement of only 17 kWh, which is an 81% reduction compared to the BEV without opportunity charging. BEVs of the break time and highway charging share the same battery size of 37 kWh. All the vehicles use Level 2 charging for overnight charging.

Table 5-5 Vehicle parameters and changes of weight and battery capacity for Case B

Scenario ID	Scenario	GVW (kg)	Battery capacity (kWh)	Overnight charging level (-)
S0	Diesel vehicle	2,400	-	-
S1	Overnight conductive charging	3,200	88	Level 2
S2	Overnight inductive charging			
S3	Break time conductive charging	2,700	37	Level 2
S4	Break time inductive charging			
S5	Loading time conductive charging	2,800	47	Level 2
S6	Loading time inductive charging			
S7	Unloading time conductive charging	2,500	17	Level 2
S8	Unloading time inductive charging			
S9	Highway inductive charging	2,700	37	Level 2

#### 5.2.4. Suitability evaluation

The results of the FSI and ESI are presented in Table 5-6. For service lifetime 10 years, none of the scenarios meet the financial suitability requirement. But, for service lifetime 15 and 20 years, S7 meets it by a slight margin of 0.1% and 0.5%, respectively. The ESI for S7 also meets the requirement, which means that the conditions of scenario S7 for service lifetime 15 and 20 years are suitable for BEV usage. Controlling for the type of charging technology, all the opportunity charging scenarios improve on both the FSI and the ESI. However, only S7 contributes suitable scenarios. The reason could also be the high number of stops that each vehicle in a courier service makes.

Table 5-6 Summary of suitability indicators for Case B

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	7.9%	5.7%	4.7%	-29.7%
S2	9.2%	6.9%	5.8%	-22.9%
S3	3.3%	1.8%	1.6%	-34.8%
S4	6.2%	4.5%	4.1%	-28.6%
S5	3.0%	3.1%	2.3%	-33.6%
S6	6.0%	5.8%	4.8%	-27.2%
S7	0.6%	-0.1%	-0.5%	-37.1%
S8	3.5%	2.5%	2.0%	-31.1%
S9	6.9%	5.1%	4.7%	-24.8%

Greyed out boxes meet the suitability thresholds

### 5.3. Case C: Fast food restaurant replenishment

Case C is about the replenishment transport operations for a fast food restaurant in Singapore. Company C was interviewed in October 2015. Company C provides logistics services to the fast food chain, including warehousing and all freight transport services. It handles the inbound transport into the warehouse from overseas and local suppliers and the distribution to various outlets. Company C is a global logistics company providing services particularly (though not exclusively) to fast food restaurants. The fast food chain is also one of

the largest fast food chains in the world, and in Singapore. The interviewee knows the operations in detail although his primary role is Quality Assurance Executive. This is because of the very important cleanliness and refrigeration requirements set by the Agri-Food & Veterinary Authority Singapore (AVA), which sets guidelines for the transportation of food.

**5.3.1. Interview results**

The interview focused on the distribution services that Company C provides to the fast food chain company. There are 122 restaurants scattered throughout the city, which is served by a single DC. The outlet addresses were not provided by the interviewee, but can be obtained from the website. The warehouse location is where the interview was held.

Despite the large number of restaurants served, the vehicle fleet size is only 4 delivery trucks, working only 6 days a week. The restaurants are visited once, at least every two days. Each vehicle is fitted with a refrigeration unit for the food items, which needs to maintain a temperature below 4 °C.

There is only one shift per day, which starts at about 6:00 am and ends at about 4:00 pm. However, since the peak periods for the restaurants are during lunch hours, there is a two-hour break for drivers from 12:00 noon to 2:00 pm. The drivers and the vehicles are at the warehouse during this time. Each loading takes on average 30 minutes, while it takes about 15 minutes for unloading. Each route covers about 6 to 9 stops with each shipment weighing about 200 kg.

**5.3.2. Vehicle activity model**

The customer addresses are already provided by the fast food chain company’s website. Each outlet order is 200 kg according to the average value. All the outlets are served over a two-day period. Hence, the route is assumed to repeat itself every two days. The routing and route assignment is conducted according to the standard methods, except that the period of assignment is two days. In other words, for calculation purposes the fleet size is 8, which is double the actual size of 4 vehicles. Selected statistics are presented in Table 5-7. Note that the average distance travelled is quite high and does not deviate much from the maximum: a difference of 12.9 km for the morning route and 18.0 km for the afternoon.

Table 5-7 Route statistics according to time group for Case C

Time group	Number of routes (-)	Average number of stops (-)	Average (Maximum) distance (km)	Average duration (h)
Morning	8	7.3	65.0 (77.9)	4.1
Afternoon	8	8.0	39.0 (57.0)	3.8

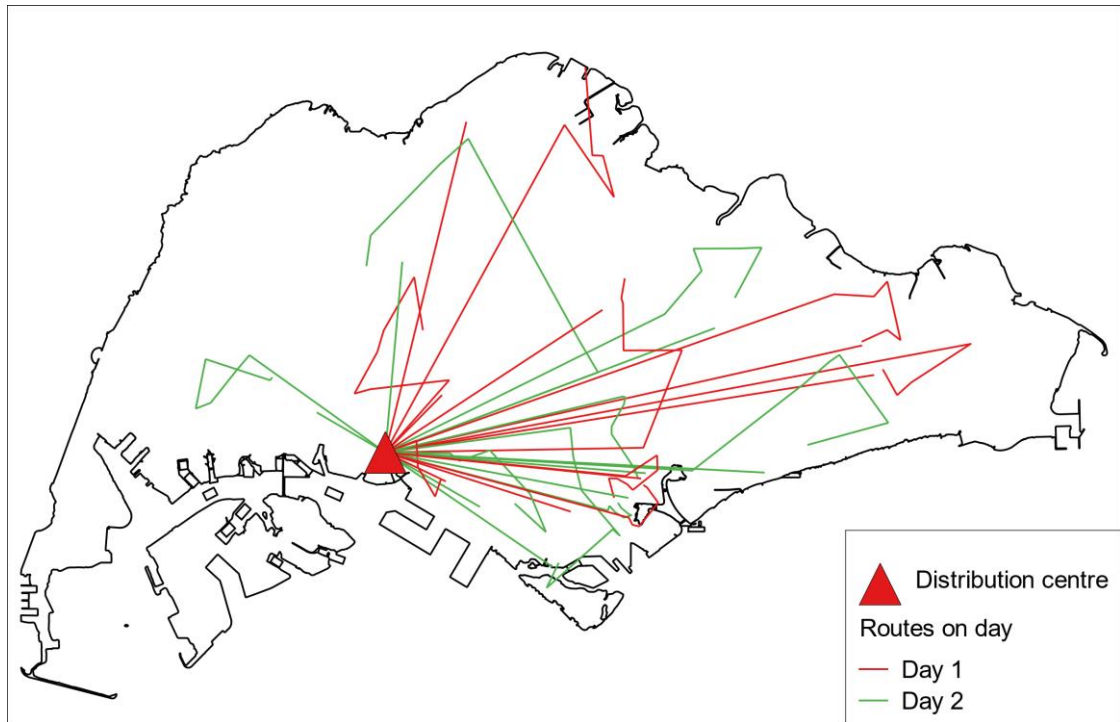


Figure 5-5 Visualised routes in Case C

The routes are rather simple, making only on average 8 or less stops per route. Figure 5-5 shows the pattern of vehicle movement for both days. Visually it would appear that a lot of time would be spent travelling on main roads or highways to reach the stop locations.

### 5.3.3. Vehicle system specification

For Case C, all four opportunity charging strategies can potentially be used. The key parameters of the electric mobility system are presented in Table 5-8. A BEV without opportunity charging requires a battery capacity of 110 kWh, which is an additional 1.1 tonnes compared to the DV. The best opportunity charging strategy is the unloading time charging with only 39 kWh, which is a 65% decrease in battery capacity and 700 kg decrease in GVW compared to the overnight charging strategy. It also only has a weight increase of about 400 kg compared to the DV. The next best opportunity charging scenarios are the loading time and highway charging with a battery capacity of 60 kWh, which is 50 kWh less than the overnight charging scenarios. All overnight charging need Level 2 charging.

Table 5-8 Vehicle parameters and changes of weight and battery capacity for Case C

Scenario ID	Scenario	GVW (kg)	Battery capacity (kWh)	Overnight charging level (-)
S0	Diesel vehicle	4,400	-	-
S1	Overnight conductive charging	5,500	110	Level 2
S2	Overnight inductive charging			
S3	Break time conductive charging	5,100	70	Level 2
S4	Break time inductive charging			
S5	Loading time conductive charging	5,000	60	Level 2
S6	Loading time inductive charging			
S7	Unloading time conductive charging	4,800	39	Level 2
S8	Unloading time inductive charging			
S9	Highway inductive charging	5,000	60	Level 2

#### 5.3.4. Suitability evaluation

The results of the FSI and ESI are presented in Table 5-9. All the scenarios also meet the environmental suitability requirement. Only scenarios S2 and S9 with service lifetime 10 years fail to meet the financial suitability requirement, thus are considered not suitable. Opportunity charging strategies are not necessary to fulfil the financial suitability requirement with S1 having an FSI of at least -0.6%. Nevertheless, considering the service lifetime of 10 years, the use of opportunity charging during unloading time can produce a higher savings of 4.5%. The reduction in ESI for S7 compared to S1 are 2.6%.

Table 5-9 Summary of suitability indicators for Case C

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	-0.6%	-2.9%	-2.3%	-57.3%
S2	0.6%	-1.7%	-1.2%	-53.2%
S3	-3.8%	-3.4%	-4.6%	-58.6%
S4	-1.0%	-1.0%	-2.2%	-54.7%
S5	-2.9%	-4.8%	-5.1%	-59.2%
S6	-0.2%	-2.5%	-2.9%	-55.3%
S7	-5.1%	-5.7%	-6.1%	-59.9%
S8	-2.3%	-3.1%	-3.7%	-56.1%
S9	0.2%	-2.0%	-2.4%	-53.7%

Greyed out boxes meet the suitability thresholds

## 5.4. Case D: Independent stores replenishment of frozen food

Company D is a marketing and distribution company of ice cream, and was interviewed in October 2015. It distributes this ice cream to any convenience store, supermarket, or restaurant (henceforth referred to as “store”) that will buy. The transport operations described is the distribution activities of frozen food to the many stores, as well as the supply chain format used by the company, called “van sales”. The interviewee is the IT and Project Manager for the company, but he oversees all distribution and fleet related operations.

### **5.4.1. Interview results**

The interview focused on the transport operations and not on the supply chain part. Nevertheless, the drivers are both sales representatives and transporters in their respective service areas. The supply chain format used, “van sales”, is akin to the Vendor Managed Inventory style used in several niche situations. In short, the stock levels (of the ice cream) at the stores are managed by drivers. In particular, the stock level check, the replenishment, and the invoicing are conducted right after each other by the driver at the store. The driver may also rearrange and tidy up the ice box at the store. Since the driver does not know which inventory is needed until the stock check at the store, the driver must bring along a variety of ice cream types on the vehicle in anticipation of what might be needed. In essence, this means the driver carries on the whole trip more stock than is needed. In fact, the loading of the vehicle with fresh inventory is also done at the end of the shift, not at the beginning of the shift as it usually is done.

In the existing fleet, there are 24 vehicles in total, of which 20 vehicles are equipped with eutectic plates for deep refrigeration, while 4 use an on-board compressor-based refrigeration unit. Eutectic plates are used to maintain a cold temperature. It must be frozen every day at the depot parking lot. Hence, while it is being driven it does not use any energy. However, it can only maintain the temperature for a set number of hours, in this case about 8 hours. For the ice cream, the products must be kept below -18 °C according to AVA regulations.

The total number of customer addresses was not revealed in the interview. Each vehicle only makes one route per day and starts at 8:00 am and ends before 4:00 pm. The drivers may take a break of 30 minutes for lunch, typically at 11:30 am. Each driver is in charge of a single service area divided according to postal codes. There are no associated time windows at the customer locations. The interviewee did provide a sampling of GPS-derived data, such as daily driven distance, driven duration, and the number of stops made, for one of the vehicles for 6 days a week for 4 weeks. The vehicles are used more on weekdays with an average distance 69 km for about 11 stops, while on Saturday it is driven about 50 km for about 6 stops. The average driving duration is about 2 hours on weekdays and about one and a half hours on Saturday.

### **5.4.2. Vehicle activity model**

The receiving stores are randomly chosen according to 24 service areas, depending on postal codes. In Singapore, the postal codes can typically be grouped into postal sectors, according to the first two digits of the six-digit code. But this exceeds 24, which is the desired number of service areas. The URA (Urban Redevelopment Authority, 2016 [accessed 21 September 2016]) also provides a categorisation of the postal sectors into 28 postal districts.

This categorisation is then combined to define the 24 service areas for the case study (see Table 5-10).

Using the standard method, a randomly picked address list for customers is created, categorised according to 24 service areas. Next is the random assignment of the shipment weight. Note that since the driver does not know beforehand, if a sale is made; there are some stops without sales made. The ratio of this happening when compared to instances when sales are made is assumed to be 1:2. This ratio is used in the random assignment of shipment weight.

Also, the vehicle does not use energy for refrigeration, since it is predominantly done using eutectic plates. Nevertheless, to simulate the weight of the system, it is assumed that the whole refrigeration system weight is 1,000 kg.

Table 5-10 Service areas for Case D

Service areas	2-digit postal sectors	General location
1	01 to 08	Raffles Place, Cecil, Marina, People's Park, Anson, Tanjong Pagar
2	14 to 16	Queenstown, Tiong Bahru
3	09, 10	Telok Blangah, Harbourfront
4	11 to 13	Pasir Panjang, Hong Leong Garden, Clementi New Town
5	17 to 21	High Street, Beach Road (part of), Middle Road, Golden Mile, Little India
6	22, 23	Orchard, Cairnhill, River Valley
7	24 to 27	Ardmore, Bukit Timah, Holland Road, Tanglin
8	28 to 30	Watten Estate, Novena, Thomson
9	31 to 33	Balestier, Toa Payoh, Serangoon
10	34 to 41	Macpherson, Braddell, Geylang, Eunos
11	42 to, 45	Katong, Joo Chiat, Amber Road
12	46 to 48	Bedok, Upper East Coast, Eastwood, Kew Drive
13	49, 50, 81	Loyang, Changi
14	51, 52	Tampines, Pasir Ris
15	53 to 55, 82	Serangoon Garden, Hougang, Ponggol
16	56, 57	Bishan, Ang Mo Kio
17	58, 59	Upper Bukit Timah, Clementi Park, Ulu Pandan
18	60 to 64	Jurong
19	65 to 68	Hillview, Dairy Farm, Bukit Panjang, Choa Chu Kang
20	69 to 71	Lim Chu Kang, Tengah
21	72, 73	Kranji, Woodgrove
22	77, 78	Upper Thomson, Springleaf
23	75, 76	Yishun, Sembawang
24	79, 80	Seletar

Based on the final order list, the vehicle routing procedure is conducted. Here, the values of distance, number of stops and driving duration were used to calibrate the route duration constraint in the routing procedure. Also, it was assumed that the unloading time if a sale is made is 25 minutes; and 10 minutes if no sale is made. The final route duration constraint used was 350 minutes. A comparison with the weekday average values obtained from the interviewee is presented in Table 5-11. The simulated version shows a higher number of stops visited, but on average a lower distance and duration of travel. Additionally, the average driving duration for the day is also lower for the simulated version by about 0.6 hours (36 minutes). Naturally, this depends on the stop density.

The simulated version seems to have its customers in a higher density, leading to a higher number of stops visited with a lower average distance travelled and average driving duration. The maximum route distance is comparable, which gives the extreme case for the driving distance. Also, the average work duration is 7.0 hours (including the 30-minute break), which is slightly below the 8 hours required by the vehicle. In conclusion, the VAM is taken to be precise enough to represent the case.

Table 5-11 Route statistics according to time group for Case D

Data set	Average number of stops (-)	Average (Maximum) distance (km)	Average work duration (h)	Average driving duration (h)
Real (Weekday)	10.9	69 (82)	-	2.2
Simulated	14.8	55 (84)	7.0	1.6

The routes for Case D are displayed in Figure 5-6. It is expected that the actual routes would be more scattered, since the average number of stops per routes are lower even with a higher average distance per route. The routes also feature a higher proportion of time spent within the built-up area, and less time just spent on roads.

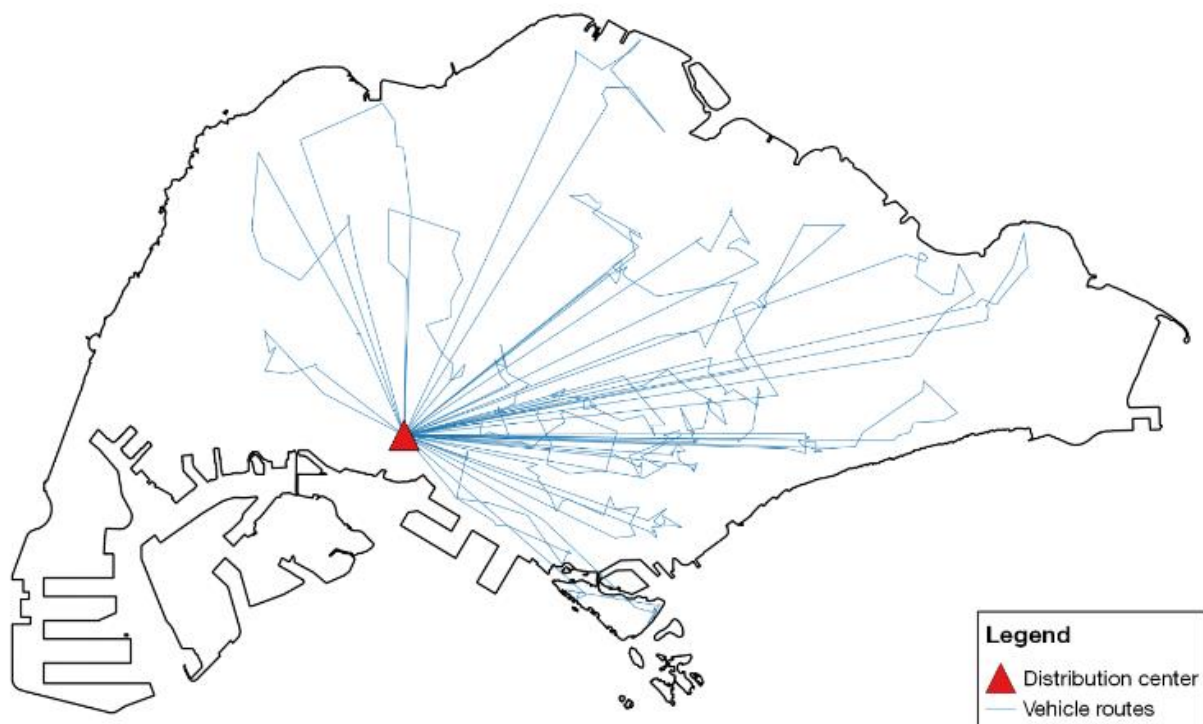


Figure 5-6 Visualised routes in Case D

### 5.4.3. Vehicle system specification

For Case D, only the loading time charging strategy is not applicable. This is because there is only one route per day, and it occurs at the end of the work shift. Hence, scenarios S5 and S6 are not included in the following analysis. The vehicle system parameters are presented in Table 5-12.

On the weight, a key observation is that the DV in S0 is a LGV (with GVW equal or less than 3,500 kg), but the BEVs for overnight and highway charging is HGV (with GVW more than 3,500, but equal or less than 16,000 kg). The BEVs of the other scenarios are also LGV. This change will affect the comparison of the costs for purchasing and operating the vehicles.

The size of battery needed, if no opportunity charging strategy was used is 54 kWh, with a weight increase of 500 kg. The highway charging strategy does not change the system parameters. The most effective opportunity charging strategy is unloading time charging with a 56% reduction of battery capacity. The vehicle with this strategy only has a weight increase of 200 kg compared to the DV. The next best is the break time charging strategy with a battery capacity of 34 kWh. All the BEV scenarios use Level 2 charging.

Table 5-12 Vehicle parameters and changes of weight and battery capacity for Case D

Scenario ID	Scenario	Total vehicle weight (kg)	Battery capacity (kWh)	Overnight charging level
S0	Diesel vehicle	3,200	-	-
S1	Overnight conductive charging	3,700	54	Level 2
S2	Overnight inductive charging	3,700	54	Level 2
S3	Break time conductive charging	3,500	34	Level 2
S4	Break time inductive charging	3,500	34	Level 2
S7	Unloading time conductive charging	3,400	24	Level 2
S8	Unloading time inductive charging	3,400	24	Level 2
S9	Highway inductive charging	3,700	54	Level 2

#### 5.4.4. Suitability evaluation

The results of the FSI and ESI are presented in Table 5-13. None of the scenarios meet the financial suitability requirement, but all meet the environmental suitability requirement. For service lifetime 15 and 20 years, the FSI drop below 1% to 0.9% and 0.7%, respectively. The ESI are very low, with the highest being 17.3% under the threshold. Hence, Case E has a stark contrast between the FSI and ESI. Nevertheless, none of the scenarios are considered suitable.

The scenarios without opportunity charging, S1 and S2, and the highway charging scenario, S9, has relatively very high FSI compared to S3 to S8. This can be attributed to the use of vehicles with higher weight class than the diesel vehicle scenario (see Table 5-12). Using the highway charging strategy does not confer any benefits to the financial or environmental suitability.

Table 5-13 Summary of suitability indicators for Case D

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	13.5%	12.5%	12.9%	-59.2%
S2	14.7%	13.5%	13.8%	-55.3%
S3	1.9%	2.1%	1.4%	-59.9%
S4	4.8%	4.6%	3.7%	-56.1%
S7	1.9%	0.9%	0.7%	-60.4%
S8	4.8%	3.4%	3.1%	-56.6%
S9	17.3%	16.0%	16.2%	-53.2%

Greyed out boxes meet the suitability thresholds

## 5.5. Case E: Furniture home delivery service

Cases E and F are developed based on an interview with the same company, referred to here as Company E. Both serve a different aspect of UFT. Company E is a global furniture retailer, with two large stores in Singapore. Case E is a home delivery service for the furniture retailer. The home delivery service, not restricted to only online retail, is fairly common, ranging from pizza to electronics. Especially for furniture, such a service is important in Singapore,

since car ownership is low and even for car owners, the vehicle sizes may not be large enough for transporting furniture. The transport activity is undertaken by a third-party service provider, but the orders, as part of the customer service by Company E, is managed and scheduled in-house. The interviewee is the Retail Logistics Manager, who has intimate knowledge of the transport operations from the retail perspective. The standard methods for developing the case study are used.

### **5.5.1. Interview results**

Company E operates two large retail stores in Singapore, which double up as storage space for inventory. The home delivery service originates from both stores, henceforth referred to as S1 and S2. Each store makes about 200 deliveries a day on average. The customers' locations are predominantly in residential areas. The planning and operations of both stores are conducted separately. The products are generally boxed un-assembled furniture products.

The fleet size is 20 to 22 trucks from S1 and 30 trucks from S2. The routes are customized every day depending on the demand. In addition to the delivery of the products, the driver and assistant also may provide assembly services on location. According to the interviewee, the duration of a route could range from 20 to 30 minutes for only a delivery, but from one to three hours for delivery and assembly. The duration of unloading also may range from 60 to 90 minutes. Naturally there is a contradiction here with the route duration, but the interviewee described the extremes as being quite feasible. The loading duration is also described as taking 60 to 90 minutes.

As is common for home deliveries, customer time windows are important and strict, such that the recipient is available and at the delivery location. There are four time windows every day, in three-hour periods from 9:00 am to 9:00 pm. There is only one shift per day. The interviewee only mentioned one break per day from 12:00 noon to 1:00 pm. Each vehicle may service from four to six routes per day, each having four to six customers. The operations run seven days a week.

### **5.5.2. Vehicle activity model**

The data provided in the interview are quite limited. The customer list is created using the standard method, using a random selection based on the major regions in Singapore. The customers in the North, North-East and East regions are served by S1, while the Central and West regions are served by S2. The customers are also randomly assigned a shipment weight of either 500 or 1,000 kg in equal proportion.

The information obtained via the interview is used only as a guideline, since it seems that the interviewee described only the extreme cases of a very heterogeneous operation. Hence, several major assumptions are made, which simplify the modelling procedure. First, it is assumed that the loading time is 1 hour and the route duration is constrained to 5 hours

(including loading time). The unloading time varies as depending on the weight of the shipment. It is assumed that half of the customer’s order products with weight of 500 kg; the other half orders 1,000 kg. The unloading time is 30 minutes for shipment weight of 500 kg and either 60 or 90 minutes for shipment weight 1,000 kg, in equal parts. Second, it is assumed that each vehicle only takes 2 to 3 routes per day. Third, it is assumed that there are two one-hour breaks in the day, at 12:00 noon and at 6:00 pm.

Table 5-14 presents some of the statistics of the routes created. One notes that the average number of stops is much below the values given by the interviewee, which was from four to six. Also, on average the vehicles run only two to three routes per day. The average duration of each route ranges from 3.7 h to 4.1 h depending on time of day. Hence, there is much challenge in building a route based on the information provided. The route duration exceeds that provided by the interviewee (from 20 minutes to 3 hours), but still the number of stops does not approach four to six. Also, the number of deliveries does not even come near to the 200 deliveries per store mentioned in the interview. The visualisation of the routes are presented in Figure 5-7

Table 5-14 Route statistics according to time group for Case E

Time group	Number of routes (-)	Average number of stops (-)	Average (Maximum) distance (km)	Average duration (h)
Morning	52	2.5	29.8 (66.8)	4.1
Afternoon	52	2.5	20.7 (33.1)	3.9
Evening	15	2.7	19.3 (31.3)	3.7

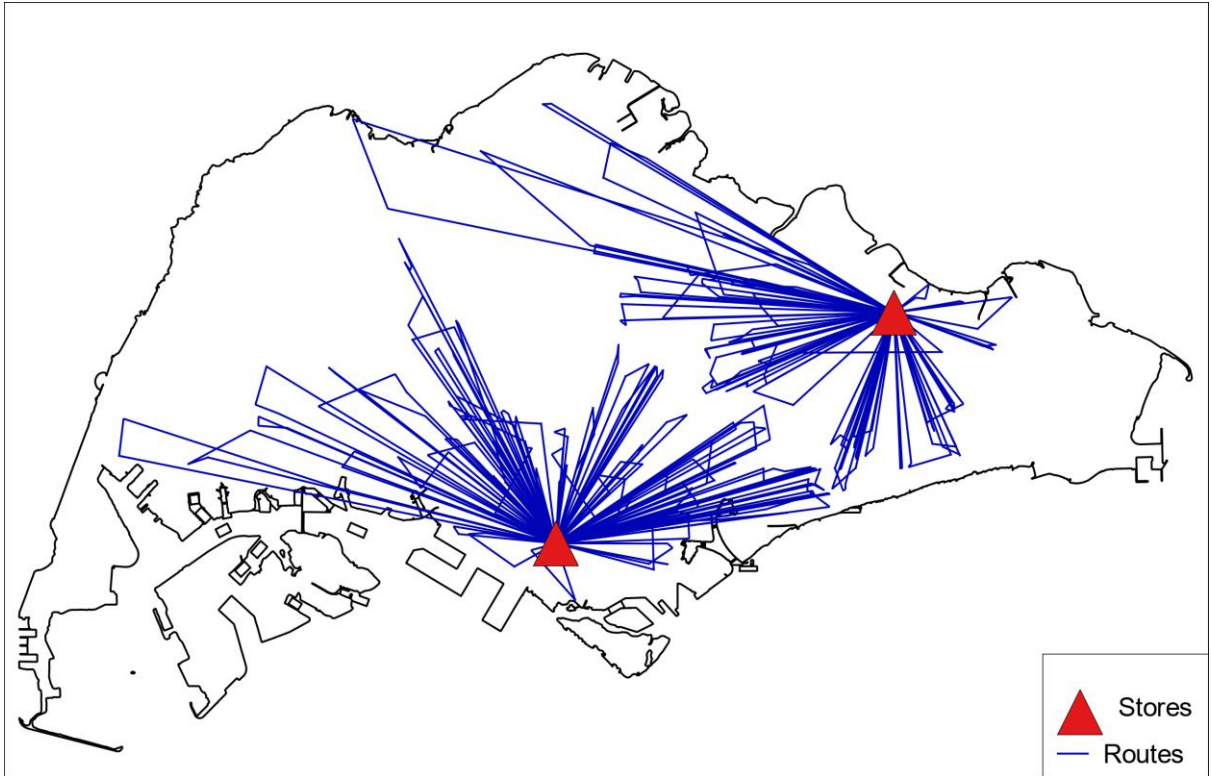


Figure 5-7 Visualised routes according to the stores in Case E

### 5.5.3. Vehicle system specification

For Case E, all four opportunity charging strategies can potentially be used. The vehicle system specifications are presented in Table 5-15. Without opportunity charging, the electric vehicle needs 60 kWh of battery capacity to complete the route, which is an increase of only 500 kg compared to the diesel vehicle. The most effective charging strategy is the unloading time charging strategy with a 300 kg weight decrease and a 52% battery capacity reduction compared to the scenario without opportunity charging. The BEV also only has an increase of 200 kg compared to the DV. The BEVs of the break time and highway charging strategies have the same specifications, which are 39 kWh battery capacity. All the BEV scenarios use Level 2 overnight charging.

Table 5-15 Vehicle parameters and changes of weight and battery capacity for Case E

Scenario ID	Scenario	GVW (kg)	Battery capacity (kWh)	Overnight charging level (-)
S0	Diesel vehicle	4,500	-	-
S1	Overnight conductive charging	5,000	60	Level 2
S2	Overnight inductive charging			
S3	Break time conductive charging	4,800	39	Level 2
S4	Break time inductive charging			
S5	Loading time conductive charging	4,900	49	Level 2
S6	Loading time inductive charging			
S7	Unloading time conductive charging	4,700	29	Level 2
S8	Unloading time inductive charging			
S9	Highway inductive charging	4,800	39	Level 2

### 5.5.4. Suitability evaluation

The results of the FSI and ESI are presented in Table 5-16. In S7, the financial suitability requirement is met for only service lifetime 15 and 20 years, but in S3, it is met for all three service lifetimes. The ESI only meets the requirement for scenarios with conductive technology (S1, S3, S5, and S7). Hence, only S3 and S7 have scenarios that fully meet both suitability requirements. This means that the use of break time and unloading time charging strategies are needed if Company E would like to use BEVs.

Table 5-16 Summary of suitability indicators for Case E

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	1.2%	0.3%	0.4%	-37.3%
S2	1.9%	0.9%	1.0%	-31.3%
S3	-0.1%	-0.1%	-0.5%	-38.6%
S4	1.5%	1.3%	0.7%	-32.7%
S5	1.0%	0.2%	0.4%	-37.3%
S6	2.7%	1.7%	1.8%	-31.3%
S7	0.1%	-0.6%	-0.7%	-39.1%
S8	1.8%	0.9%	0.7%	-33.3%
S9	2.1%	2.0%	1.4%	-28.1%

Greyed out boxes meet the suitability thresholds

## 5.6. Case F: Furniture store replenishment

Company E also requires the transport operation described in Case F, in order to replenish their large furniture retail stores in the city. Making use of the Singapore port as the entry point into the city, the company makes several shuttle trips of FCL from the port and the stores per day. It can be expected that many other industries follow the same transport pattern for their stores, warehouses or factories in the city. Hence, the particular case study is quite an important case for the city, as well as other port cities globally. The transport activity is undertaken by a third-party service provider, but is briefly described by the same interviewee from Case E, the Retail Logistics Manager.

### 5.6.1. Interview results

The shuttle transports up to seven times a day to each retail store a 40-foot container. The origin is in the port; however, the exact location is not given. A single vehicle handles the transport for each retail store, hence there are two vehicles altogether, which handle the transport. The duration of unloading and loading are not described. Time windows are also not given, but the same breaks and shift-change times are assumed.

### 5.6.2. Vehicle activity model

The model assumes that one vehicle makes seven trips from their respective retail outlets to the port consecutively. In this case, the duration of the seven trips determines the operation time of the vehicle. In the previous cases, the operation time is a restricting factor for the duration of routes. The retail outlet addresses are obtained from the company's website. The size of each transport is dependent on the volume of the 40-foot container, and an assumed payload space utilization, and the assumption of density of furniture. The interior volume of the container is roughly about 67.6 m<sup>3</sup>, the utilization is assumed to be 75% (Larsson, 20 May. 2011), and the assumption of density of furniture is taken to be 6 pounds

per cubic feet (Robinson, 2013), which roughly translates into 96.1 kg/m<sup>3</sup>. The payload then is rounded up to 4,900 kg.

Time windows are not considered here. The loading time at the port is 30 minutes, while the unloading at the store is 20 minutes. As both routes are unequal in duration, the operation time is different. The total driving time for the first route is about 5 hours longer than the second. Hence, it is assumed that there is a shift change in the evening for the drivers of the first store. The schedules for the drivers of the first store (henceforth F1) are as follows: the driver starts at 7:00 am and carries out three trips before a one-hour break for lunch at about 1:00 pm. After lunch, the driver carries out two trips before a shift change at about 7:00 pm. The next driver carries out the last two trips and returns to the store at about 12:00 midnight. The schedules for the drivers of the second store (henceforth F2) are as follows: the driver starts at 7:00 am and finishes four trips by 12:00 noon. After an hour-long break, the driver resumes work at about 1:00 pm and ends at about 5:00 pm. The route statistics of the operations for both stores are presented in Table 5-17. The operations run seven days a week. The locations of the port and the stores are presented visually in Figure 5-8.

Table 5-17 Route statistics according to time group for Case F

Case	Number of trips of same route (-)	Route distance (km)	Route duration (h)
F1	7	64.7	2.1
F2	7	16.3	1.3

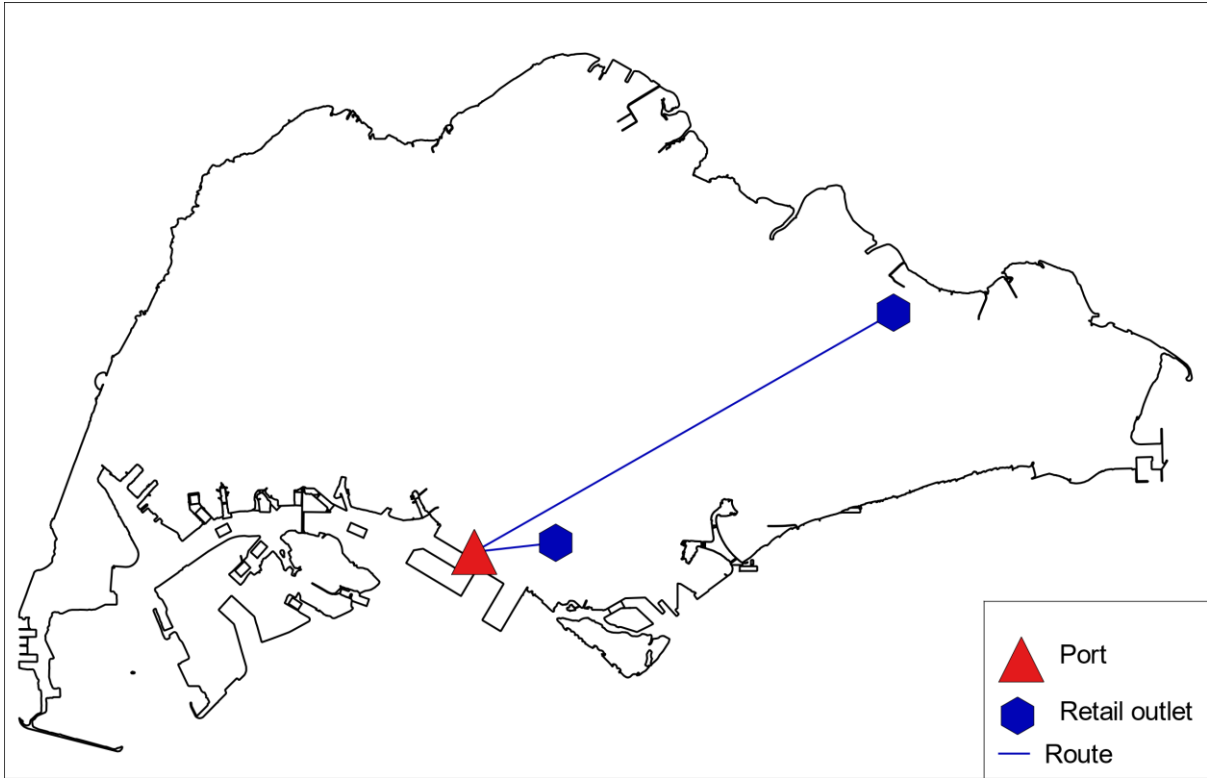


Figure 5-8 Locations and trips made from port to stores in Case F

### 5.6.3. Vehicle system specification

For Case F, all four opportunity charging strategies are assessed. The vehicle parameters for F1 and F2 are given in Table 5-18 and Table 5-19, respectively.

For Case F1, the battery capacity for the vehicle without opportunity charging usage is a massive 594 kWh, which increases the weight of the vehicle by almost 6 tonnes. Bear in mind that the payload was only 4,900 kg. The most effective charging strategy is highway charging, which reduces the battery capacity in comparison to the overnight charging strategy by 95% to 29 kWh. The result is a BEV that weighs only 200 kg more than the DV. The other opportunity charging strategies also deliver significant reductions to the required battery capacity. The break time and unloading time strategies reduce the battery capacity 332 kWh, whereas the loading time strategy reduces it 180 kWh. The overnight charging power of Level 3 is needed for the big batteries in the scenarios with overnight, break time, and unloading time charging. The others use Level 2 charging.

For Case F2, the BEV without opportunity charging uses a battery of 150 kWh, which is significantly less than the BEV in the same scenario in Case F1. The most effective opportunity charging strategy is also the highway charging with a reduction in battery capacity of 87%. It also only weighs 100 kg more than the DV. The next best strategies are loading and unloading time charging strategies with a battery capacity of 29 kWh. All the BEVs use Level 2 charging system for overnight charging.

Table 5-18 Vehicle system specifications for Case F1

Scenario ID	Scenario	GVW (kg)	Battery capacity (kWh)	Overnight charging level (-)
S0	Diesel vehicle	13,000	-	-
S1	Overnight conductive charging	18,800	594	Level 3
S2	Overnight inductive charging	16,200	332	Level 3
S3	Break time conductive charging	16,200	332	Level 3
S4	Break time inductive charging	14,700	180	Level 2
S5	Loading time conductive charging	14,700	180	Level 2
S6	Loading time inductive charging	16,200	332	Level 3
S7	Unloading time conductive charging	16,200	332	Level 3
S8	Unloading time inductive charging	13,200	29	Level 2
S9	Highway inductive charging	13,200	29	Level 2

Table 5-19 Vehicle system specifications for Case F2

Scenario ID	Scenario	GVW (kg)	Battery capacity (kWh)	Overnight charging level (-)
S0	Diesel vehicle	13,000	-	-
S1	Overnight conductive charging	14,400	150	Level 2
S2	Overnight inductive charging	13,800	90	Level 2
S3	Break time conductive charging	13,200	29	Level 2
S4	Break time inductive charging	13,200	29	Level 2
S5	Loading time conductive charging	13,100	19	Level 2
S6	Loading time inductive charging			
S7	Unloading time conductive charging			
S8	Unloading time inductive charging			
S9	Highway inductive charging			

#### 5.6.4. Suitability evaluation

The results of the FSI and ESI for cases F1 and F2 are presented in Table 5-20 and Table 5-21, respectively. The overall results for both cases are very positive, with only Case F1 having a few unsuitable scenarios and with Case F2 having none. The environmental suitability requirement is met by all scenarios, including the scenarios without opportunity charging, which means that opportunity charging is not necessary for both F1 and F2.

In F1 S2, S4 and S8 have scenarios which do not meet the requirement. S3 and S4 have exactly the same outcomes. The best opportunity charging strategy for F1 and F2 is the loading time strategy.

Table 5-20 Summary of suitability indicators for Case F1

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	-0.4%	-0.3%	-3.4%	-43.6%
S2	3.4%	3.1%	-0.2%	-38.3%
S3	-2.1%	-4.2%	-5.5%	-44.9%
S4	2.4%	-0.1%	-1.6%	-39.6%
S5	-8.8%	-10.8%	-11.3%	-45.8%
S6	-5.8%	-7.9%	-8.4%	-40.6%
S7	-2.1%	-4.2%	-5.5%	-44.9%
S8	2.4%	-0.1%	-1.6%	-39.6%
S9	-4.5%	-5.3%	-5.8%	-36.5%

Greyed out boxes meet the suitability thresholds

Table 5-21 Summary of suitability indicators for Case F2

Scenario	FSI for service lifetime:			ESI
	10	15	20	
S1	-3.5%	-3.0%	-4.1%	-46.7%
S2	-2.5%	-2.0%	-3.2%	-41.6%
S3	-3.5%	-3.9%	-4.4%	-46.5%
S4	-1.6%	-2.2%	-2.7%	-41.4%
S5	-5.2%	-5.4%	-5.8%	-46.4%
S6	-3.1%	-3.4%	-3.9%	-41.3%
S7	-5.4%	-5.6%	-6.0%	-46.5%
S8	-3.4%	-3.7%	-4.1%	-41.4%
S9	-3.3%	-3.8%	-4.2%	-39.1%

Greyed out boxes meet the suitability thresholds

## **6. Discussion of results**

The purpose of the CCA is to isolate factors, whether hidden or accounted for in the study, which contribute to different quantitative outcomes in the study. Here it is important to distinguish between the final results, such as the suitability indicators, and the intermediate ones. The aim of this section is the analysis of the results, specifically in tying in the results to specific factors that are distinct to the systems.

In this chapter, the following influences are discussed:

- lengthening the service lifetime,
- UFT attributes,
- charging system technology,
- the fit of opportunity charging strategies,
- improvements in battery technology,
- changes in electricity prices, and
- changes in emissions factors for electricity generation.

Also, the potential for financial incentives to encourage BEVs is discussed. This particular issue is important, because of its policy implications. But, first an overview of all the cases and scenarios are presented.

### **6.1. Overview of all cases**

There are seven unique cases (A to F2), which have different reactions to the methods used and the suitability requirements. The frequency that each suitability requirements decides the failure of the scenarios are presented in Table 6-1. The first observation one makes is that the environmental suitability requirement alone did not “fail” any scenarios. In cases A, B, and E, it fails together with the financial suitability requirement. The number of scenarios, which fail both requirements, are 19 more than the scenarios, which fail neither. The scenarios, which fail only the financial suitability requirement, is almost half the scenarios, which fail both requirements.

Cases A, B and E have a very high number of scenarios, which fail both suitability requirements. Cases C, D, and F1 only have failed scenarios related to the financial suitability requirement. For Case D, all its scenarios are eliminated because of it. Case F2 is the only case without any failed scenarios.

Table 6-1 Frequency of scenarios, which fail the suitability requirements

Case (Total BEV scenarios)	Fail suitability requirements			
	Both	Financial ONLY	Environmental ONLY	Neither
Case A (27)	24	3	0	0
Case B (27)	24	1	0	2
Case C (27)	0	2	0	25
Case D (21)	0	21	0	0
Case E (27)	15	7	0	5
Case F1 (27)	0	4	0	23
Case F2 (27)	0	0	0	27
<b>Total</b>	<b>82</b>	<b>38</b>	<b>0</b>	<b>63</b>

The spread of the FSI values according to the cases are presented in Figure 6-1. Each bin spans 1%. At the extremes are the scenarios from case D, which have an FSI more than 10%, and the scenarios from case F1, which have an FSI less than or equal to -10%. The median of the FSI falls within the range of 0 to 1%. 55% of the scenarios fail the suitability requirement of 0. If companies can accept a higher threshold value, such as 1% (which means that the cost is 1% more than that of the diesel vehicle scenario), the number of failed scenarios drop to 46% and case D has two scenarios, which pass the requirement.

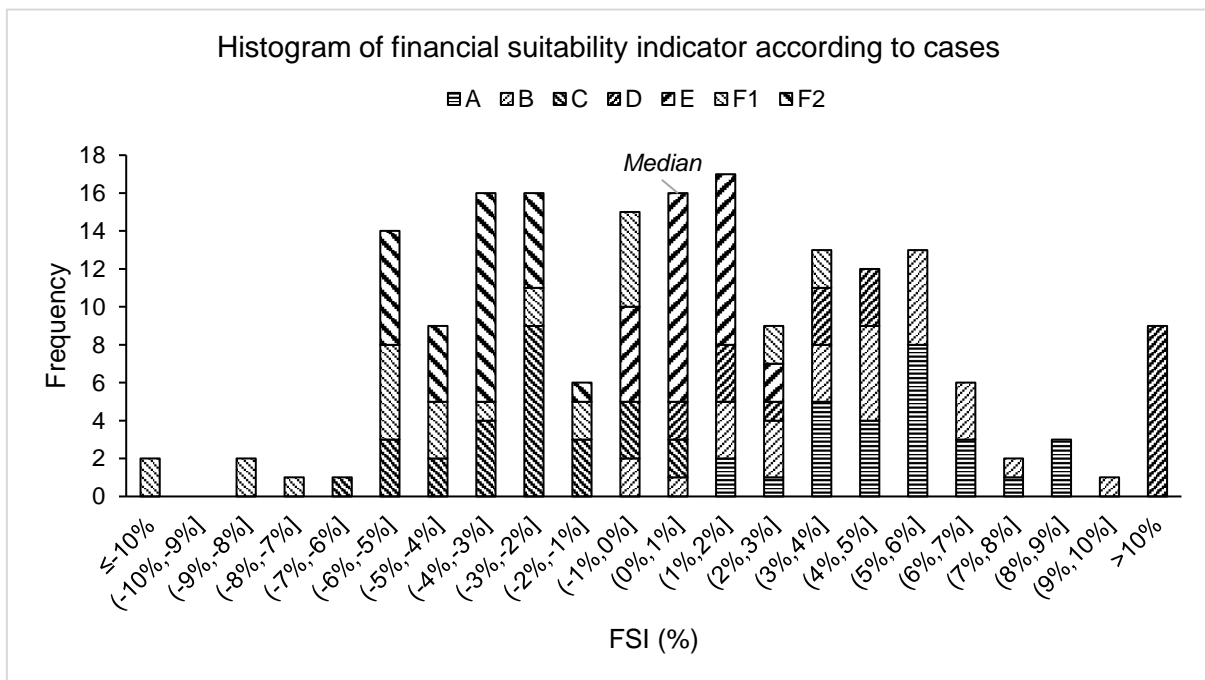


Figure 6-1 Histogram of financial suitability indicator according to cases

Alternatively, if the threshold value is reduced by 1%, the number of failed scenarios increase to 67% and case B loses two of its scenarios, which pass the requirement. This makes the choice of the suitability requirement threshold value quite important. Note that the choice of the threshold value for the financial suitability requirement is one that the policy maker presumes the freight carrier company makes. While it is most reasonable to assume that the

cost over the lifetime of service does not exceed that of the diesel vehicle, some companies may be willing to assume higher costs in order to achieve other sustainability goals.

In Figure 6-2, the distribution of the ESI of the scenarios are presented. The ESI is only counted once per scenario in each case, unlike as for the FSI indicators, which are multiplied by 3 to account for the different service lifetimes. Almost half of the scenarios have an ESI less than or equal to -46%. The median is also found in the range of -40 to -39%, which is at least 3% less than the threshold value of -36%. The suitability requirement eliminates 34% of the scenarios. If increased to -35%, this percentage does not change. But, if reduced to -37%, the percentage of failed scenarios increases to 43%; also all the scenarios of Case A fails. The sensitivity of the environmental suitability evaluation to the threshold value is lower than for the financial suitability evaluation, but still at a case basis, it can eliminate a single use case.

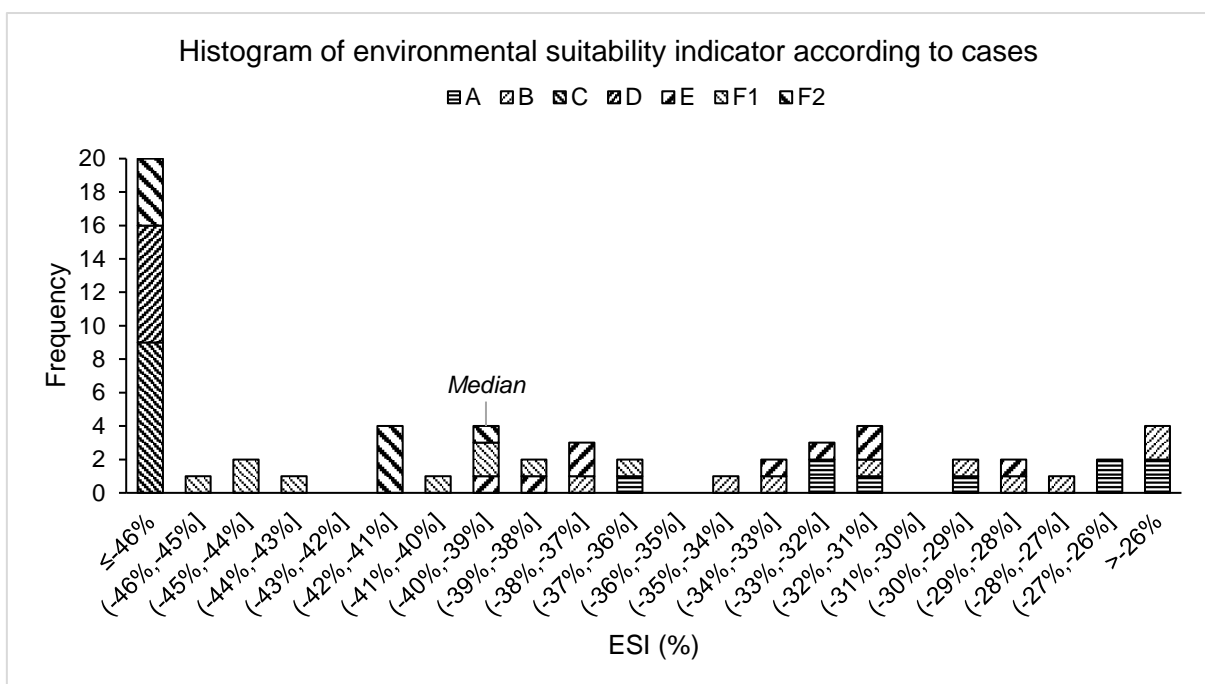


Figure 6-2 Histogram of environmental suitability indicator according to cases

Even for the environmental suitability, there is a need for a sensitivity analysis, with an appropriate sample size to decide the appropriate threshold value. The value of -36% works in that at least one scenario for each case is permitted. A further step is to determine why some of these scenarios fail; some having reductions less than 26%.

## 6.2. Service lifetime influence

For each case and charging strategy and method, a scenario is created for the financial suitability indicator for three service lifetimes – 10, 15, and 20 years. The years correspond to available maximum lifetime limited by the COE in Singapore. The vehicle owner must pay for an extension of the COE at the end of the first 10 year period, which is covered by the initial

COE. The owner can choose an extension of 5 or 10 years, with a half and full cost for the COE paid.

Here, the effect of extending the lifetime from 10 years to 15 and 20 years on the FSI is examined. It is assumed that there are no annual changes to the emissions of CO2, hence this service lifetime bears no relevance to the calculation of the ESI. In the discussion of the FSI, the cost categories shown in Table 6-2 will be useful to see a detailed breakdown of where the costs come from.

Table 6-2 Notation for cost categories

<b>Notation</b>	<b>Cost category</b>
<b>C1</b>	Vehicle purchase price minus resale value
<b>C2</b>	Battery replacement cost
<b>C3</b>	Charging equipment cost
<b>C4</b>	Road tax
<b>C5</b>	Salary
<b>C6</b>	Insurance
<b>C7</b>	Maintenance cost
<b>C8</b>	Energy cost

The logic of the financial calculation method used – the lifecycle cost analysis – generally assumes that the longer the “lifecycle” (or service lifetime), the better the advantage the BEV has over the DV in terms of the NPV. The reason for this is that the heavy initial investment is balanced out by savings in operating cost over the lifetime.

Table 6-3 shows how the contribution of the cost categories to the FSI changes for each case, when the service lifetime is extended to 15 and 20 years. The categories used are for major purchases (C1, C2, and C3) and for the operating costs (C4, C5, C6, C7, and C8).

The results confirm the general notion that lengthening the usage will reduce FSI because of the costs of the major purchases, while operating costs show very little changes. Nevertheless, the size of the impacts depends on the attributes of the different cases. Also, note that the cost for battery replacement is included in the major purchases category although it may be considered a maintenance cost. This likely reduces the size of the impact, since the longer the service lifetime, the higher the chance that the battery is replaced.

Table 6-3 Change according to contribution of cost categories to the FSI when the service lifetime is lengthened.

Case	Change from 10 to 15 years (%)		Change from 10 to 20 years (%)	
	Major purchases	Operating costs	Major purchases	Operating costs
<b>A</b>	-1.6%	0.0%	-2.3%	-0.1%
<b>B</b>	-1.2%	-0.1%	-1.8%	-0.1%
<b>C</b>	-1.1%	-0.3%	-1.3%	-0.5%
<b>D</b>	-1.0%	0.1%	-1.2%	0.1%
<b>E</b>	-0.6%	-0.1%	-0.7%	-0.1%
<b>F1</b>	-1.4%	-0.2%	-2.8%	-0.4%
<b>F2</b>	0.0%	-0.2%	-0.4%	-0.3%

Table 6-4 Count of financially suitable scenarios per case by service lifetime

Cases	10 years	15 years	20 years
<b>A</b>	0	0	0
<b>B</b>	0	1	1
<b>C</b>	7	9	9
<b>D</b>	0	0	0
<b>E</b>	1	2	2
<b>F1</b>	6	8	9
<b>F2</b>	9	9	9

Extending the service lifetime also causes some scenarios to pass the financial suitability requirement, thus making the scenarios suitable. The changes are summarized in Table 6-4. The most important result is for case B, which at 10 years does not have a single suitable scenario, but at 15 and 20 years has one suitable scenario. The improvements affect four out of seven cases (B, C, E, and F1). Case F2 does not change because all the scenarios are already suitable. Notably, case A does not have any changes, although the sizes of the changes are the largest (see Table 6-3).

Efforts to extend the service lifetime of the vehicle do pay off for most of the cases, even when considering the replacement costs of the battery. Policy makers can consider altering the COE constraints particularly for BEVs, such that the default duration is 15 years. With further research on the technical lifespan of the vehicle (excluding the battery, which can be replaced), the need for a regular renewal to “keep up” with the latest vehicle innovations is obsolete. Nevertheless, this has to be discussed within the broader context of urban transport policy.

### 6.3. Case comparisons for scenarios without opportunity charging

In this section, the scenarios without the use of opportunity charging for service lifetime at 10 years are compared according to their cost breakdown, as well as their energy usage and CO2 emissions. The scenarios are grouped into three sets, which are:

- Set 1: Cases A, B, and E
- Set 2: Cases C and D
- Set 3: Cases F1 and F2.

These combinations are chosen due to similarities to their case descriptions, as well as differences to their suitability outcomes. The reasons for the combinations are given in each individual section.

#### 6.3.1. Set 1: Cases A, B and E

The cases A, B and E have the following in common: distribution to a very large number of customers at home or business addresses, using a big fleet, and a vehicle cycle from morning to late in the evening. Table 6-5 shows several statistics on the vehicle utilization of the different cases. The first difference one notes is the much higher payload capacity needed for case E than the others, which leads to almost a doubling of GVW of the vehicles. This is linked to an average energy consumption rate difference of about 0.1 kWh/km for S1 scenarios.

Table 6-5 Statistics on per vehicle utilization in terms of duration, distance and energy for cases A, B and E

Case	A		B		E	
	S0	S1	S0	S1	S0	S1
GVW (kg)	2,400	3,100	2,400	3,200	4,500	5,000
Payload capacity (kg)	1,000		1,000		2,500	
Battery capacity (kWh)	-	78	-	88	-	54
Average vehicle operating time (h)	8.4		10.3		9	
Average distance travelled (km)	73		99		55	
Average energy consumed (kWh)	78	29	104	39	80	27
Average energy consumption rate (kWh/km)	1.07	0.40	1.05	0.39	1.45	0.49

Though the average work duration is quite similar, the intensity of driving is the highest in case B, with an average distance travelled of 99 km, compared to 73 km for case A and 55 for case E. Since case E involves furniture delivery and assembly, the time spent stationary is higher than for the other cases, which reduces the available time for driving (out of the total operating time).

On average, the vehicles in cases A and E consume almost the same amount energy. However, the battery capacity for case A is 24 kWh higher than for case E. One potential reason is the larger difference between the most intensively and the averagely used vehicle in

case A. This means that the majority of the fleet does not use its full battery capacity, resulting in unnecessary expenditure.

When comparing the differences in the NPV components (see Figure 6-3), the impact of the battery capacity on the vehicle purchase price (C1) is quite obvious. For vehicles from cases A and B, which are in the same weight class, a higher battery capacity implies a higher vehicle purchase price. The difference is stronger when compared to case E, which is much lower than both cases A and B.

Charging equipment (C3) and insurance costs (C6) are the next major contributors to the difference between the BEV and DV (i.e. between S1 and S0). But, the magnitudes are much smaller than the vehicle purchase price. Hence, the main contribution to a positive NPV-difference is the vehicle purchase price, though the vehicle insurance and charging equipment are also significant.

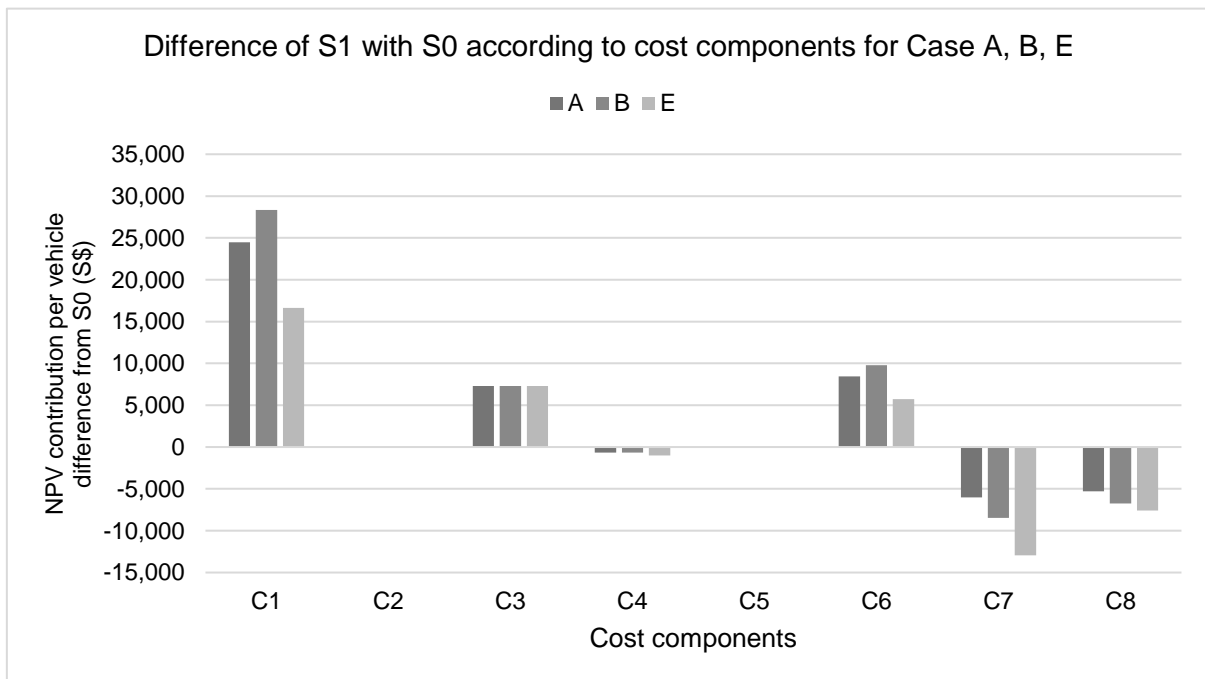


Figure 6-3 Change in NPV according to different cost categories for case A, B and E

Reducing the NPV-difference are the cheaper maintenance (C7) and energy (C8) costs. Individually, the magnitudes are lesser than the magnitude of the vehicle purchase price. One also notes that advantage brought by the lower maintenance costs is higher than for the energy costs. Within weight classes, maintenance costs varies according to the total distance travelled. Since the weight class for case E is higher, the magnitude of the difference is also higher although the total distance travelled is lower than the other cases. For the energy cost, the magnitude depends on the difference between the energy consumption rate between the DV and BEV (see Table 6-5).

In conclusion, the comparison between the cases A, B and E, as vehicle purchase price is usually the larger positive contributor to the FSI (by way of the NPV difference calculation), the factors that lead to a larger vehicle purchase price needs to be examined. In the calculation

methods, the battery capacity is designed to accommodate the longest distance travelled. The higher battery costs lead almost proportionally to a higher contribution to the FSI for each case. This implies that keeping the longest distance travelled by the vehicle in a fleet is important for the FSI. But, on the other hand, the “benefit” of lower costs increases the more the vehicle is used. To leverage both these conclusions, the following is recommended: the work done by the vehicles in the fleet should be more balanced, such that the battery is sized closer to the average amount of energy consumed. This can be achieved by optimizing the routes and assignment of routes according to energy usage, instead of the more commonly used objective, costs.

### **6.3.2. Set 2: Cases C and D**

Cases C and D are replenishment deliveries to multiple stores around Singapore for temperature-controlled food. There are several differences between the cases, which are relevant for our study. The first is that in case C, the vehicle uses a compressor-based refrigeration, which consumes energy during the transport operation, whereas in case D, the vehicle uses a pre-cooled eutectic system. The eutectic system is cooled, while the vehicle is stationary at the depot, and hence there is a significant amount of energy used in case C for refrigeration compared to case D. Case C will also need to keep its engine switched on during stops to power the refrigeration. The eutectic system, however, has a significant weight contribution to the empty weight of the vehicles in case D.

The second difference is the payload capacity. In case C, the payload capacity required is 2.5 tonnes, whereas in case D, it is 600 kg. This may stem from the different sales model, both cases use. In case D, the company operates a van-sales model, which means that sales are made only when the van arrives at the stores and determines what needs to be replenished. No one knows, how much will be sold before then. The vans operate as a mobile warehouse. Hence, the drivers carry how much they think they might be able to sell on their route (with some buffer). In case C, the company can properly optimize the routes, since it is known beforehand how much product is to be shipped to each store. It does not carry the risk of having carried “too much”. The outcome of this is that the DV used is of a higher weight class than for case D.

Table 6-6 Statistics on per vehicle utilization in terms of duration, distance and energy for cases C and D

Case	C		D	
	S0	S1	S0	S1
<b>Scenario</b>				
<b>GVW (kg)</b>	4,400	5,500	3,200	3,700
<b>Payload capacity (kg)</b>	2,500		600	
<b>Battery capacity (kWh)</b>	-	110	-	54
<b>Average vehicle operating time (h)</b>	8		6.5	
<b>Average distance travelled (km)</b>	104		55	
<b>Average energy consumed (kWh)</b>	290	67	84	28
<b>Average energy consumption rate (kWh/km)</b>	2.79	0.64	1.53	0.51

The average distance travelled by the vehicles in case D are half that of in case C. This can be attributed to the lesser vehicle operating time, and the spread of the stops. The deliveries in case D are mainly to small shops dispersed in residential areas, and are not located far from each other, whereas in case C the outlets are part of a franchise that are usually located in commercial areas. This also results in a higher distance travelled on highways than in case D.

The ratio of energy consumption rate for S0 compared S1 in case C is more than four times. The ratio is higher than case D, which is about three times larger. This can be attributed to the energy consumed for refrigeration. As far as averages are concerned, this implies an advantage for the BEVs in case C compared to the DV. This advantage is less pronounced in case D.

These differences affect in part the differences in NPV between S0 and S1 for both cases. Figure 6-4 summarizes the differences. One observes that there are several odd values for case D in C4, C5 and C7. These can be attributed to the higher weight class for the S1 vehicle compared to the S0 vehicle in case D. This change in weight class affects the calculation model used because of the discrete categories used for the cost component rates. While the road tax (C4) increase is justifiable because of the legal distinction between the light duty vehicle and the heavy duty vehicle, the values for salary (C5) and for maintenance costs (C7) are proper limitations of the model. Nevertheless, even if these values were ignored, the differences between S1 and S0 are still positive, hence the scenario S1 would still be considered unsuitable. This despite the difference between purchase prices being quite low (roughly S\$15,000).

In contrast to case D, case C features a large positive-difference for the vehicle purchase price and an almost equally large negative-difference for the energy cost. The positive-difference for the vehicle purchase price is due to the large battery for case C, whereas the negative-difference for the energy cost can be attributed to the high energy consumption rate ratio mentioned previously. The maintenance cost also has a high negative-difference,

though much smaller than for the energy cost. It is smaller, because maintenance cost depends on distance travelled, but energy cost also depends on idle time.

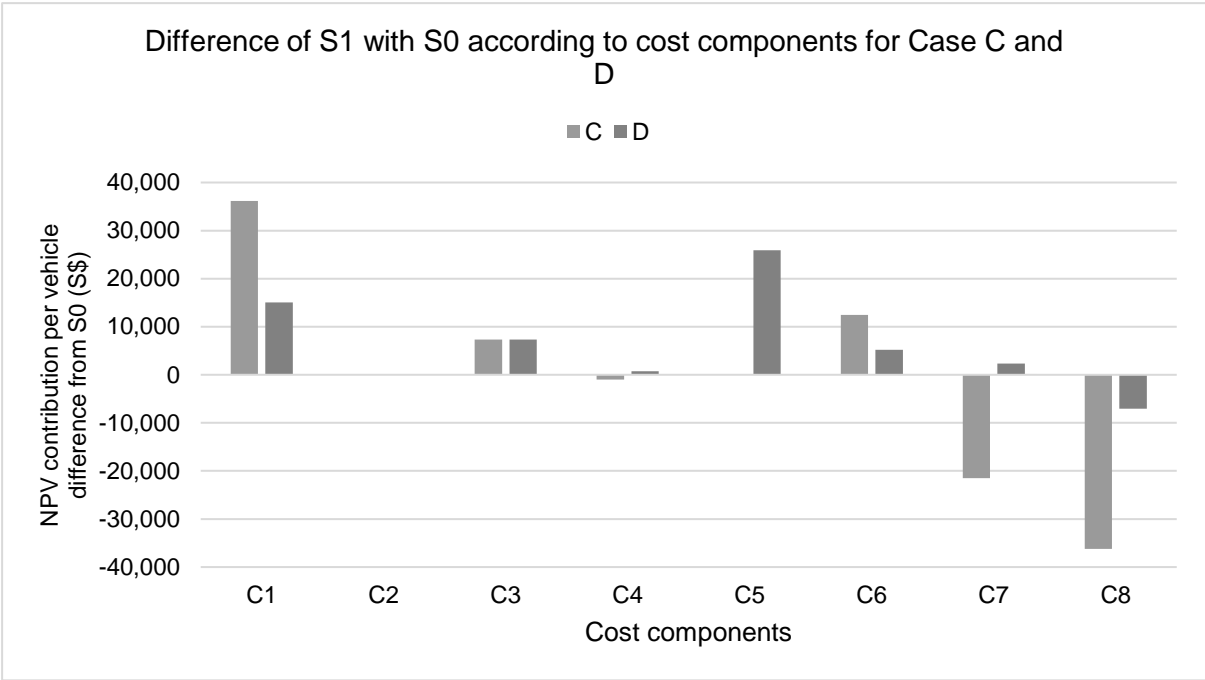


Figure 6-4 Change in NPV according to different cost categories for cases C and D

In conclusion, the case D provides an important example for accounting for the difference a weight class makes, not in terms of the technology, but because of contextual factors, such as road tax, salary, and maintenance costs. Though here, maintenance costs and salary are clearly limitations in the modelling, which could be replaced by a finer categorisation. The calculation of salary may also fall under influence of policy, where higher weight classes require a different driver’s license, often related to a higher salary rate. In case C, one observes that there is a strong case for using BEVs for delivery of refrigerated goods, as the ratio of average energy consumption rate is high. The ratio is high not only because of the energy needed for refrigeration, but also because the vehicle idling energy is taken into account.

**6.3.3. Set 3: Cases F1 and F2**

Cases F1 and F2 are practically the same, differing only in terms of the distance travelled for each route. The key statistics are presented in Table 6-7. For both cases, the fleet size is exactly one, which means that unlike the other cases, the discrepancy between the maximum distance travelled and the average does not play a role here. The vehicle in F1 travels roughly four times the vehicle in F2. This causes the battery capacity for the BEV in F1 to also be roughly four times that of the BEV in F2. The weight of the battery makes the GWV of the BEV in F1 higher than that of the BEV in F2 by about 4.4 tonnes. Surprisingly, despite

the much higher weight, the energy consumption rate for both scenarios are almost equal in both cases.

Looking at the NPV cost categories in Figure 6-5, one firstly observes that the NPV difference for the vehicle purchase price for case F1 is more than S\$200 thousand, whereas for case F2 it is less than S\$ 50 thousand. The maintenance cost and energy cost are also in the same order of magnitude. The case F1 also requires Level 3 charging for overnight charging, which makes a large positive-difference contribution.

Table 6-7 Statistics on per vehicle utilization in terms of duration, distance and energy for cases F1 and F2

Case	F1		F2	
	S0	S1	S0	S1
GVW (kg)	13,000	18,800	13,000	14,400
Payload capacity (kg)	4,900		4,900	
Battery capacity (kWh)	-	594	-	150
Vehicle operating time (h)	14.8		9.4	
Distance travelled (km)	453		114	
Energy consumed (kWh)	1589	474	405	116
Average energy consumption (kWh/km)	3.51	1.05	3.55	1.02

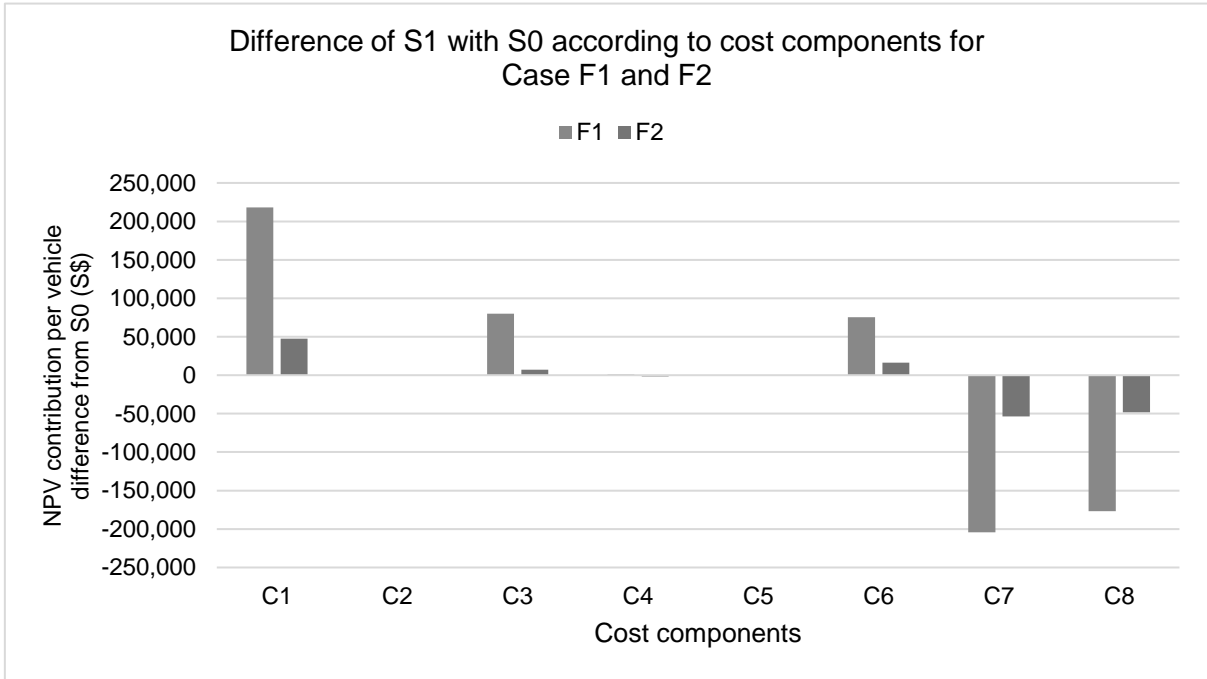


Figure 6-5 Change in NPV according to different cost categories for cases F1 and F2

The effect of the distance travelled of F1 being four times that for F2 is the four times more cost paid for maintenance, and the vehicle purchase cost. The ratio for the energy cost of F1 over F2 is less than four, which is probably because of the increase in average energy consumption for the BEV caused by the 4.4 tonnes increase in GVW.

In summary, the comparison between cases F1 and F2 show the role played by the distance travelled on the NPV. Besides the charging equipment cost, the scalable components

(C1, C6, C7 and C8) show an almost similar ratio. This can be attributed to the fact that because the fleet size is one, the battery capacity was modelled on both the maximum and the average distance travelled. The total distance travelled relates directly to the both the maintenance and energy cost, whereas the maximum distance travelled relates to the vehicle purchase cost. Reducing this variance may prove to be a key solution to increasing suitability of the electric mobility.

## 6.4. Influence of charging system technology

The use of conductive or inductive methods of energy transfer has a significant impact on the suitability of the BEV according to both the financial and environmental indicators. Figure 6-6 shows the spread of the percentage increase when inductive charging is used instead of conductive charging for scenarios without opportunity charging, with break time, loading and unloading time strategies. In other words, the scenario S1 is compared with S2, S3 with S4, S5 with S6, and S7 with S8.

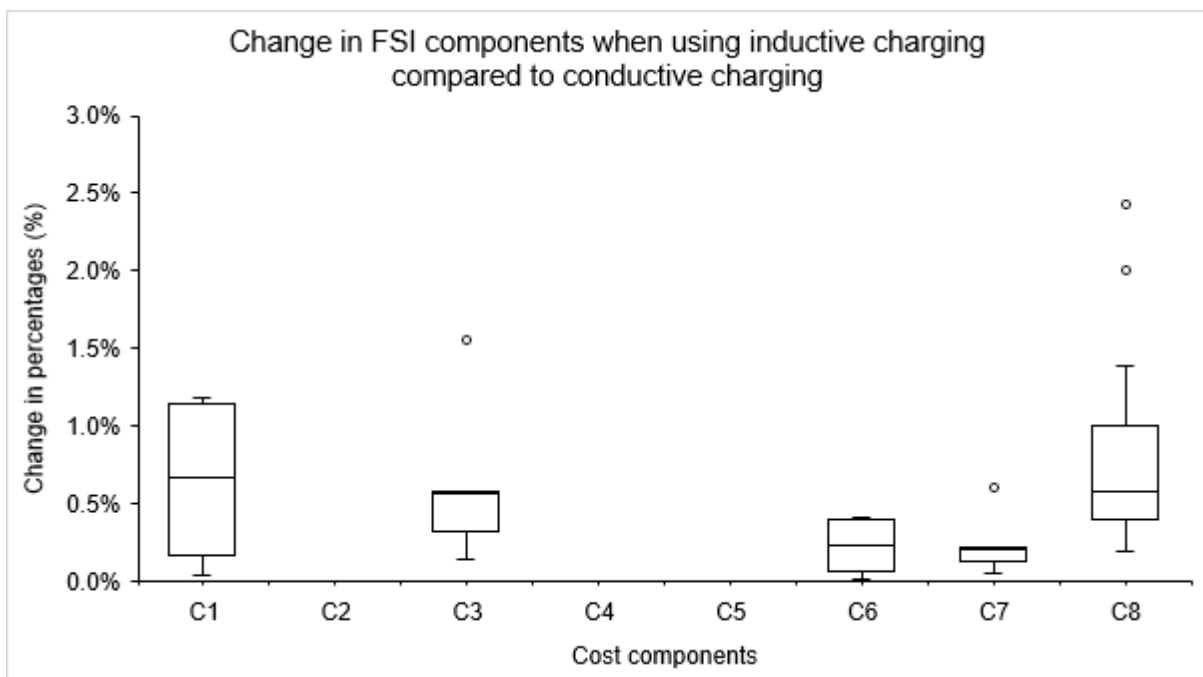


Figure 6-6 Influence of inductive charging systems on cost components

As expected, any changes, if there are any, results in a higher FSI component percentage. There are no changes in battery replacement costs (C2), road tax (C4) and salary (C5). As insurance cost (C6) is always proportional to the vehicle purchase cost (C1), the increase is also seen in the figure. In this case, the cost of maintenance (C7) is due to the increase in charging equipment cost (C3). The addition of the inductive charging receiver causes a median increase of about 0.7% to the vehicle purchase cost. In total, the FSI increase ranges from 0.7 to 4.5%, with a median of about 2.7 % (not shown in figure).

The drop in energy efficiency due to the inductive charging’s inefficiency affects both the energy costs and the CO2 emissions. The energy costs increase ranges from 0.2 to 2.4% with a median of about 0.8%. The increase in the ESI ranges from 4 to 7% compared to its conductive charging counterpart. These increases are significant enough to cause some cases, where the conductive charging scenarios are tested to meet the suitability requirements, to subsequently fail it in the inductive charging counterpart.

**6.5. Fit of opportunity charging strategies to the case studies**

In most cases there is a significant improvement of the suitability conferred by the use of an opportunity charging strategy. In this section, only the effect of the opportunity charging strategies on the vehicle purchase cost (C1), battery replacement cost (C2), and the energy cost (C8) are considered. The vehicle purchase cost is expected to reduce as the vehicle battery size reduces. However, with the higher number of charging activity, the battery replacement cost is expected to increase. Energy cost is also expected to increase since the charging efficiency increases the amount of energy finally transferred to the vehicle.

Figure 6-7 shows the effect the different opportunity charging strategies have on the vehicle purchase cost. Note that the comparison is done using the inductive charging scenarios only, i.e. S4, S6, S8, and S9 are compared with S2. This is to make it more comparable to the highway charging strategy, which only uses inductive chargers.

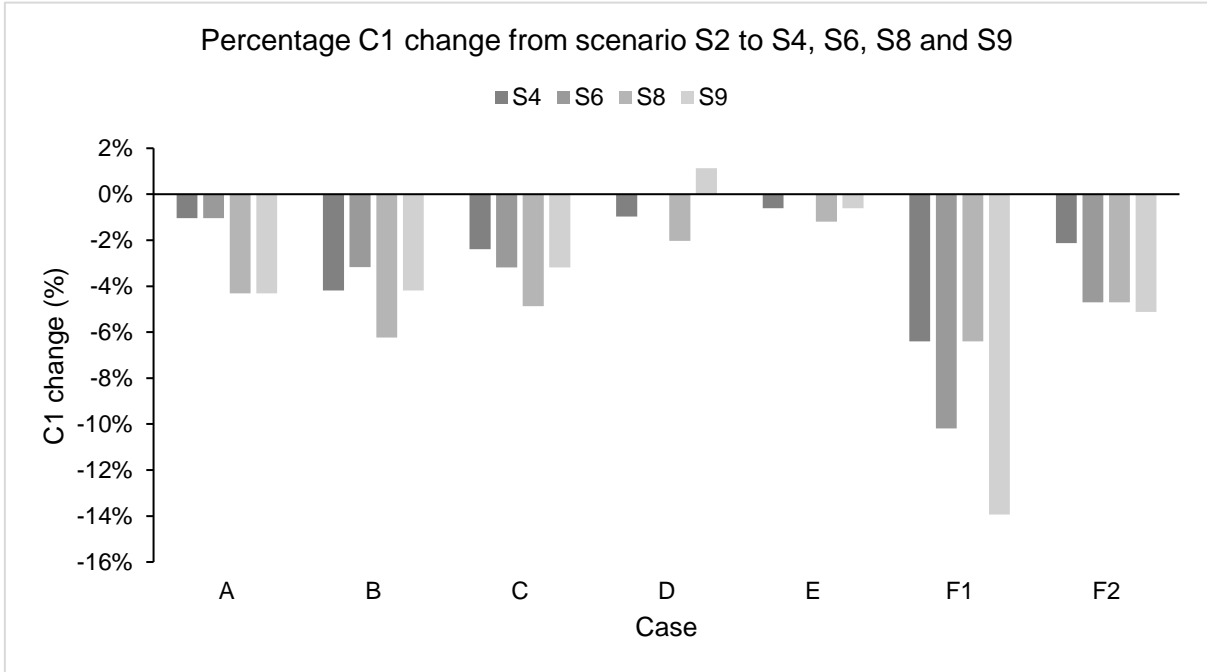


Figure 6-7 Change in percentage contribution of vehicle purchase cost (C1) by case and charging strategy

Comparison between and the case studies are summarized in two aspects: “pattern” and “scale”. The “pattern” reveals the hierarchy of effectiveness and fit that the charging strategies have on a particular case. Only cases B and E exhibit similar patterns of fit (in

decreasing fitness: Unloading – Break time and Highway – Loading), though they differ in scale. The other cases do not. As previously discussed in Section 6.3, cases A, B and E are very similar in route characteristics. However, case A was developed on a set of data obtained directly from the company, whereas cases B and E are based on synthesized data using the methodology outlined in previous chapters. The use of a synthesized transport demand may lead to developing a trend, which possibly would not be true, if actual transport demand data were used.

Only case D has an increase in the vehicle purchase cost compared to the scenario without opportunity charging. This is due to the need for a higher power inductive charging receiver on the vehicle, as well as because the use of the highway charging strategy did not reduce the battery capacity required. This has only occurred in case D, which implies that the route characteristics, which were focused mostly on urban roads, were not compatible with this opportunity charging scenario. On the other hand, case F1 has a very high compatibility with highway charging.

While the initial investment cost from the vehicle purchase cost generally reduces, there is an increase in the cost for the replacement of batteries, during the lifetime of the vehicle. As previously discussed, the cost of the battery is usually one of the highest costs in the vehicle purchase. The trade-off in reducing the battery capacity is the increase in opportunity charging energy cost and the increase in battery replacement cost. This can be seen in Figure 6-8, which combines these cost together.

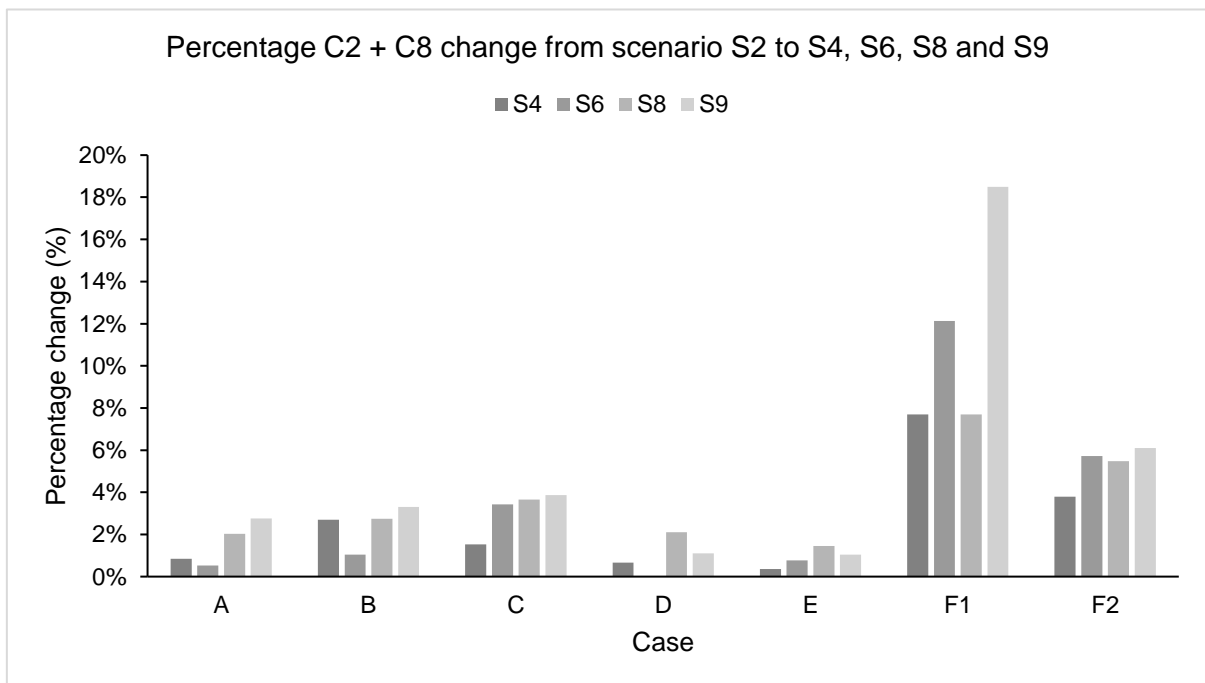


Figure 6-8 Change in percentage contribution of battery replacement and energy cost (C2 + C8) by case and charging strategy

Here, a similar “scale” of effects with the vehicle purchase cost in Figure 6-7 is observed. Cases A, B, C and F2 are in the middle-range. Case F1 is on the higher end of the spectrum, compared to both cases D and E, which are small.

Nevertheless, the final impact on the FSI is the result of also the other cost categories. Figure 6-9 presents the change in FSI because of the use of opportunity charging. Here, especially the impacts of reduction of the GVW, which reduces among others the salary costs, road tax costs, and maintenance costs are observed. Case D illustrates this perfectly, since it exhibited only a small scale of impacts, when only the vehicle, battery replacement and energy costs were considered.

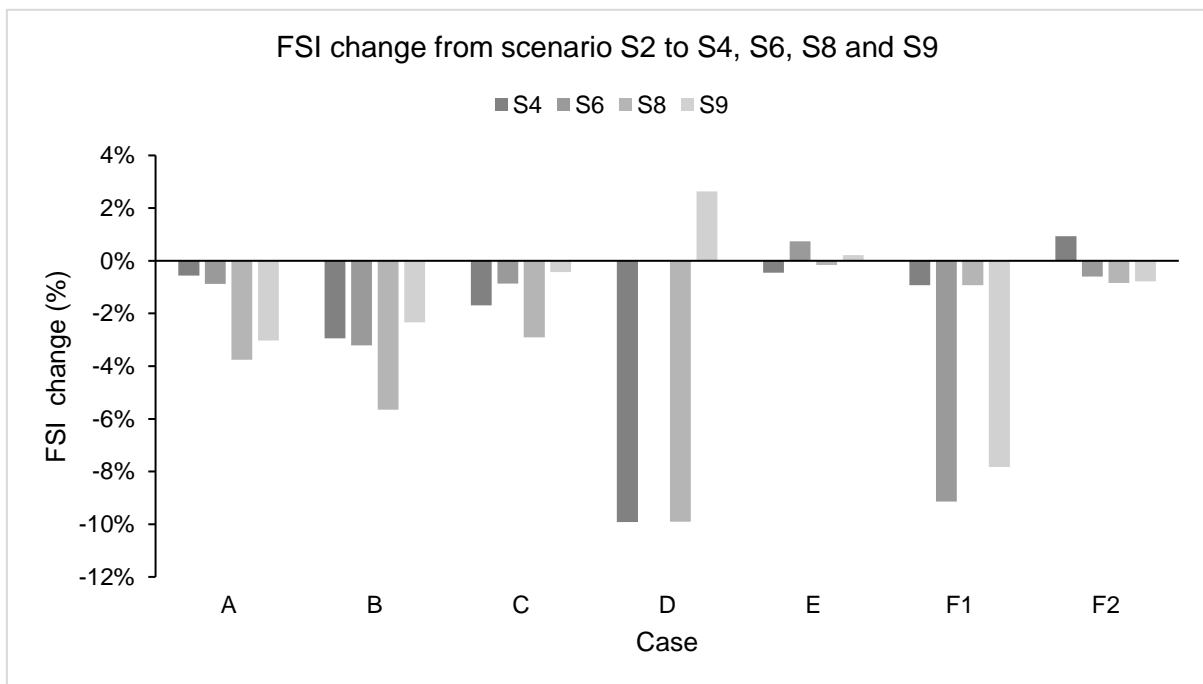


Figure 6-9 Change in FSI by case and charging strategy

Finally, the change in ESI are depicted in Figure 6-10. The type of charging equipment does influence the energy efficiency of the work done by the vehicles in the fleet. Hence, the different charging strategies, which may influence the type of equipment used, will change the emissions of carbon dioxide. However, the patterns here are also indiscernible. In general, there is a decrease in carbon dioxide emissions, and thus a decrease in ESI. However, in some cases, especially when highway charging is used, the ESI increases.

In summary, comparing the changes in the suitability indicators does not give reason to assume that suitability can be generalized depending on the characteristics of the cases. It is instead recommended that calculations with as accurate data as possible be repeated for each individual case.

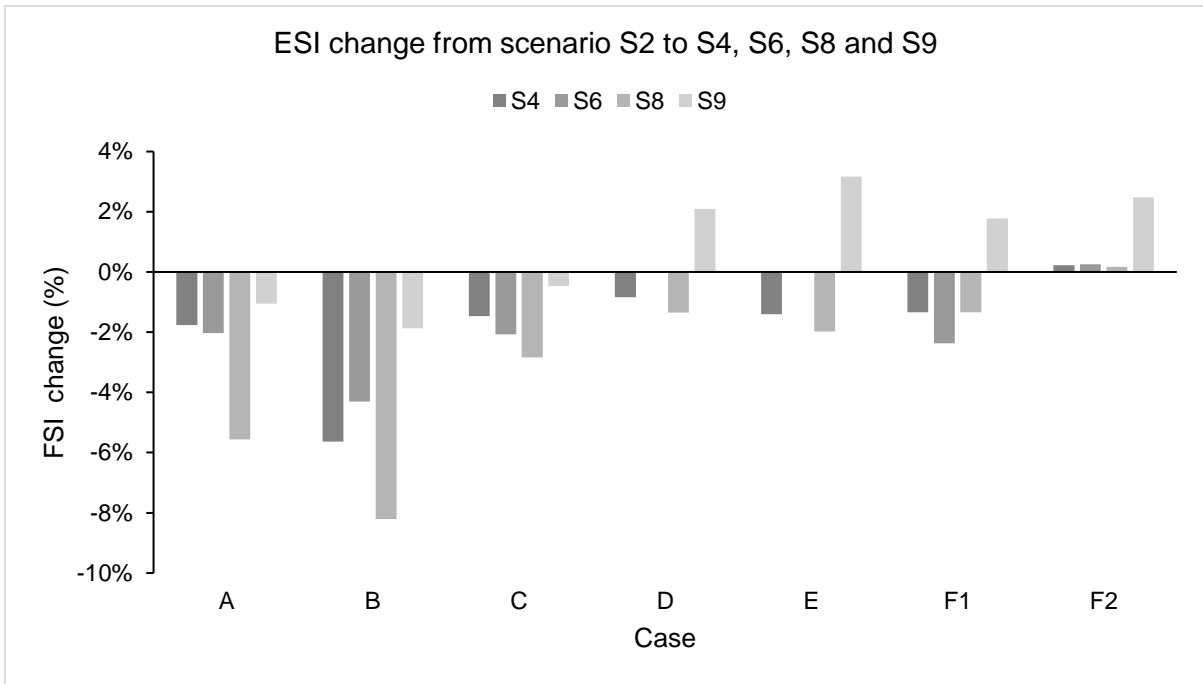


Figure 6-10 Change in ESI by case and charging strategy

## 6.6. Improvements in battery technology

Improvement in battery technology is a high priority in research and industry, since it has been identified as a key component of the vehicle and a major lever to improvement of performance. In this section, the influence of the price and weight of the battery per unit of energy were investigated. The comparisons are made on the basis of S1 alone.

### 6.6.1. Reduction in price of battery per unit of energy

The price of the battery is expected to reduce either through the use of different chemical compositions, more effective battery configurations or due to greater economies of scale. Using a fixed percentage reduction of initial battery costs of plus and minus 10 and 20%, the changes of the FSI are calculated (see Figure 6-11). The values of -10 and -20% roughly correspond to the year 3.5 and 7.3, when based on (4.59) with a yearly 3% reduction in the battery cost.

The changes in FSI are symmetrical and proportional to the change in the battery price. The changes in FSI when the battery price changes by 10% range from 0.4 to 2%, whereas when the battery price changes by 20%, the change in FSI ranges from 0.9 to 3.7%. Although the changes are not small, they are still in general smaller than the changes brought about by a compatible opportunity charging strategy.

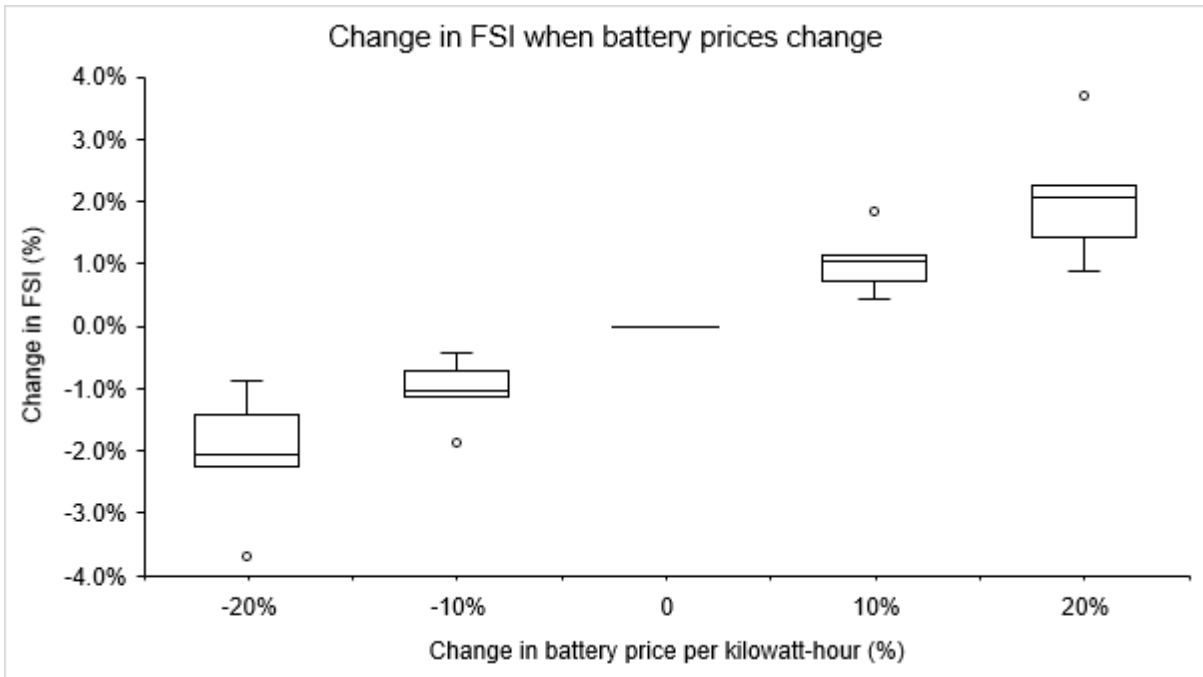


Figure 6-11 Change in FSI for all cases, when battery price per kilowatt-hour changes

### 6.6.2. Change in weight of battery per unit of energy

The weight of the battery is a significant fraction of the weight of the vehicle and may have influence of the financial suitability of the scenario. The change of the FSI and ESI dependent on the change in the specific energy are presented in Figure 6-12 and Figure 6-13. The inverse of the weight per unit of energy is used, i.e. the specific energy of the battery in kWh/kg.

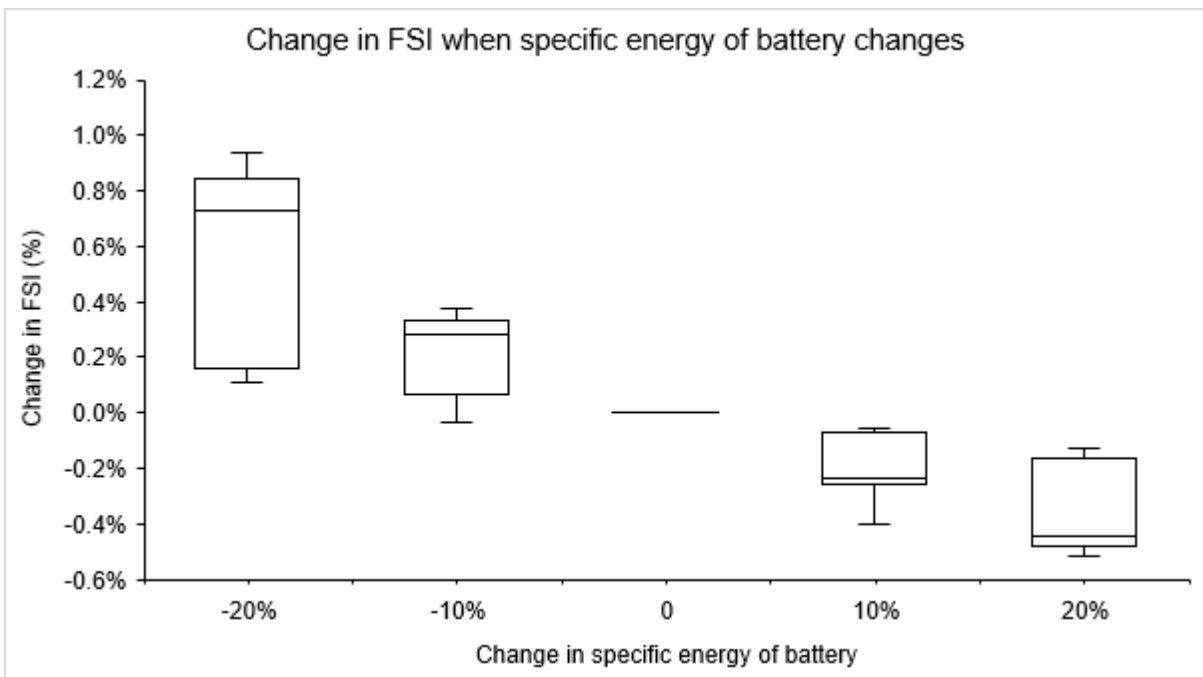


Figure 6-12 Change in FSI for all cases, when specific energy changes

The change in specific energy of the battery does amount to any large changes in the FSI. An increase of 20% causes a reduction of maximum 0.5%, whereas a decrease of 20%

causes a maximum increase of 0.9%. A similarly low percentage change is found for the ESI, where the highest reduction is at about 2%, whereas the highest increase is at about 3%. These values may make a slight difference, when evaluating the suitability requirements, but the size of the impacts are nevertheless considered small.

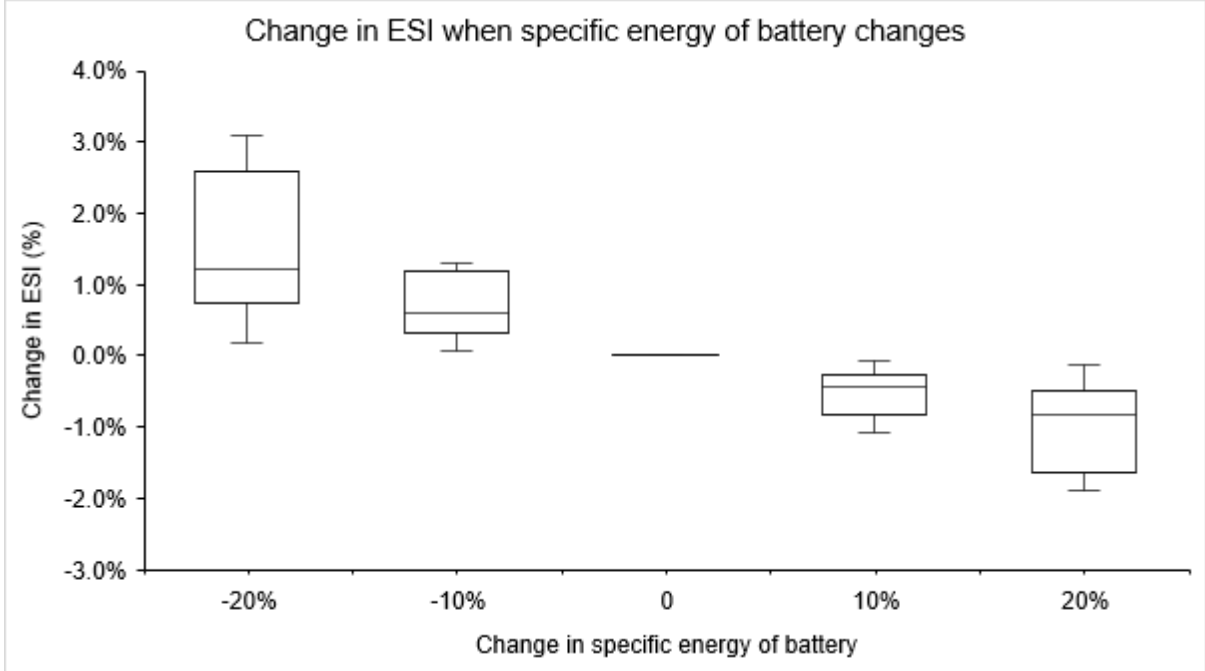


Figure 6-13 Change in ESI for all cases, when specific energy changes

### 6.7. Changes in electricity prices

The changes in fuel and electricity prices can be expected, though difficult to predict. In the study, the prices of both fuel and electricity remain constant throughout the calculation period. However, in case the energy costs do change, it will be useful to check to what extent it will influence the financial suitability of electric vehicles. Figure 6-14 shows the changes to the FSI, when electricity prices change.

The values are symmetrical. Though the extreme values can reach up to 3% and 1.5% for a 20% and 10% change respectively, the median values are all less than 1%. Hence, it can be concluded that the FSI is not very sensitive to the changes in electricity prices.

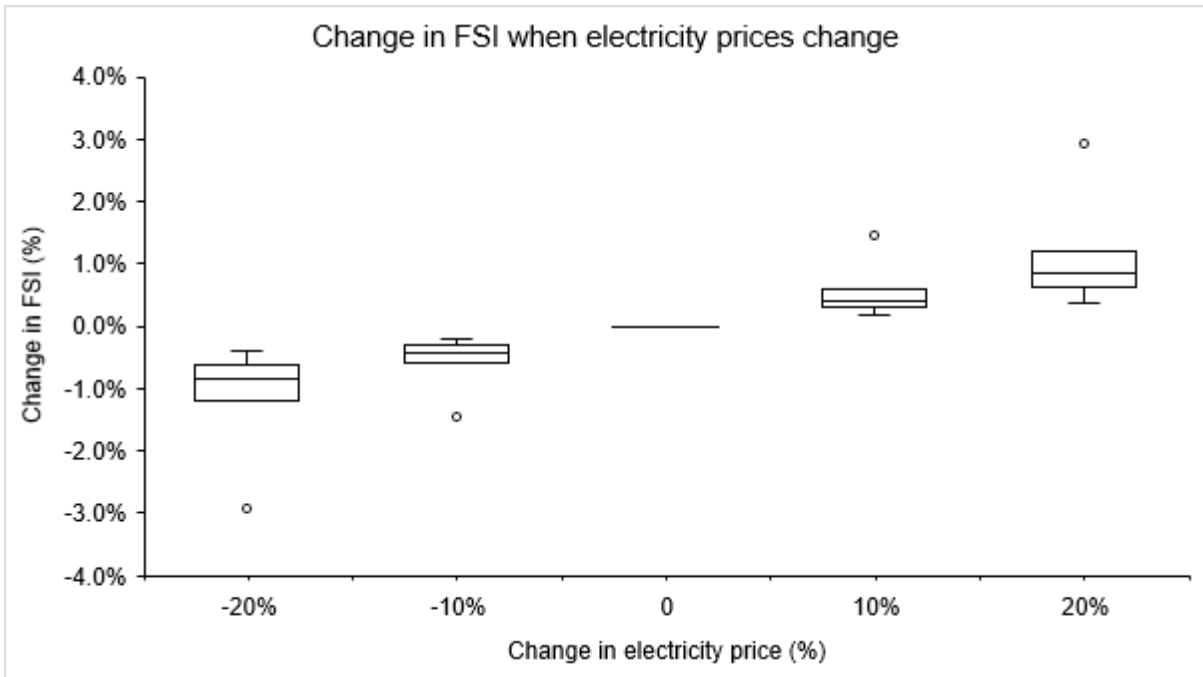


Figure 6-14 Change in FSI for all cases, when electricity prices change

### 6.8. Changes in emissions factors for electricity generation

The electricity generation in Singapore runs mostly on natural gas. Renewable energy at the current state is almost negligible, however there are plans to install more solar energy panels, wherever possible. Hence, it is possible that the emissions factor of electricity generation might reduce in the future. The influence of increasing and decreasing the emissions factors by 10 and 20% are presented in Figure 6-15.

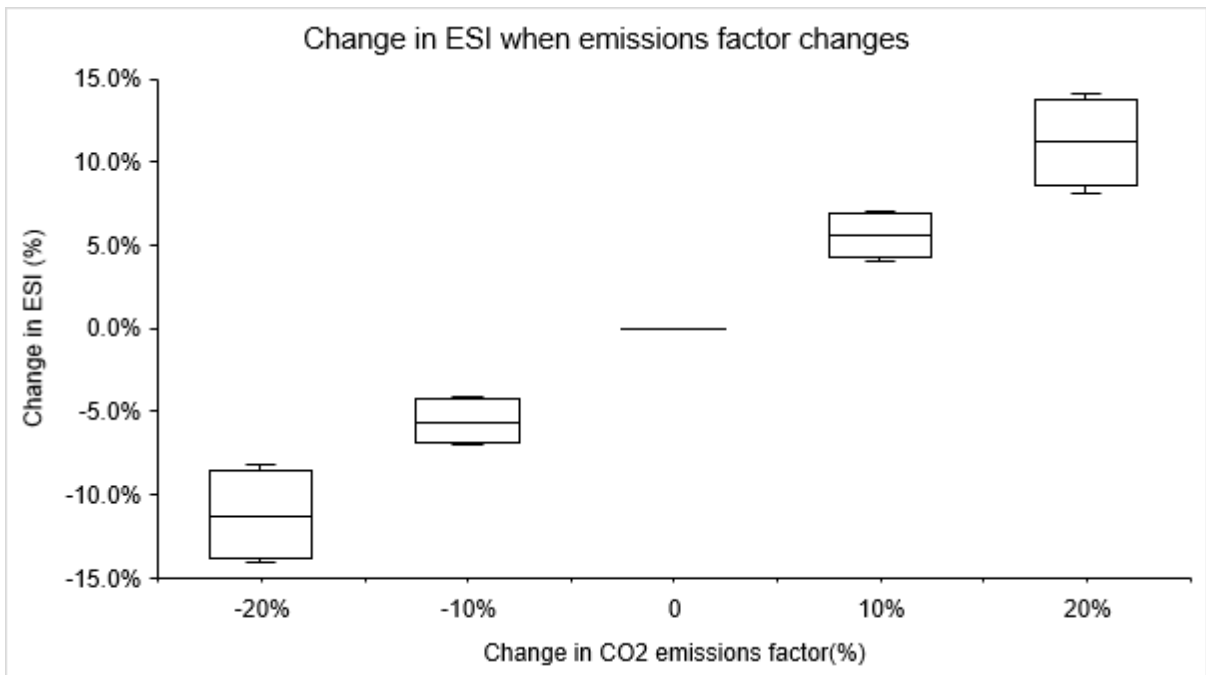


Figure 6-15 Change in ESI for all cases, when CO2 emissions factor changes

The values are found to be symmetrical. The potential for any changes are quite large, almost reaching 15% for a 20% in the emissions factors. A change of 10% can be also create a change in the ESI of maximum 7%. Hence, the use of renewable energy is a vital part of the strategy to improve the sustainability of the UFT system, together with the use of BEVs.

### 6.9. Incentivising BEV purchases

By comparing the difference between the NPV over 10 years for the BEV (S1) and DV (S0), one can determine if and to what extent financial incentives can play a part. Current policy already incentivises clean vehicles in the introduction of the ARF (see Table 6-8).

Table 6-8 Current financial incentive and NPV differences per vehicle for each case

Case	Diesel ARF (S\$)	NPV difference S1 and S0 per vehicle (S\$)	ESI (%)
A	2,357	28,261	-31%
B	2,357	29,510	-30%
C	2,681	-2,834	-57%
D	2,487	49,481	-59%
E	2,697	8,110	-37%
F1	4,074	-6,252	-44%
F2	4,074	-31,952	-47%

The right most column lists the expected environmental benefit of using BEVs. Cases A and B do not meet the requirement, while the others do. The second column on the left lists the amount already paid under the current policy. The column next to it is the difference between the NPV of S1 and S0 for the service lifetime of 10 years. For cases A and B, it is apparent that even if financial incentives were introduced, the scenario still fails the environmental suitability requirement, which means that the additional incentive is not justified. Case C, F1, and F2 have a reduction in NPV, which means a financial incentive is not needed.

The question remains of whether policy should then be introduced to reduce the financial loss for cases D and E. As previously noted, S1 in case D has a high contribution to the NPV coming from the salary component, due to the higher vehicle weight class. The contribution is about half NPV difference in the table. Even so, the amount that the policy needs to pledge exceeds S\$ 25 thousand per vehicle, which is unimaginable that the government will fund. Any fair government policy will also apply to all other commercial vehicles. Conversely, the ARF could be increased by same amount, however that may also have large economic impacts, such as raising the cost of transport services, goods, or reducing employment wages.

Another potential solution is if another category for the COE bidding could be added. The current price for the COE included in the model is \$S 50,000, which is well above the “needed” financial incentive. But, the COE serves a different function, as a vehicle population control, hence it should not be removed totally. Instead, introducing another category for auction, exclusively for BEV freight vehicles would maintain the market characteristic of the

auction process, while reducing competition with the bids for DV purchases, and thus the price of the COE. It will also mandate a fixed number of BEVs to be introduced per year.

### 6.10. Summary

In this chapter, an attempt to calculate the influence of various factors on the FSI and ESI was conducted. In this section, the impacts will be summarized. First, the impact of opportunity charging strategies on the FSI and the ESI are presented in Figure 6-16 and Figure 6-17.

The use of opportunity charging strategies holds potential to improve the suitability of BEVs in terms both the FSI and the ESI. However, the calculation of these should be conducted within the full case context, since no discernible patterns were discovered. The median FSI values show a reduction of about 1% for the break time, loading time, and on highway charging scenarios, compared to about a 2.9% reduction for the unloading time strategy. The change in ESI reveals that the influence of each charging strategy varies less systematically. On highway charging can in some cases increase the ESI by about 3%. The unloading time strategy has the widest range of the changes in ESI caused, reaching -8.2%. The median for the change is about 2%.

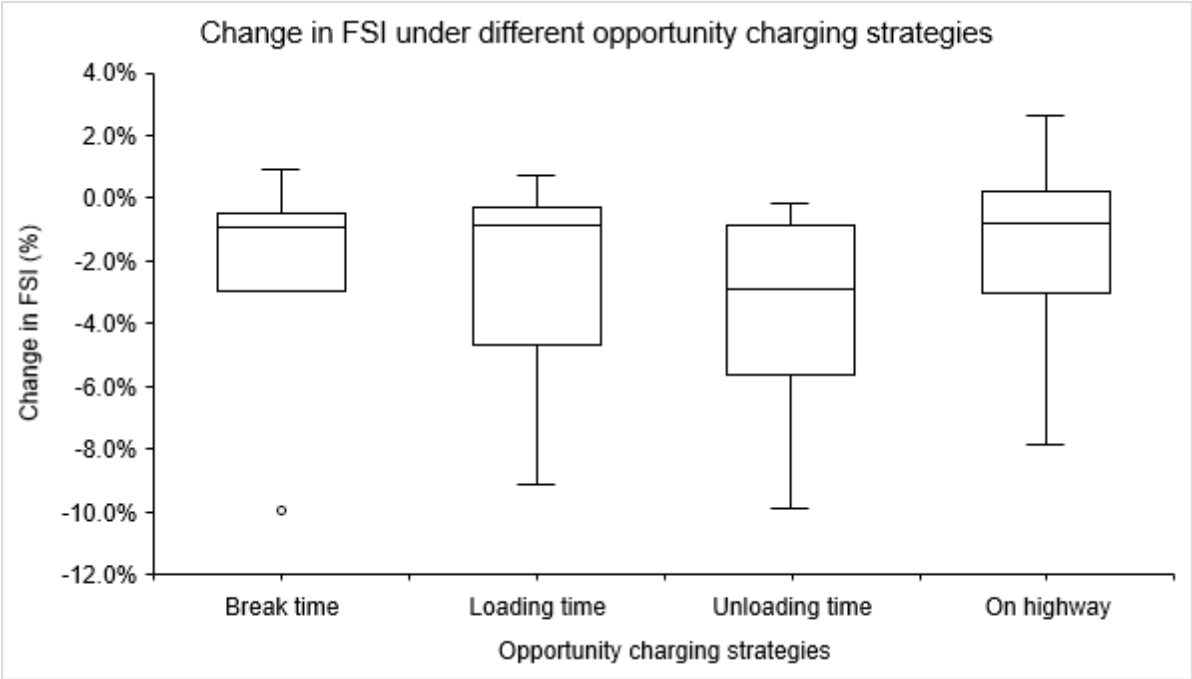


Figure 6-16 Change in FSI for all cases, depending on opportunity charging strategy

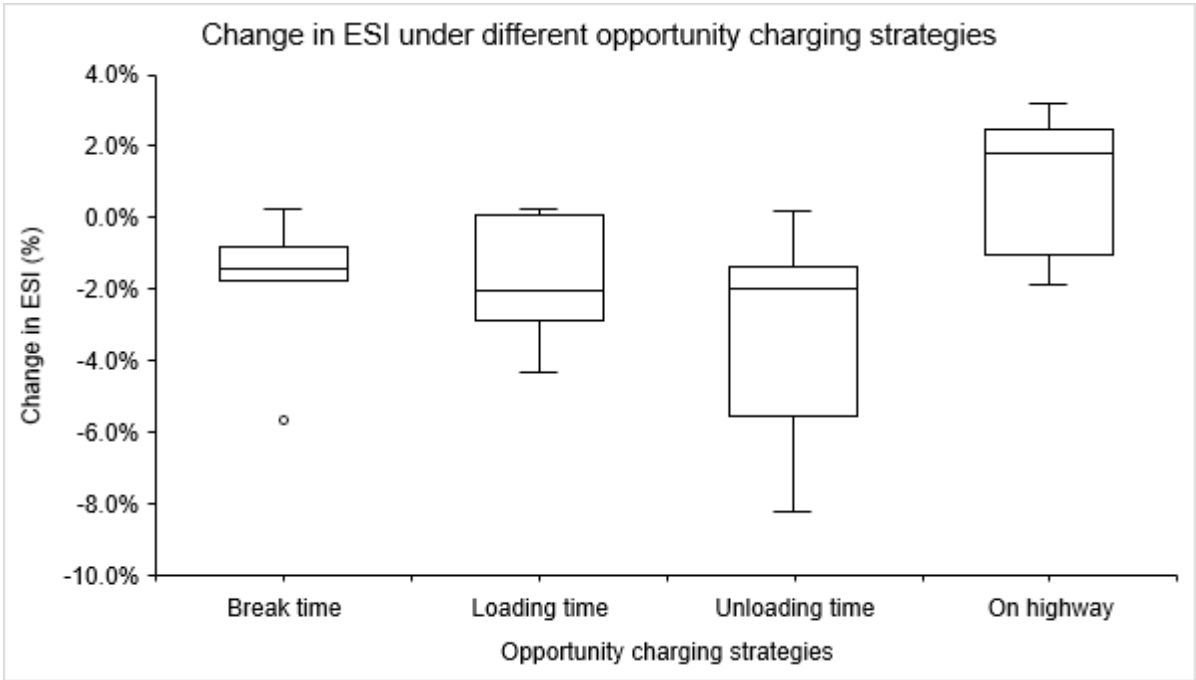


Figure 6-17 Change in ESI for all cases, depending on opportunity charging strategy

Figure 6-18 summarizes some of the ways one can improve the FSI by improving the usage and technology conditions. The two main ways to decrease the FSI are by decreasing the battery price by 20% and by increasing the service lifetime by 10 years. Most of these result in median values less than 1%. These values are comparable to that achieved by the opportunity charging scenarios.

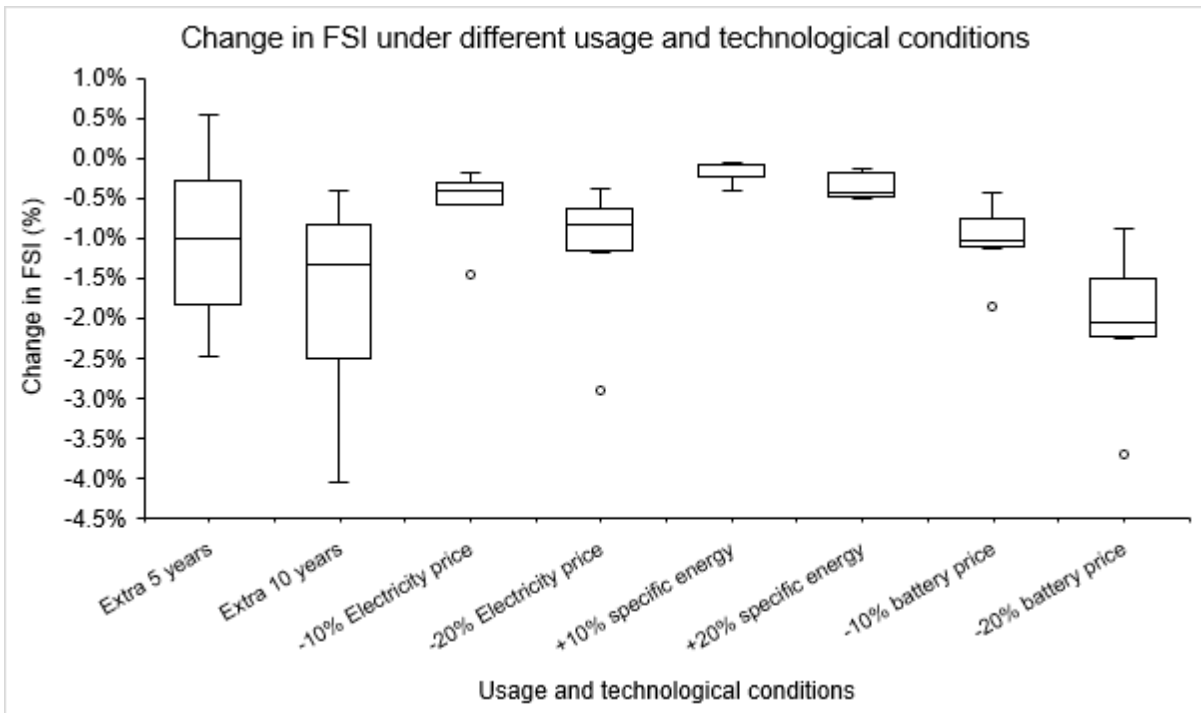


Figure 6-18 Changes in FSI under different usage and technological conditions

The next chapter will be devoted to discussing methodological issues, which are relevant for this study.

## **7. Discussion of methodology and methods**

In this chapter, key parts of the methodology and methods are discussed in terms of its effectiveness to achieve the aims of the research. It is not meant to be exhaustive, but to highlight the most important methodological decisions made and its implementation in the study.

### **7.1. Factors that influence the suitability of the electric mobility system.**

The third research question RQ3 asked of “the quantitative and qualitative attributes of UFT, which influence its suitability with an electric mobility system”. It may be argued that the methodology does not quantify the extent to which the “attributes” of UFT type affect its suitability to adopt (battery) electric vehicles. In particular, there is a hope that the study may form a basis to generalize the results of the study to other cases, which have not been explicitly studied here. However, as Section 6.5 shows, the influence different charging strategies in the case studies in this study cannot be easily estimated *ex ante*. Even cases that have similar characteristics, such as type of industry and vehicle size, do not respond to the different charging strategies in a similar way. Hence, the study does fail to relate attributes of the UFT case to the suitability to BEVs. Instead, the study shows that the suitability of each case must be studied individually.

Nevertheless, through the discussions chapter (Chapter 6), the extent that various factors influence the suitability of the BEVs is examined. This is done in a *ceteris paribus* manner to properly isolate the factors. Also, the comparative case analysis methodology is chosen in order to help understand the differences that the quantitative attributes of the cases bring to the suitability indicators.

The attributes, which the methods have been deemed successful to identify, are the variation in intensity of travel (such as distance travelled), energy usage rate (such as total weight of vehicle and the use of electrified refrigeration), and the use of inductive charging in contrast with conductive charging. However, in general, the study could not establish sufficient linkage on the suitability of different UFT cases to the different types of charging strategies. Certainly, the existing methodology has not adequately established a definitive link which can show a clear preference pattern for the different types of charging strategies.

### **7.2. Method for simulating vehicle activity**

The study uses static transport models that do not receive feedback from the limitations of the BEVs to create routes and daily activity schedules for each vehicle in the fleet. In other words, a major assumption in the study is that the transport activity of the fleets does not

change, even if a different vehicle type is used. However, one would reasonably expect that companies would change their scheduling or routing, depending on the characteristics of the vehicles, such as lower costs per distance travelled or perceptions of range anxiety.

This feature of the study is chosen explicitly to reduce the variability of the transport decisions that could be made, upon which the study focuses on the constraints that are already in place which are not dependent on the vehicle. The main constraints are then the payload capacity of the vehicle and the operational schedule of the vehicle. It is possible that the companies would hire their drivers to work extra hours to make up for the higher vehicle investments, which would also affect the whole structure of the logistics system, such as the time windows of the receivers.

One possible extension to the study, which may change the transport activity, but also improve the suitability of BEVs, is the use of a vehicle routing problem that is suited for BEVs. The advantages shall be a better balancing of energy demands of the different vehicles, leading to a reduction in the required battery capacity. It shall also be able to optimize the scheduling of opportunity charging activity, which in the current study is still handled statically.

### **7.3. Time preference**

The study incorporated the notion of time preference is the lifecycle cost analysis through the use of the discount rate. The discount refers to the reduction of perceived value in financial costs or profit occurring in the future. Hence, it emphasizes the importance of financial transactions closer to the present time instead of what happens in the future. Though a wide-range of values have been used in existing studies and literature (see discussion in section 4.10.15), the study used a 5% discount rate. This is an assumption with strong implications for the FSI, especially considering that advocates of BEVs “hope” that the reduction in operating costs in the future may offset the large increase in investment costs for purchasing the vehicle and charging systems.

“Time preference” is an observable phenomena in behavioural economics, however it is also very subjective. For example, a company currently holding much savings may have preference for future profits, since its present day costs are shielded by the savings. This may reverse for companies less optimistic about the interval between the present and the time when the breakeven of costs is achieved.

Table 7-1 presents the FSI of the different cases for S1 averaged across service lifetime 10, 15 and 20 years, with discount rate 5% and the change to the FSI when the discount rate is changed. If the FSI depends heavily on future benefits, i.e. operating cost reduction, the average change will have a higher magnitude. In the S1 of Case F1, the BEV is expensive due to the very large battery. But, in comparison to the S0, the operating costs is much reduced. Hence, when F1 discounts the future at a discount rate of 15%, the FSI increases by 11% from

-1%. The reverse holds for case D, which because of its limited operating time per day, is less utilized overall, implying less potential operating cost savings.

Table 7-1 Change in FSI for different discount rate, when compared to 5% discount rate

Case	Average FSI for discount rate 5%	Average change in FSI for discount rate		
		0%	10%	15%
A	6%	-2%	2%	4%
B	6%	-2%	2%	5%
C	-2%	-3%	3%	5%
D	13%	-1%	1%	2%
E	1%	-1%	1%	2%
F1	-1%	-5%	6%	11%
F2	-4%	-2%	2%	4%

The discussion about financial suitability, even if the lifecycle perspective was used, needs a proper determination of the extent to which the future is weighted. A different discount factor can change the ability of the vehicle system to meet the suitability requirement.

**7.4. Suitability requirements**

In this study, each scenario had to pass three suitability requirements. The first, the operational suitability requirement, was implicit, and served as a constraint on the scenarios developed. The constraint were used in the specification of the vehicle system; determining the size of the battery, the size of the payload capacity, and the power level of the charging equipment. These specifications together with the vehicle activity were used to calculate the indicators used in the other two suitability requirements; the financial and environmental suitability indicator. There are two questions, which are pertinent to be discussed here in a section on methodology. The first is whether the two explicit suitability requirements sufficient and necessary. The second is whether the threshold values chosen were the right choices.

The first question has been discussed in Section 3.5.1 on the “suitability indicators”, but focused on sustainability aspects. There it was discussed that both the check on the financial viability and the reduction on CO2 emissions are necessary requirements. The critic can point out to other requirements that might also be necessary, and should be included. For example, in cities, where air or noise pollution is a severe problem, the advantage of the BEV as a clean and silent vehicle would be much desired. There are two types of requirements that were not included in the study. The first is when the outcome is clearly to pass the requirement. For instance, local air pollution will be reduced by 100% by BEVs, which will definitely pass any threshold value. The second type of requirement is when the target itself is unclear. This is exemplified in using noise pollution as an indicator. It is clear that reducing noise pollution is desirable, but the question is to what extent it should be reduced. If the target is simply a

reduction of noise, then BEVs will undoubtedly reduce it, just based on the considering the technical characteristics of an operating BEV. Any other threshold value for a requirement that falls under the public administrator's purview needs to be determined by a political or legal process. This brings us to the next point.

The selection of a threshold value for indicators that decides on the suitability of the scenario is a key methodological question. Both suitability requirements addressed the wishes of the different actors: the transport operator and the public administrator. The financial suitability requirement is based on the premise that the transport operator is not willing (i.e. without coercion) to adopt BEVs in its fleet, if the costs to do so are higher than in the diesel vehicle scenario. The environmental suitability requirement is based on the premise that the Singapore government is not willing to permit or support the introduction of BEVs for freight transport, unless it potentially causes a sufficient reduction of CO<sub>2</sub> emissions. The requirements, in terms of degree of change, are in a sense arbitrary, although reasonable. The requirements aim at setting the necessary level of impacts for the consideration in further purchasing or policy discussions. Other means to then determine the "optimal" decision can be used, though they should be conducted with a higher precision in the case of the fleet purchase decision or with greater generality for the policy decisions.

Nevertheless, if one would like to "simulate" the outcome if these thresholds were altered, the histograms for both suitability indicators provided in section 6.1 can be used.

## 8. Conclusions and further research

This study is set against a backdrop of the desire of private and public sectors to investigate the suitability of BEVs for UFT. The main reason for the initiative, which usually stems from the public sector, is the environmental benefits, such as the reduction of carbon dioxide emissions that the electric powertrain brings. However, the private sector is most concerned that specifically the use of BEVs would financially disadvantage carriers and vehicle owners, especially considering the high investment costs for electric vehicles.

The main hypothesis of the study is the following:

*“Battery electric vehicles, when used with opportunity charging, are suitable for urban freight transport operations.”*

Suitability is defined as satisfying three requirements. First, the vehicle should fulfil the operational demands of the transport operations. This requirement cannot be compromised. Therefore, it is not quantified using an indicator, but rather is treated as a hard constraint in the modelling. Second, the lifecycle cost of BEV's should not exceed that of the diesel vehicle. For this calculation, 10, 15 and 20 year-long service lifetime of the fleet has been investigated. Third, the resultant carbon dioxide emissions reduction should meet the local targets. In the case of Singapore, the reduction goal is 36% by 2030.

The study has used six case studies, based on data obtained from interviews with five companies, to test the hypothesis. A detailed transport model was used to enable the evaluation of opportunity charging strategies, that is, strategies where the vehicles are charged statically during operational downtime and/or dynamically while driving on highways. Based on the six case studies, scenarios were created corresponding to the opportunity charging strategy and the type of charging technology.

It was found that, although opportunity charging did in most cases improve the financial and environmental suitability indicators, the improvement was sometimes insufficient to meet the respective requirements. One instance of the CEP operations, case A, and the case of replenishment of frozen food, case D, failed to meet both the suitability requirements. The other CEP operation, case B, only had two scenarios (out of 27), which met both suitability requirements. Similarly, the furniture home delivery service, case E, only had five scenarios, which met both requirements. In the case for replenishment of fast food restaurants, case C, and in the case of the replenishment of furniture retail outlets, case F (encompassing both F1 and F2), almost all the scenarios of each case met both suitability requirements.

### 8.1. Further research

In this work, it was shown that opportunity charging scenarios can significantly improve the suitability of the BEVs. However, their suitability ultimately depends on the vehicle cycle

and the operational characteristics. Some of the hypotheses that were developed in this study are interesting for further research and are presented below.

Service lifetime is an important determinant of the financial suitability of the vehicle system. Except for the battery, there is currently very little information on the degradation of the rest of the vehicle throughout its lifetime. Furthermore, it is not known whether extending vehicle's lifetime poses safety risks. In comparison to the ICEV, which pollutes more and is costlier to operate with age, the BEV could maintain its best qualities till the end of its life, with minimal maintenance. This issue merits further research, since this would positively influence the financial and environmental suitability of the BEV as well as have other important policy and market implications, such as the initial COE limit, vehicle loans, or even fleet rental business models.

Inductive highway charging is an important technological option, unless a conductive system suitable to the wide range of vehicle dimensions is introduced. However, inductive charging also causes a significant financial and environmental detriment compared to using conductive charging. It is thus recommended that the conductive charging is used whenever possible, unless the efficiency of inductive charging improves. Conversely, diverse charging plug standards and the inconvenience of plugging-in the charging cable may reduce the attractiveness of the conductive charging for fleet owners and drivers, especially if opportunity charging is part of the operational system. Here, research into customer (i.e. fleet owners and drivers) preferences would be fitting, considering also perception and appropriateness of such requirement as a potentially professional standard.

Opportunity charging, as mentioned, does improve in most cases the suitability of the BEV system. There are three main categories considered. The first is based on a schedule, the break time charging strategy. The driver charges at the same time every day based on the timetable. The second is based on the charging, while handling activities are being conducted, which are the loading and unloading time charging strategies. Depending on the type, the vehicle is charged at either the customer's location or its own depot location. The third is dynamic charging, while on the road. In the study, the highway charging strategy was investigated. This occurs whenever the vehicle is at a particular (type) of link on the road network. According to the results, the best performing type is the second one, which squeezes in charging activity whenever it is at either the own location or the customer's location. Charging at the customer location was usually most effective. However, the dynamic charging strategy worked exceptionally well for the Case F1, in which the vehicle spent a lot of time on the highway.

Further research could explore more advanced business models for opportunity charging, beyond the simple service-based approach applied in this study. For example, highway charging infrastructure might fall under the purview of the government, which

manages road infrastructure; in such case, the billing procedures, subscriptions, and also the amendments to traffic regulations would need to be investigated. Similar questions can be asked for the other opportunity charging strategies.

Furthermore, the outcomes of this study could be relevant for the battery industry: specific technological developments could significantly influence the suitability of BEV for urban freight rendering them profitable to the battery industry. The following was observed with respect to the improvements in battery technology (or production scale). Improving the specific cost would positively influence the suitability of the FSI. ESI would most benefit from improving the specific energy. Besides these, improvements in battery lifetime, and charging and discharging efficiency would be welcomed.

Emissions factors of electricity production were not examined in detail in this study, but the brief analysis showed that the environmental suitability of BEV depends strongly on the means of electricity production. Considering the local emissions, the requirement of 36% reduction was achieved by all financially suitable scenarios. Therefore, improvements in emission factors are not crucial for the suitability of BEV for urban freight (at the given target level). Despite not being crucial, the study would benefit from more accurate emission estimation models in Singapore, as it was also discussed that the energy consumption model is most likely an overestimation for BEVs.

Finally, the policy implications of this study could be elaborated given a more detailed calculation of the necessary financial incentives for BEV purchases. Nevertheless, a brief first analysis suggests that financial incentives may not be necessary, as there are already good arguments for the BEVs to be adopted, especially with the right selection of opportunity charging strategies. Although it is common to assert that the public sector should provide incentives for industry and private persons to shift to electrification, this study showed that there are multiple options to achieve financial suitability without incentives.

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# Appendix A. Template for interview

## Survey on Express Service

Name of respondent (Optional)	
Position within company	
Date form is filled	
Depot (Warehouse) address	

The survey intends to capture - and model based on a Vehicle Routing and Scheduling Problem solution – the typical daily driving schedule of the fleet of trucks in Singapore. The forms can be as flexible as needed according to the data available and accessible. Please make small comments or notes, in that case.

There are four categories, which cover the scheduling details of the operation, information about the vehicle fleet, typical orders, and some spatial information. For the spatial information, the **Regions** referred to are loosely based on the URA planning regions, as shown in diagram below (Figure 1). Please contact me, if this format is too inconvenient or confusing.

**Any information provided will only be used for academic purposes, i.e. the PhD dissertation of Tharsis Teoh. If the information is to be published, it can be appropriately anonymized, e.g. by referring to case study as “Express services”. No names of personnel will be included in any publication.**

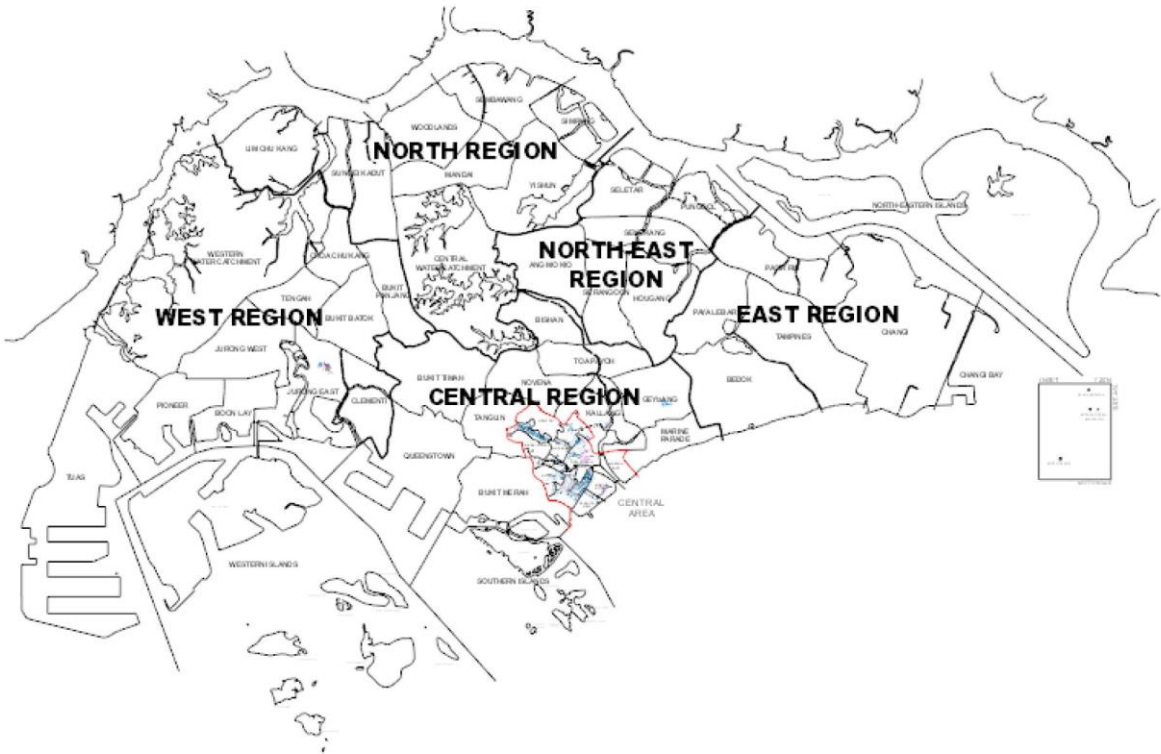


Figure 1 Spatial zones in Singapore

## Schedule

Main time windows for customers (e.g. 10 am to 12 pm; 2 – 6 pm; 6 – 8 pm)	
Typical shift hours per vehicle (e.g. 9 am - 8 pm)	
Breaks per day (e.g. 12 -1pm)	
Number of employees per vehicle (e.g. 1 driver, 1 co-driver)	
Number of routes driven per vehicle (e.g. 2)	
Total duration of a route (e.g. 9- 12pm & 1-7pm)	
Loading duration (e.g. 1 hour)	
Unloading duration (e.g. 5 minutes)	

## Fleet information

Vehicle type (e.g. Rigid panel truck 5tonne )	
Size of fleet (e.g. 5)	
Number of customers served per vehicle route(e.g. 3)	
Loading capacity in volume/load units) (e.g. 5 EURO pallets or 8 m <sup>3</sup> )	
Special equipment (e.g. automated tail lift)	
Distance travelled per day (e.g. 100 km)	

## Typical orders per day

	Minimum	Median/Average	Maximum
Single shipment volume/load units (e.g. 1 EURO pallet or 3 m <sup>3</sup> )			
Estimated weight per shipment (e.g. 50;80;160 kg)			

## Information by region (see Figure on page 1)

Region	Total Shipment demand (Volume/Load units)	Number of stops		
		Minimum	Median/Average	Maximum
Central				
East				
North-East				
North				
West				