ABSTRACT
Between 1950 and 2013 the total amount of Swedish travelling has increased from about 20 billion to about 140 billion passenger kilometres. This included an increase in travelling with private cars from about 3 billion to about 105 billion passenger kilometers, and in bus travelling from about 2.5 billion to about 5 billion passenger kilometers. The European commission has indicated that public transportation (if powered by clean fuels) is a suitable way to reduce environmental and health problems. This thesis focuses on sustainable personal road transport, and aims to develop and test a new approach to examining the economic and socio-ecological sustainability effects of various road vehicles for private travelling and related business models. A special focus is set on comparing various bus systems for public transport and ways (business models) for private people to access cars. The main comparison parameters are the total cost of ownership and carbon dioxide emissions of different energy carriers for buses and cars. The Design Research Methodology is used to guide the research approach. The approach also builds on the Framework for Strategic Sustainable Development, which includes, for example, principles that define any sustainable future and a strategic planning process. The approach first employs Strategic Life Cycle Assessment to give a quick overview of sustainability challenges in each bus life cycle stage from raw materials to end of life. Several analysis tools such as Life Cycle Costing, Life Cycle Analysis, Product Service System, and Business Model Canvas mapping are then iteratively used to “dig deeper” into identified prioritized challenges. Literature reviews, interviews, and simulations are used as supporting methods.

The results from a first theoretical test of the new approach suggest that a shift from diesel buses to electric buses (powered by renewable energy) could significantly lower carbon dioxide emissions, while also significantly lowering the total cost of ownership. The theoretical calculations were followed up by testing of electric buses in real operation in eight Swedish municipalities. The tests verified the theoretical results, and showed that electric buses are better than diesel buses both from a sustainability point of view and a cost point of view, and also that electric bus operation is a practically viable alternative for public transport. The new approach was tested also by comparing a variety of business models for private car travelling. The results indicate, among other things, that only people who travel more than 13.500 kilometers per year would benefit from owning a car. In all, the thesis suggests a simultaneous shift from diesel buses to electric buses in public transport and, for the majority of the car drivers that drive less than 13.500 kilometers per year, switching from car ownership to car use services would be favourable for an affordable transition of the transport sector towards sustainability.
An Approach to Business Modeling for Sustainable Personal Road Transport

Lisiana Nurhadi
An Approach to Business Modeling for Sustainable Personal Road Transport

Lisiana Nurhadi
Licentiate Dissertation in Strategic Sustainable Development

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Above all, I thank God for the blessings which made it possible to successfully complete this licentiate research. Otherwise, I would have not reached this point.

Karlskrona, March 2016

Lisiana Nurhadi
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>FSSD</td>
<td>Framework for Strategic Sustainable Development</td>
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<td>BMC</td>
<td>Business Model Canvas</td>
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<td>PSS</td>
<td>Product Service System</td>
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<td>LCC</td>
<td>Life Cycle Costing</td>
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<td>TCO</td>
<td>Total Cost of Ownership</td>
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<td>LCC</td>
<td>Life Cycle Assessment</td>
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<td>SLCA</td>
<td>Strategic Life Cycle Assessment</td>
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<td>NPV</td>
<td>Net Present Value</td>
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<td>PHEV</td>
<td>Plug-in Hybrid Electric Vehicle</td>
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<td>BEV</td>
<td>Battery Electric Vehicle</td>
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<td>EV</td>
<td>Electric Vehicle</td>
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<tr>
<td>SP</td>
<td>Sustainability Principle</td>
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<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
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<td>DRM</td>
<td>Design Research Methodology</td>
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<td>RC</td>
<td>Research Clarification</td>
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<td>DS I</td>
<td>Descriptive Study I</td>
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<td>PS I</td>
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<td>DS II</td>
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Thesis disposition

The thesis includes an introduction and the following papers, which have been slightly reformatted from their original publication to fit the format of this thesis. The content of the papers remains unchanged.

Paper A


Paper B


Paper C


Paper D

Related work

The following publications were not included in this thesis but contribute to the same projects that the thesis was part of.


Abstract

Between 1950 and 2013 the total amount of Swedish travelling has increased from about 20 billion to about 140 billion passenger kilometers. This included an increase in travelling with private cars from about 3 billion to about 105 billion passenger kilometers, and in bus travelling from about 2.5 billion to about 5 billion passenger kilometers. The European commission has indicated that public transportation (if powered by clean fuels) is a suitable way to reduce environmental and health problems.

This thesis focuses on sustainable personal road transport, and aims to develop and test a new approach to examining the economic and socio-ecological sustainability effects of various road vehicles for private travelling and related business models. A special focus is set on comparing various bus systems for public transport and ways (business models) for private people to access cars. The main comparison parameters are the total cost of ownership and carbon dioxide emissions of different energy carriers for buses and cars. The Design Research Methodology is used to guide the research approach. The approach also builds on the Framework for Strategic Sustainable Development, which includes, for example, principles that define any sustainable future and a strategic planning process. The approach first employs Strategic Life Cycle Assessment to give a quick overview of sustainability challenges in each bus life cycle stage from raw materials to end of life. Several analysis tools such as Life Cycle Costing, Life Cycle Analysis, Product Service System, and Business Model Canvas mapping are then iteratively used to ”dig deeper” into identified prioritized challenges. Literature reviews, interviews, and simulations are used as supporting methods.

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In all, the thesis suggests a simultaneous shift from diesel buses to electric buses in public transport and, for the majority of the car drivers that drive less than 13,500 kilometers per year, switching from car ownership to car use services would be favourable for an affordable transition of the transport sector towards sustainability.
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1. Introduction

This chapter introduces the sustainability issues of the global transport sector, the research focus, and the aim and scope of the thesis.

1.1 Sustainability challenges in global transport

In 2010 more than 60 percent of the 87 million barrels of oil consumed every day were used to power the global transportation sector. According to the World Economic Forum (2012), a business-as-usual scenario with continued dependence on fossil fuels and little use of renewable energy is not feasible. Also, the European Commission (2011) has emphasized that future transport should be energy efficient, have low carbon dioxide emissions, and become independent of fossil fuels. Unfortunately, the focus of the European Union (EU) is sometimes too narrowly set on the use phase, excluding life-cycle phases like manufacturing (Nurhadi et al., 2014a). This means that their current goals are not sufficient to ensure sustainable transport system development.

Transitioning to more sustainable transportation alternatives implies both challenges and opportunities, which will require huge investments in research and development (R&D). Building the necessary infrastructure could create immediate jobs and sustained economic growth (World Economic Forum, 2012). Experts suggest the transitions that could be made include the introduction of new technologies, opportunities for new actors, and the potential to change customer behaviour; these could potentially lead to the development of new successful business models (World Economic Forum, 2012).

1.2 Sweden’s national goal

Recent Swedish national personal transport investigations and other similar international reports (e.g., Swedish Government Official Report, 2013; The International Society of Sustainability Professionals ISSP, 2008) have concluded that there is likely an overarching logical sequence of societal planning measures that will be needed to properly accelerate a required move towards sustainable road transportation:

1. Plan cities to minimize the need for transport.
2. Plan cities so that the remaining necessary transport can be shifted towards:
   a. walking and biking, especially within a few kilometers of work or grocery stores.
   b. effective public transport (including electric buses and rail transport like trams and railroads).
   c. personal cars.
3. Promote energy-efficient vehicles, such as battery electric and hydrogen fuel cell buses and cars powered with renewable fuels.

In line with what would be intuitively expected, some studies have suggested that Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs) charged with renewable energy have a higher potential to become sustainable alternatives than current fossil-based alternatives (Faria et al., 2012; The International Energy Agency IEA, 2013). According to the European Commission, cleaner energy, such as renewably-sourced electricity, is promising as the new preferred power for short-distance journeys (The European Commission, 2012). However, one of the major obstacles to rapid market diffusion is the higher initial investment required for electric motor systems, as compared to conventional combustion engine technologies (Tate et al., 2008).

1.3 A short history of passenger transportation

As a result of increased private car use, public transport’s share of total passenger travel by road and rail has declined from about 50 percent in 1950 to 20 percent in 1970. Since then it has remained at around 20 percent, with smaller annual variations (Figure 1). Between 1950 and 2013, the total amount of Swedish travelling has increased from about 20 billion to about 140 billion passenger kilometers (Figure 1). This included an increase in travelling with private cars from about 3 billion to about 105 billion passenger kilometers, and in bus travelling from about 2.5 billion to about 5 billion passenger kilometers (the Swedish Bus Industry Union, 2013; Swedish Traffic Analysis, 2014). Between 1975 and 2016 the number of Swedish cars in traffic increased from about 2.6 million to 4.7 million, and in December 2015 there were more than 34,000 newly registered cars (SCB, 2015).
1.4 Could the trend turn towards public transportation?

The European Commission has stated that public transport is a suitable way to reduce environmental and health problems in urban areas (especially if it runs on alternative and clean fuels) and they also encourage a mix of transport modes (The European Commission, 2015). This is in line with Swedish national goals for Green House Gases (GHG) neutrality by 2050 and a fossil fuel independent vehicle fleet by 2030. It is therefore critical to start working on reducing Sweden's carbon dioxide (CO₂) emissions from the road transport sector within a short time frame (Swedish Government Official Report, 2013). Given that private car use has grown significantly over the past decades (Figure 1), and the above mentioned desired logic for societal planning, the question is: would it be possible to decrease the number of cars, while increasing public transport and other modes of transport such as walking/biking, and decrease the total traffic? (Swedish Bus Industry Union (Svenska Bussbranschens Riksförbund), 2013).
1.5 Research context

This thesis is performed within a research team that focuses on fast transformation towards sustainable transport and energy systems. The author’s research is focused on business models and economic analysis of personal road transport in this context. The majority of the thesis has been conducted within the first phase of a project called GreenCharge, which aimed to build a roadmap for how municipalities and counties in the southeast of Sweden could speed up the transformation towards a fossil-independent vehicle fleet by 2030. This combined research and demonstration project was run by Blekinge Institute of Technology and many partners, including 25 municipalities, four county boards, and several companies, between 2011 and 2015. The involvement of many partners implied a good test and development platform to the overall aim of this thesis.

1.6 Aim and scope

The thesis aims to explore support for development of the current transport sector in a sustainable direction that could be attractive to the users and other actors involved. More specifically, the aim is to develop a new approach to examining the economic and socio-ecological sustainability effects of various road vehicles for private travelling and related business models. A special focus is set on comparing various bus systems for public transport and ways (business models) for private people to access cars. The main comparison parameters are the Total Cost of Ownership (TCO) and CO₂ emissions for the studied alternatives.

1.7 Overarching research questions

To guide this thesis further, the aim is complemented with some overarching research questions:

- RQ1. How can a business modeling approach be constituted to better support decisions for sustainable transport system development?
- RQ2. What are the economic and socio-ecological sustainability consequences of various bus systems for public transport?
- RQ3. What are the economic and socio-ecological sustainability consequences of various car types and related business models (e.g., owning, leasing, etc.) for private car travelling?
2. Research approach

This chapter describes the research approach that the author has adopted. It addresses how the research has been carried out and it highlights the main motivation for the chosen methodology. The choice of research methods is followed by a description of data collection and analysis, and validity threats.

2.1 Research framework

The primary research has been guided by the Design Research Methodology (DRM) introduced by Blessing and Chakrabarti (2009). It has been found helpful to adapt DRM as it provides a more specific approach to this type of research (Figure 2). DRM is used to provide a new approach and pointers to existing approaches to carry out the stages of the research process in an iterative way; for example, by using particular case studies to be able to interact with the object of the thesis, as it is hard to have controlled experiments, while also constantly changing or evolving the knowledge and experience with team members to improve the thesis. DRM consists of the four main phases below (Blessing and Chakrabarti, 2009):

- During the research clarification phase, the goal and focus of the research are clarified, for example, through literature studies.
- During the descriptive study I, a better understanding of the problem is developed, for example, through literature analysis and empirical studies.
- During the prescriptive study, a solution to the original problem is developed based on the improved understanding of the condition combined with the assumptions, experience, and synthesis.
- During the descriptive study II, the solution to the original problem is tested and evaluated.

In this thesis the phases of the DRM have been used iteratively rather than in a linear way:

- **Research clarification (RD):** Clarified the goals of the thesis and the conceptual framework, and formulated the research questions.
- **Descriptive study I (DS I):** Now having a clear goal and aim, the intention was to make the description detailed enough to determine which factors should be addressed to improve the task as effectively as possible. Since it was not enough detailed to only rely on the literature studies, the author observed and did informal interviews with the case study companies to obtain a better understanding of the current situation. For example, information on different energy carriers for buses and cars was collected through phone interviews. Email conversations were conducted with people involved in the relevant
industries in order to gain a better understanding regarding the state of practice in the industry, as well as collect necessary data and information.

- **Prescriptive study I (PS I):** Papers A, B, and D subsequently used Strategic life-cycle assessment (SLCA) to identify sustainability ‘hot spots’ and also provided more detailed sustainability assessments with Life-cycle assessment (LCA) and Life-cycle costing (LCC). The comparison parameters fall within costs and various emissions. More specifically, the LCC calculated TCO for buses (paper A and B) and cars (paper D). In paper D the current business models for cars were mapped out with business model canvas (BMC).

The author’s research process has progressed through the first three stages of the DRM framework, but has not yet progressed into the Descriptive Study II (as showed in figure 2). The following will also be included in the future research process:

- **Descriptive study II (DS II):** To get feedback, verified by an interview with an expert, with the intentions of evaluating and validating the solutions for future work.

![Diagram of DRM methodology]

**Figure 2.** How DRM, Design Research Methodology (Blessing and Chakrabarti, 2009), is applied in this research and how it is planned to be used in future research.
2.2 Methods used within the research framework

2.2.1 Data collection and analysis

The choice of research methods was guided by the following: a description of the research questions, a literature study, interviews with companies, preliminary feedback from experts, simulation, and verification. The motivation behind the selection for data collection and analysis are described below:

- **The literature studies** were conducted using databases (e.g., Science Direct, Inspec, and Scopus) and Internet search engines (e.g., Scopus, Summon, and Google Scholar), as well as various Swedish government reports and European commission reports (e.g., the Swedish Environmental Protection Agency, the European Commission, the Swedish Transport Administration, universities) for papers A-C.

- **The case studies** were conducted with bus and car companies. The data collection for the case studies primarily used interviews for papers A to C. The analysis of case studies involves a purely qualitative analysis where raw data from interviewees at case companies was categorized and coded by the use of mathematical and algorithm models in papers A to D.

- **Simulation** primarily focused on measurable characteristics of a process. A qualitative approach for the case study was given within a simulation done by Volvo bus for paper A. The result of the data analysis was sent back to the companies in order to get feedback and validation of the data from the expert or interviewee.

- **Verification** for papers A and B was described in paper C through real-life testing (Borén et al., 2016a).

2.2.2 Research quality and validity

Demonstrating the validity of research is challenging and not an easy task. Semi-structured interviews and research meetings have provided the essence of the research work, but do not reflect the essence of the conclusions where the research interprets these results through the author’s worldview and experience. Certainly, the research process can never be repeated as a controlled experiment; the researcher, the interviewee, and the context would have changed, and yet something can be learnt in the process. For validity reasons, the findings of the study have been compared with the findings of other researchers, and iterations of mutual feedback have been performed with the interviewees from the case studies.
3. Knowledge domains

This chapter aims at describing the definitions and theoretical constructs that form the backbone of the research presented in this thesis.

3.1 Product service systems

The term Product Service System (PSS) emphasizes a shift in the business paradigm from selling specific products to delivering a function (through the mix of products and services). This opens up to satisfying the users through more resource-efficient services that could bring both dematerialization and environmental benefits (Tukker and Tischner, 2004). Despite their potential to reduce the environmental impacts, PSSs are not by default more environmentally benign compared to conventional systems (Kjaer et al., 2016; Thompson, 2012; Tukker and Tischner, 2004). A general trend of car access is that pure products and car ownership is transitioning towards PSSs that include mixtures of pure products and services, which are connected in new offerings from sellers to buyers (Tukker & Tischner, 2004). For example, car leasing or car pooling does not include buying a physical product (a car). This makes it even more possible to increase awareness towards a trend of sharing services with the Internet as the enabler. Within such a PSS the selling companies do not pass over the car ownership to the buyers but are rather responsible for maintenance, repair, and control for a regular fee. However, the final choice of business models depends on people’s opinions, their needs, and driving behaviour (Canet et al., 2015).

3.2 Backcasting from sustainability principles

The research of this thesis utilizes a well-established approach to plan strategically for sustainable development; the Framework for Strategic Sustainable Development (FSSD) (Broman and Robért, 2015). The FSSD uses backcasting from sustainability principles (SPs) to explore approaches on how to move strategically towards a sustainable vision. The social sustainability definition (principle 4 below) is currently being further elaborated (Missimer, 2015). However, the following SPs are used in this thesis:

“In a sustainable society, nature is not subject to systematically increasing . . .
1 …concentrations of substances extracted from the Earth’s crust;
2 …concentrations of substances produced by society;
3 …degradation by physical means, and in that society;
4 …people are not subject to conditions that systematically undermine their capacity to meet their needs.
The FSSD also includes an operational procedure – ABCD planning (Holmberg and Robért, 2000) which is illustrated in Figure 3. In the first step (A) a funnel metaphor is used to explain the systematic character of the sustainability challenge, as well as the self-benefit of having and working towards a sustainable vision (avoiding hitting the wall of the funnel while moving to the vision in the opening of the funnel). The current challenges and assets in relation to the vision are then captured in (B). Possible steps towards the vision are captured in (C), and these are prioritized into a strategic plan in (D).

![Diagram of FSSD funnel metaphor and ABCD planning procedure](image)

Figure 3. The funnel metaphor and ABCD-planning procedure of the FSSD. Adapted from Broman and Robért (2015).

### 3.3 Business modeling

Business modeling is used as a broad description, both formal and informal, to represent core features of a business, including offerings, strategies, infrastructure, operational processes, and policies. In line with that, business modeling describes the rationale of how an organization creates, delivers, and captures value (Osterwalder and Pigneur, 2009).

A tool for mapping companies’ business models is the Business Model Canvas (BMC) template (Figure 4), which is a visual chart divided into nine building blocks (Osterwalder and Pigneur, 2009):
Key partners: refer to the partners needed to acquire resources from outside the companies and to fulfil various activities that are outsourced.

Key activities: refer to a number of activities performed inside the company.

Key resources: refer to the assets required to perform both internal key activities and external key partner activities.

Value proposition: refers to the resolution of customer problems and how the satisfaction of customer needs is described.

Customer relationships: refer to relationships that are established and maintained with each customer segment.

Customer segments: refer to specific sub-sections of the customer base that lend themselves to be treated with an adapted focus.

Channels: refer to how the value propositions are delivered to customers (e.g., through communication, distribution, and sales channels).

Cost structure: refers to what the most important costs inherent in the business model are and which key resources and activities are the most expensive.

Revenue stream: refers to what values the customers are really willing to pay and how they actually choose to pay.

Figure 4. Business model canvas (Osterwalder and Pigneur, 2009).
3.4 Linking business models and sustainability

A review of the literature reveals that the concept of business model innovation often appears to incorporate everything that is relevant for a business, from strategy to economic model (DaSilva and Trkman, 2014). To keep competitive advantages, companies need to innovate their business models intelligently, along with technology and the innovation process (Amit and Zott, 2012; Chesbrough, 2010). Integrating the sustainability into the core of the business model itself seems to make it more competitive as many companies that have changed their business models accordingly are finding success (Amit and Zott, 2012; Chesbrough, 2010). Nearly half of the companies changed their business models as a result of sustainability opportunities (Franca, 2013). As mentioned by many studies including Jiao and Evans (2016), business model as a holistic innovation concept should introduce sustainability into the business logic and take a multi-stakeholders perspective at an industry level. Thus business model innovation that includes sustainability as a permanent element and as a source of potential value gain is growing. This means that being sustainably proactive is as important as being, or remaining, profitable in business (Franca, 2013). However, integrating the business model into sustainable innovation practices is a relatively underexplored area of research (Boons and Ludeke-Freund, 2012).

3.5 Strategic life-cycle assessment

Strategic life-cycle assessment (SLCA) is a qualitative method to address social and ecological sustainability (Ny et al., 2006). It is meant to quickly identify the most important sustainability challenges to further guide necessary decisions and actions. Using colours instead of numbers (Figure 5), SLCA maps out violations against the four above mentioned universally applicable sustainability principles throughout the product life cycle from raw material extraction to end of life. Thus SLCA creates a more strategic and systematic approach than focusing on simply identifying and minimising known negative impacts.
3 Knowledge domains

3.6 Life-cycle assessment

Life-cycle assessment (LCA) is a well-established broad approach that assesses environmental impacts associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). According to ISO (2006), the LCA can be divide into four major phases (Figure 6):

- The Goal and scope definition defines the goal and borders of an LCA.
- The Inventory analysis defines the characteristics of data collection and calculation procedures. For example, it involves the energy and raw materials used, emissions (to the atmosphere water and land) that are quantified for each process, and are then combined in the process flow chart.
- The Impact assessment evaluates the potential significance of the LCA results.
- Interpretation phase defines the results that are reported in the most informative way possible, and the need and opportunities to reduce the impact of the products or services on the environment are systematically evaluated.

Figure 5. Strategic life-cycle assessment (SLCA), source: www.thenaturalstep.org.
3.7 Life-cycle costing

Life-cycle costing (LCC) has evolved from an international standard for Buildings and Constructed Assets (the International Organisation for Standardisation (ISO), 2008). Since then, many other fields have worked with LCC (The Green Icon, 2010; The International Electrotechnical Commission, 2004). LCC is a technique that enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operational costs (ISO, 2008). In other words, LCC is a technique to establish the total cost of ownership (TCO). It can take into account any costs that the selection team feels are appropriate. Economic life cycle data from throughout the product and service value chains, including energy carrier manufacturing, operations, and maintenance, are all examples of costs that could be included in an LCC. The LCC theory foundation is properly developed along with important decisions and activities to undertake an LCC analysis (Flanagan and Norman, 1993; ISO, 2008; Ristimäki et al., 2013):

- Defining alternative strategies to be evaluated - specifying their functional and technical requirements.
- Identifying relevant economic criteria – for example: discount rate, analysis period, component replacement frequency, and maintenance frequency.
- Acquiring and grouping of significant costs - in what phases different costs occur and what cost category.
- Performing a risk assessment - a systematic sensitivity analysis to reduce the overall uncertainty.
3.7.1 Net present value

Net present value (NPV) is widely used in businesses to compare cash flows at different time periods, where NPV is used in capital budgeting to analyse the profitability of a projected investment or project. The Present Worth or Present Value (PV) is indicated as usually less than or equal to Future Worth (FW) or Future Value (FV), because the money has an interest rate and is indicated as the discount value of money in the future (discount rate). Because of the time value of money, money in the present is worth more than the same amount in the future. This is both because of earnings that could potentially be made using the money during the intervening time and because of inflation. In other words, a dollar earned in the future will not be worth as much as one earned in the present. Therefore, companies may often have different ways of identifying the discount rate (Leland and Tarquin, 2012).

3.7.2 Sensitivity analysis through spider plot diagrams

Sensitivity analysis is an interactive process that tells you what effects changes in one variable will have in others. In this thesis, sensitivity analysis is applied to investigate how changes in various costs categories will influence the life cycle cost. By identifying the relative importance of risky cost variables, the decision makers can adjust the projects to reduce the risk and consider responses when the outcomes appear. The major benefit of sensitivity analysis is that it explicitly shows the robustness of the ranking of alternative projects (Flanagan and Norman, 1993). For example, when considering the life cycle costing of two alternative products, if the total cost of fuel would exceed the expectation by 10%, would this change the preferences between the two? Perry and Hayes (1985) have suggested the spider plot as an effective graphical presentation of sensitivity analysis. Spider plot is a graphic visualisation where it shows the changes in each single variable input that could affect the outcome (Eschenbach, Ted G 1992). This means, in turn, that each parameter line on the spider plot indicates the relative significance of that parameter on the TCO (Flanagan and Norman, 1993).
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4. Summary of appended papers

This chapter provides a summary of appended papers, its research questions, their relation to the thesis, and author contributions to the papers.

4.1 Paper A

Published as:


This paper primarily addresses the two first overarching research questions regarding (1) a new approach and (2) its application for bus systems. This has been further specified into asking how to advance from a narrow focus on efficiency or carbon dioxide emissions towards an integrated sustainability perspective when choosing public bus transport systems in medium-sized cities. And how, if at all, such a new perspective would change the preferred choice of bus transport system.

Paper A suggests a new approach that could integrate energy efficiency, carbon emissions, and other socio-ecological sustainability issues with the economic potential of public bus transport systems. This paper then investigates whether it is possible to transform public bus transport systems towards sustainability, and this paper also recommends powertrains and energy carriers for city buses that might be preferable for Swedish cities with less than 100,000 people. Several energy carriers are compared (diesel, biodiesel, biogas, and electricity) in different powertrains (internal combustion engines, electric hybrids, and pure electric). Wind power is assumed to deliver all the yearly-required electricity to the grid. A timeframe of eight years is used, which is stipulated by procurement of the case. For each type of bus, the same driving pattern is used in the calculations: five city-buses in Karlskrona, Sweden, (lines 1 and 7) with average speed profiles (25 km/h) with a stop at almost every bus stop, total drive cycles of 93,000 km/bus/year, and a total of 465,000 km/year. Comparisons are made with bus lines in Jönköping and Sundsvall, Sweden.

The results suggest that shifts from diesel buses to electric buses (powered by renewable energy) could potentially contribute to sustainable growth in the transportation sector. From an economic perspective, electric buses have the lowest TCO, more than 25% lower than diesel buses (Figure 7).
Nurhadi, L., 2016 An Approach to Business Modeling for Sustainable Personal Road Transport

Figure 7. Electric buses have the lowest Total Cost of Ownership (SEK/km) from 2013-2020 compared to other buses.

**Relation in thesis**

The paper provides a theoretical comparison of a public bus transport system in different powertrain configurations, in addition to discussing whether it is possible to transform public bus transport systems to more sustainable public bus transport systems. The findings could help strengthen the recommendation to decision makers on which powertrains and energy carriers might be preferable for city buses in Sweden.

**Author’s contribution**

The author has taken part in planning and writing the paper, has collected data and information of TCO from bus experts, has calculated TCO, has led the writing process, and created the results by co-creation with colleagues. This paper was presented by the author at the conference of European Working Group Transportation 16 in Portugal in 2013.
4.2 Paper B

Published as:


This follow-up paper goes further into answering the second overarching research question by expanding the analysis from paper A with three more detailed sensitivity-related questions on the economic assessment of the public bus transport systems:

1. Which factor is the most influential and significant in determining TCO?
2. What happens to the TCO of an electric bus if the...
   ...future investment cost is overestimated by 10 %, 20 %, or 30 %?
   ...travel line distance is decreased by 10 %, 20 %, or 30 %?
   ...number of operational years is increased by 10 %, 20 %, or 30 %?
   ...energy cost is increased by 5 %, 10 %, 20 %, or 30 %?
   ...maintenance cost (or fast charger cost) is reduced by 10 %, 20 %, or 30 %?
3. Which of the factors described above are more important for the TCO when the effect of each factor is compared to the others - two by two (pair analysis)?

The total cost of ownership (TCO) is compared for two electric buses with different driving ranges and different types of chargers. A sensitivity analysis is used to identify which factors are most likely to change the estimated cost values for the electric buses. A “what if” analysis captures this in a spider plot graph to understand the responsiveness of each factor on the outcome of the TCO for an electric bus. This could also help reduce uncertain factors that may impact the TCO, since economic factors such as future investment costs, operating expenses, and fuel costs may vary.

The result (Figure 8) suggests that electric bus A (with one extra battery and one normal charger, or one extra battery and two normal chargers) would be preferable in terms of cost effectiveness, since normal chargers are cheaper and allow for a longer battery life. This might be a good solution for a city or suburb where a fully charged electric bus can be available as a back-up after a bus has been driven 200-300 km. Electric bus B (with one extra battery and two fast chargers) could be an intermediate solution for a city that runs on tight schedules, since it charges within ten minutes.
Figure 8. How cost varies depending on electric buses’ configuration compared to hybrids.

The steeper the line a certain factor gets in the spider plot (Figure 9) the higher its ability is to change the TCO. The most influential and significant factor identified was line distance per year, the second operational year, and the third investment and maintenance costs. The cost of a normal charger and an extra battery did not significantly impact the TCO. The TCO would be significantly lower if the electric bus was driven more than 100,000 km per year and operated for more than nine years.

Figure 9. How TCO of electric bus A (with one extra battery and two normal chargers) varies with changes (%) in different parameters.
A pair analysis shows what would happen to the TCO of an electric bus if two variables are paired, as well as what are the minimum and maximum values. The result of the pair analysis (Figure 10) is based on N = 8 input variables, so there are N*(N-1)/2 = 8*(8-1)/2 = 28 pairs to evaluate. A line distance of 121,000 km per year and 10 operational years could generate the lowest Present Worth of TCO. On the other hand, the highest cost was caused by low line distance of 65,000 km per year and six operational years.

Figure 10. A tornado graph that shows how minimum and maximum value of Present Worth of the Total Cost of Ownership (PW of TCO) of bus 'A' depends on pair analyses of two influencing factors at a time.
Relation in thesis

This paper strengthens the previous paper, which recommended the electric powertrain, where the result could be used to avoid many uncertain economic factors within the decision-making process for public bus procurement in Sweden.

Author’s contribution

The author has made the TCO calculation, completed the sensitivity analysis diagrams, and led the writing process. The author presented this paper at the European Working Group Transportation 17 conference in Seville, Spain in 2014.

4.3 Paper C

Published as:


This third paper went further into verifying the answer to the second overarching research question. Real-life testing of an electric bus was used to check the validity of the theoretical calculations on TCO and other sustainability performance indicators from papers A and B. More specifically this paper investigated the electric energy use and external noise levels of the electric bus. It also received opinions from passengers, drivers, and other stakeholders during real-life use in wintertime in the south of Sweden. The electric bus testing was carried out from November 2014 to April 2015 in eight municipalities in southern Sweden; six tests took place in urban and two in suburban traffic. The operated electric bus was the Ebusco 2.0 electric bus, which used a 311 kWh battery pack.

The resulting average energy use was in Paper C found to be 8 % less (0.96 kWh/km) than what was estimated in the previous study (paper A). The new energy measurement data from Paper C could thereby verify that the TCO for electric buses when used in public urban transport and charged with new renewable energy is up to 25 % less than for diesel buses (Table 1). In all, this supports the conclusion that electric buses are preferable for use in Swedish public urban and rural transport, which can probably also be applied to other European (especially Nordic areas) with similar climate.

Table 1: Average energy use results in each municipality and average results for use in urban traffic.
### Relation in thesis

This paper acted as a further investigation to verify the two previous studies (papers A and B) by determining both the energy use of the electric bus during the winter in the south of Sweden and the noise from electric, hybrid, and diesel buses. The findings in the study were more practical facts, and data of currently used electric buses could be suitable for implementation in public transport.

### Author’s contribution

The author has taken part in re-calculating TCO based on the new energy measurements recorded in paper C, supported the finding of noise measurement standard, and provided support during the buses’ noise measurement.

### 4.4 Paper D

#### Submitted as:


This fourth paper aimed to further address the first and second overarching research questions by developing and testing an approach toward comparing sustainability effects (mainly approximated through CO$_2$-emissions) and Total Cost of Ownership of various business models (regular purchase, car pooling, car leasing, and taxi) applied to
private cars with different energy carriers (biogas, ethanol, gasoline, plug-in hybrid, and electric).

The results (table 2) were reviewed by a green motoring organization, Miljöfordon Syd, as well as two car pooling companies, Sunfleet and Move About. The results indicate that out of all the options, electric vehicles are the most competitive – from both an ecological and economic perspective. Moreover, out of all the business models, car pooling was found to be generally preferable for short to medium distances, reducing CO₂-emissions by 20-40 % compared to a regular purchase car. Meanwhile, a leased car, of course, emits the same amount of CO₂-emissions as the regular purchase car if both are driven the same number of kilometers per year. Taking a closer look at the cost effectiveness of various uses of electric vehicles (Figure 11), it was found that people who travel by car less than 2,000 kilometers per year should consider using a taxi, while car pooling is most cost-effective for those who travel between 2,000 and 8,500 kilometers. For those who travel between 8,500 and 13,500 kilometers per year, car leasing is the most cost-effective, and regular purchase is the best option for those who travel more than 13,500 kilometers per year.

**Relation in thesis**

The paper develops and tests an approach to comparing sustainability performance and TCO of various business models. This brings new opportunities, and if most car owners were to accept these changes, given that more than half of the population travel by car less than 13,500 kilometers per year, necessary transportation could be ensured and the number of cars needed for such transportation would be significantly reduced. This, in turn, would result in less fossil fuel use, fewer emissions, and decreased issues related to human health. This paper also contributed to the current assessment of the GreenCharge project.

**Author’s contribution**

The author has done literature studies, collected data, and interviewed the relevant companies to get their insights and analyse the data into the paper. The author also has calculated TCO, completed its diagrams, and led the writing process.
Table 2. How CO₂ emissions and TCO costs are reduced when moving from regular purchase, car leasing, or car pooling to taxi services, especially for electric vehicles.

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<th>Biogas car</th>
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Based on Studies from Gröna bilister (Gröna Bilister-The Green Motorist, 2014), Sunfleet’s sustainability report in Sweden (2014), (Faria et al., 2012; 2013; Toyota Motor CorporationMizuho Information Research Institute, Inc, 2004; WWF for a living planet, n.d.). Kg CO₂ e/year = Kilogram CO₂ equivalent per year; Km/ year = Kilometre per year; SEK/year = Swedish Kronor per year.
Figure 11. Taxi is most cost-effective below 2,000 km/yr., car pooling between 2,000 and 8,500, car leasing between 8,500 and 13,500, and regular purchase above 13,500.
5. Business modeling for sustainable personal road transport

This chapter makes a short description of the new approach for business modeling for sustainable personal road transport suggested by this thesis and what it is based upon.

5.1 Background and development of the new approach

The aim was to identify a new approach for business modeling for sustainable personal road transport. The requirements on this new approach included that it should be

- based on a scientifically strict definition of sustainability
- generic enough to apply for most contexts
- user oriented to foster solutions attractive to users

In parallel to this thesis the Framework for Strategic Sustainable Development (FSSD) was used to build a vision of a sustainable personal passenger road transport (Robèrt et al., 2016) and to explore ways to move strategically towards the vision (Borén et al., 2016a). The new approach of this thesis was iteratively developed and tested through papers A to D. It was applied on vehicle systems and their socio-ecological and economic sustainability effects throughout their life-cycles. More specifically, there was a theoretical case study that investigated whether and how electric bus systems could be preferable in medium-sized Swedish cities (papers A and B). There was also real-life testing to follow up the results of the theoretical bus study (paper C). Finally, there was a case that compared the sustainability effects of various ways to access cars that run on various energy sources (paper D). These cases formed the basis to suggest a generic approach that could assess how vehicle systems for passenger transport could be adapted to fit within the requirements of a sustainable society. The socio-ecological part of the proposed new approach integrated energy efficiency, CO$_2$ emissions, and other sustainability issues. The economic analysis part focused on cost effectiveness from a total cost of ownership perspective and how this was influenced by various uncertain factors.

5.2 The structure of the new approach

The new proposed approach combined several existing methods and techniques (see chapter 3) in a new way (Figure 12). The use of the new approach is further described in each attached paper but it could be summarized as consisting of a few overarching elements where the first three were introduced in papers A and B, the fourth in paper D and the fifth in paper C:
1. **Overarching scoping sustainability assessment.** Based on the above described FSSD-based sustainability vision and preliminary description of how to get there, this thesis focused on some bus systems and combinations of car systems and business models. An SLCA was performed on the studied systems to identify prioritized sustainability challenges in relation to the vision along the life cycle stages (raw material, production, packaging and distribution, use, and end of life). These challenges or ‘hot-spots’ were then targeted for further more detailed analysis.

2. **Detailed sustainability assessment.** LCA was used to further assess the negative environmental consequences for society of the ‘hot-spots’ that were identified in the studied systems by the SLCA.

3. **Detailed economic sustainability assessment.** LCC was used to calculate the total cost of ownership of the studied systems.

4. **Business modeling.** Various business models of the conceived new transport solutions were mapped out in more detail using product service system and business model canvas techniques. Then these solutions were fed back into the above mentioned sustainability assessment elements to identify (1) overarching socio-ecological sustainability effects, (2) detailed ecological effects and (3) detailed economic effects.

5. **Noise and energy measurements.** To verify the theoretical calculations of noise and energy use for various buses some measurement techniques were developed and tested in practice.

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![Diagram](image-url)

**Figure 12.** How the steps of the new approach are connected and how they grew out of the thesis papers. Papers A and B uses SLCA to scope an integrated LCA and LCC analysis, PSS and BMC are added in paper D and noise and energy measurements in paper C.
6. Discussion

This chapter discusses the main results and their validity, compares the results with other related studies, provides key conclusions, and further work.

6.1 Main results

This thesis aimed to explore support for development of the current transport sector in a sustainable direction that could be attractive to the users and actors involved. More specifically, the aim was to develop a new approach to examining the economic and socio-ecological sustainability effects of various road vehicles for private travelling and related business models. A special focus was set on comparing various bus systems for public transport and ways (business models) for private people to access cars. The main comparison parameters were the TCO and CO₂ emissions for the studied alternatives.

Paper A was a first theoretical test of the new approach for a public bus transport system primarily using several energy carriers (diesel, biodiesel, biogas, and electricity) in different powertrains (internal combustion engines, electric hybrids, and pure electric). Paper B was a follow-up study to Paper A that emphasized sensitivity analysis of TCO for two electric buses with different driving ranges and different types of chargers. The idea with paper B was to deepen the study of the economic aspect of LCC from Paper A. Paper C was another follow-up study of Papers A and B and it was focused on real-life testing and the verification of assumptions and results from the previous studies. It also investigated whether electric buses are suitable for use in public transport. Paper D further developed the new approach and assessed the sustainability performance of various business models for cars.

6.2 Answering the overarching research questions

The following reasoning shows how the results of this thesis are providing the answers to the research questions (RQs):

RQ1. A new approach was suggested in paper A that combined a traditional economic analysis and integrated it with a strategic sustainability perspective. This new approach was built on the FSSD, in which principles define a sustainable future as a long-term sustainability perspective that allows planning towards a desirable future. The new approach was applied for bus transport system development planning from a strategic sustainability perspective. The new approach started with SLCA (Ny et al., 2006) to give a full scope of sustainability challenges in each bus life cycle stage from raw materials to end of life. After that, LCC (ISO, 2008), LCA (ISO, 2006), and other
analyses were iteratively used to "dig deeper" into the most significant challenges. The initial testing through a real case indicated that the support worked as intended.

RQ2. Paper A did theoretical calculations on powertrains and energy carriers for city buses for Swedish cities with less than 100,000 residents and concluded that an electric bus system could be preferable, both from an economic and a socio-ecological sustainability perspective. Then paper B used sensitivity analysis through a spider plot to indicate which elements of the TCO were the most sensitive and how they might behave. In paper C the theoretical calculations could be backed up by real bus test driving results, thus verifying the claim that electric buses are preferable to diesel and other alternatives.

RQ3. In paper D the thesis developed and tested an approach, comparing sustainability effects (mainly approximated through CO₂-emissions) and Total Cost of Ownership of various business models (regular purchase, car pooling, car leasing, and taxi services) applied to private cars with different energy carriers (biogas, ethanol, gasoline, plug-in hybrid, and electric). The least economic and socio-ecological impacts came from car pooling with an electric car (this could be an alternative primarily when driving short distances) powered with renewable energy. In fact, it was found that, from an economic cost-effectiveness perspective, people who travel less than 2,000 kilometers per year should consider using a taxi, while car pooling is most cost effective for those who travel between 2,000 and 8,500 kilometers. For those who travel between 8,500 and 13,500 kilometers per year, car leasing is the most cost-effective, and regular purchase is the best option for those who travel more than 13,500 kilometers per year.

6.3 Discussion on contributions and shortcomings

This thesis contributes to sustainable development by evaluating how socio-ecological (e.g., various emissions) and economic (mainly through TCO) sustainability effects relate to one another. It will also hopefully contribute to Southeast Swedish fossil fuel independence in the transport sector by 2030. More specifically, this thesis makes the following contributions to the research field:

- It suggests insights toward building and testing an approach that should enhance decisions on bus transport powertrains and energy carriers for medium-sized Swedish cities. The suggested approach explores further traditional economic analysis and integrates it with a strategic sustainability perspective.
- It analyses which factors (future investment, travel line, operational years, energy cost, and maintenance cost) are the most influential and significant in determining TCO. This contributes to a better decision-making process when it comes to the TCO of public bus transport systems. It also contributes to
showing which factors are more important for TCO in which the effect of each factor is compared to others (pair analysis).

- It verifies the new approach through real-life testing.

This is how some potential shortcomings of this thesis have been handled:

- The technology development is fast within the public transport’s industries. Paper A was theory-based and the data may need to be updated in relation to newer technologies and newer regulation such as Euro 5. Also, the input data from various bus manufacturers may vary (e.g., prices may vary between manufacturers of similar buses and the price may vary between countries for similar buses). However, the analyses in the study are estimated to be sufficiently representative for this thesis. Similarly, the data is consistently selected from several key resources that are deemed reliable.

- Paper B relied on input of electric bus manufacturers where costs may vary depending on bus manufacturers and the specifications of the electric buses. However, the data is deemed to be sufficiently representative as each set was consistently identified from several particularly reliable key resources. A sensitivity analysis does not aim to quantify risk, but rather to detect factors that are risk sensitive. This was still considered sufficient for this thesis. The previous study (Paper A) that recommended the electric powertrain, is thereby strengthened by this study, where the result could be used to avoid many economic uncertainty factors from the decision-making process for public bus procurement. It gave a good indicator to show the most likely TCO and its main influential factors.

- Paper C used real-life testing to verify the calculations of the TCO. To make the results even more reliable, it would be prudent to gather more data from additional suppliers to compare more electric buses. For validity reasons, though, it was considered sufficient to compare the study results with the findings of other studies.

- Paper D was theory-based and the data may need to be updated in relation to newer technologies. Also, the data for various cars varies a lot (e.g., prices may vary between manufacturers of similar cars, prices may vary between dealerships of similar cars, and the price may vary between countries for similar cars). There is a need for sensitivity analysis to support the likely percentage change of unaccounted factors. However, the analyses in the study were deemed as sufficiently representative for this overview study. They also gave a reasonable indication of the most likely TCO and CO₂-equivalent per km driven using the studied current business models. For validity reasons, comparisons have also been made with the findings of other researchers, and iterations of mutual feedback have been performed with the interviewees from the case study.
6.4 Comparison with other studies

The validity of the approach of this study is strengthened by two tandem papers for the multi-stakeholder creation of a vision and development steps for sustainable electric vehicle systems (Borén et al., 2016b; Robért et al., 2016) that also are based on the FSSD approach. These tandem papers suggest that the sustainable development of the traffic sector relies on the interaction between actors who have key roles within the transport sector, as well as for those who interplay within four essential transport planning perspectives (resource base, spatial, technical, and governance perspectives) to move towards sustainable transport solutions. The idea of comparing various business models for the same kind of vehicle has also been tried elsewhere. A study called BeliEVe (Business model innovation for electric vehicles) by the Swedish ICT Viktoria (Willander and Stålstad, 2013) found that business models in the car industry have started to move beyond physical products to also include complementing bundled services. Another business model study found that small-scale or localized development in terms of infrastructure with the combination of alternative powertrains that are using non-fossil fuels, such as biofuels, biogas, EVs, and hydrogen vehicles, could support mobility for cities and regions to capture economic advantages, as well as environmental and transport benefits (Nieuwenhuis and Wells, 2013). Yet another study compared the TCO of electric cars, hybrids, and diesel cars and found that the TCO for electric cars was the lowest (Hagman et al., 2014). Finally, the big holistic systems perspective taken by this study when comparing car types is supported by the ELMOB project in Gothenburg, Sweden, that found that transport solutions are likely increasingly going to be used for inter-modality.

6.5 Wider societal implications

This thesis has broadened the application of the sustainability assessment approach by simultaneously comparing a variety of private car and bus types. From Papers A to D, this thesis suggests that a simultaneous shift from diesel to electric buses (powered by renewable energy) in public transport and from car ownership to car use services (preferably with electric cars run on renewable energy) at the individual level bring cost-effectiveness and could be favourable for an affordable acceleration of sustainability in the transport sector. Moreover, the comparison approach suggested in this study is expected to create high value for business users when they will be able to develop and choose the most suitable business model for themselves while fostering an effective transition towards sustainable transportation. Finally, this could encourage private citizens to make wiser choices for their transportation solutions as an essential means to increase the share of more sustainable transport.
6.6 Future work

This thesis brought an approach to support the implementation of strategic sustainable development with a focus on business modeling and TCO assessments for transportation at the practitioner level. Further studies could explore new combinations of business models that are more developed than the ones that are identified today and more detailed support could be developed in future research. This could include:

- Identifying new attractive combinations of business models for private car use.
- Identifying new business models for the service ecosystems of electric vehicle charging infrastructure.
- Investigating multimodal transportation for multiple transportation modes.
- Achieving a deeper understanding of how business models can be practically implemented through the new approach suggested in this thesis.
7. References


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WWF for a living planet, n.d. WWF for a living planet.
Advancing from efficiency to sustainability in Swedish medium-sized cities: an approach for recommending powertrains and energy carriers for public bus transport systems
Paper A is published as:

Advancing from efficiency to sustainability in Swedish medium-sized cities: an approach for recommending powertrains and energy carriers for public bus transport systems

Lisiana Nurhadi, Sven Borén, Henrik Ny

Published at EWGT Conference 2014 in Porto.

Abstract

European national, regional, and local authorities have started to take action to make public bus transport services more effective and less polluting. Some see the possibility to move beyond a narrow focus on efficiency or carbon dioxide reductions towards an integrated sustainability perspective. This paper uses this perspective to build and test a new assessment approach that should enhance decisions on bus transport powertrains and energy carriers for Swedish medium-sized cities. The study suggests that a superiority of electric powertrains is revealed if a traditional economic analysis is integrated with a strategic sustainability perspective.

Keywords: Electric bus; Life-cycle assessment; Greenhouse gas emissions

1. Introduction

Public transport is vital to support travelers and commuters’ to and from suburbs and surroundings for everyone in a more environmental friendly way than using cars. Public bus transport also helps people without cars to travel safely. The present European transportation growth is however unsustainable as it is strongly linked to problems such as energy supply and climate change (The European Commission, 2011). There is therefore a need to transform public bus transport systems towards sustainability. This study focuses on recommending powertrains and energy carriers within city buses for small to medium-sized cities with less than 100,000 citizens in Sweden.
1.1 EU focuses on efficient transport at the expense of sustainability?

The European commission focus on future transport to be energy efficient, have low carbon dioxide emissions, and becoming independent of fossil fuels (The European Commission, 2011). Unfortunately, the focus in the EU directives is sometimes too narrowly set on the use phase, while excluding phases like manufacturing and its’ supply chain. This means that the directives in their current form are not enough to ensure a sustainable transport system development. The EU fuel directive (The European Commission, 2009a; 2011), that the bus manufacturers use to calculate their emission levels, is a part of this problem. In line with the EU transport ambitions, European national, regional, and local authorities have started to take action to make public bus transport services more effective. That will ensure a short-term economic return, but inherently unsustainable solutions (like fossil fuelled buses) may be kept for too long at the expense of initially costly renewable energy carrier solutions that are less polluting and more long-term resource effective since fossil fuels is likely to become exceedingly expensive over the decades to come.

1.2 A Framework for Strategic Sustainable Development

It is a complex task to make decisions about how to transform transport systems towards sustainability. A previously presented framework for planning in complex systems {Robert:2000ha} has been developed for such tasks. It has been successfully used for strategic sustainability planning both in business (Broman, Holmberg, & Robèrt, 2000; Everard, Monaghan, & Ray, 2000; Nattrass, 1999; Robèrt, 2002) and in municipalities (James & Lahti, 2004; Resort Municipality of Whistler, 2007). This framework uses four basic sustainability principles (SPs) of ecological and social sustainability (Holmberg & Robèrt, 2000; Ny et al, 2006) as boundary conditions for visioning in planning, followed by analysis, planning, and choice of tools to step-wise get there, as well as optimizing financial outcomes:

In the sustainable society, nature is not subject to systematically increasing . . .

I …concentrations of substances extracted from the Earth’s crust,
II …concentrations of substances produced by society,
III …degradation by physical means, and, in that society . . .
IV ...people are not subject to conditions that systematically undermine their capacity to meet their needs.
1.3 From efficiency towards sustainability

The public bus transport system makes a positive contribution to personal mobility, but from a sustainability perspective we also need to consider issues like costs, pollution, and social implications. Aspects of the public bus system’s sustainability implications have been described in the literature (Andersson & Norman, 2012; Börjesson, Thufvesson, & Lantz, 2010; Cooney, 2011; Gode et al., 2012; Helms, Pehnt, Lambrecht, & Liebich, 2010). How could we then advance from a narrow focus on efficiency or carbon dioxide emissions towards an integrated sustainability perspective when choosing public bus transport systems in medium-sized cities? And how, if at all, would such a new perspective change the preferred choice of bus transport system?

2 Methods

The Framework for Strategic Sustainable Development (FSSD), where principles define a sustainable future, is used to move from a shortsighted cost and environmental perspective to a long-term sustainability perspective that allows planning towards a desired future from a current state. As previously suggested by Ny and Gunnarsson in a master thesis (Gunnarsson, 2010), and as described in Figure 1, Strategic Life-cycle Assessment - SLCA (Ny et al, 2006) - is first used to give a quick full scope of sustainability challenges in each bus life-cycle stage from raw materials to end of life. After that, Life cycle costing - LCC (ISO, 2008), Life-cycle assessment - LCA (ISO, 2006) and other analyses are iteratively used to ”dig deeper” into prioritized identified challenges. Literature reviews, interviews, and simulations are used as supporting methods. Karlskrona in Southern Sweden with 35,000 inhabitants is used as the case.

Figure 1. How a new iterative approach uses SLCA to scope an integrated LCA and LCC analysis
2.1 Strategic life-cycle assessment (SLCA)

As a first part in this study, the SLCA is a qualitative method to address social and ecological sustainability aspects. It allows an approach to quickly identify the most important high-level sustainability challenges that can guide necessary decisions and activities and then, if needed, suggest complementary analyses. The SLCA displays the ‘hot-spot’ issues that are particularly important for a sustainable development. The focus is on powertrains and energy carriers that make a big difference when comparing bus alternatives for city traffic.

2.2 Life-cycle assessment (LCA) and Life-cycle costing (LCC)

The second part is to conduct a deepened sustainability study with LCA and economic potential with LCC. This requires assessment from “well to wheel” (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance). The study makes a theoretical comparison of a public bus transport system primarily using several alternative energy carriers (diesel, biodiesel, biogas, and electricity) in different powertrain configurations (internal combustion engines, electric hybrids, and pure electric), as seen in Table 1. Note that wind power is assumed to deliver to the grid at least the yearly required electricity for the electric powertrain configurations. A timeframe of 8 years is used, as this is what is stipulated by procurement of the case. For each type of bus the same driving pattern is used in the calculations: five city-buses (lines 1 and 7) with average speed profiles (25 km/h) and average load profiles, with a stop in almost every bus stop. This is based on drive cycles of 93 000 km/bus/year, and in total 465 000 km/year for five buses.

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>Description</th>
<th>Primary drive</th>
<th>Energy usage</th>
<th>Energy content (2013)</th>
<th>Cost (excl VAT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>Fossil Diesel with 5% Combustion blending of FAME</td>
<td>0.45 liter/km</td>
<td>9.96 kWh/liter</td>
<td>5,95 SEK/km</td>
<td></td>
</tr>
<tr>
<td>Biodiesel</td>
<td>Made from Rapeseed Combustion methyl Ester (RME)</td>
<td>0.50 liter/km</td>
<td>9.3 kWh/liter</td>
<td>6,30 SEK/km</td>
<td></td>
</tr>
<tr>
<td>Biogas</td>
<td>Made from household Combustion</td>
<td>0.57 Nm3/km</td>
<td>9.67 kW/h</td>
<td>6,70 SEK/km</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>Made from household Electric/Combustion</td>
<td>0.57 Nm3/km</td>
<td>9.67 kW/h</td>
<td>6,70 SEK/km</td>
<td></td>
</tr>
<tr>
<td>Plug-in hybrid</td>
<td>67% wind electricity - 33% Electric biodiesel</td>
<td></td>
<td></td>
<td>2,50 SEK/km</td>
<td></td>
</tr>
<tr>
<td>Electric bus</td>
<td>Electricity from wind power Electric</td>
<td>1.4 kWh/km</td>
<td>1 kWh/kWh</td>
<td>1,20 SEK/km</td>
<td></td>
</tr>
</tbody>
</table>
LCA is used to compare negative environmental effects on society of different energy carriers for buses during their lifetime. In line with previous LCA studies on Swedish biofuels (Börjesson et al., 2010) the authors selected the air emission categories Green House Gases (CO$_2$ eqv), Eutrophication (PO$_4$ eqv), Acidification (SO$_2$ eqv), Photochemical oxidants (C$_2$H$_2$ eqv), and Particles (PM). These all need to be decreased for a development towards a sustainable future as defined by the SPs.

The purpose of using LCC is to analyze economic lifecycle data that relates to energy carrier manufacturing, operation, and maintenance for buses. Building on energy usage for each energy carriers, this analysis is essential for decision-making when purchasing vehicles, optimizing maintenance, and planning upgrades of public bus infrastructure. The Scope and Limitation of the LCA and LCC exclude leakage or energy losses during distribution or transportation of energy carriers, bus manufacturing processes, and end of life. Nor are accidents or other external costs included. The origin of the electricity for the extraction to distribution phases is gathered from literature sources. The electricity in the use phase, though, is always assumed to come from renewable sources (e.g. new local stand-alone wind power plants). The biogas analyzed in the study is locally produced digested biogas-100. Costs and emissions of the substrate before digesting is excluded, as these factors are dependent on digestion quality, land applications, country policy, etc. Biodiesel - Rapeseed Methyl Esther (RME) is locally produced. The system expansion, replacement by-products for RME as rapeseed meal, glycerol, and straw are excluded. The functional unit used is travelled bus kilometer. LCA and LCC data are calculated based on 8 years operational period as stipulated by procurement. The Present Value method and a real interest rate of 1% (based on historical data for Sweden from the 21st century) are used to calculate the economic potential. Results for each energy carrier are based on best estimates of current energy usage per km, energy content per kWh and costs in SEK per km (Table 1). The data inventory is obtained through interviews, literature review, authors’ calculation, and bus manufacturer’s simulation. Interviews were conducted with bus dealers, bus manufacturer, drivers, and bus service providers in 2013. The interviews brought insights on economic potential of public bus transport and data input and raw data calculation in the inventory list.

2.3 Priority listing of bus types – both for EU fuel directive and form a strategic sustainability perspective

Based on the preliminary results that are available, the authors demonstrate how the desirability of the studied bus systems vary depending on whether the assessment is done with a EU fuel directive or a strategic sustainable development perspective.
3 Results

3.1 Sustainability potential with a life-cycle perspective

The SLCA conducted in this study focuses on the life-cycles (including raw material extraction, production, transport, use and waste management phases) of energy carriers within city buses (Table 2). As mentioned in section 2, LCA is then used to further analyze sustainability challenges discovered in the SLCA. There is a contribution to social sustainability (SP4) for the biodiesel, biogas and electric alternatives in the first life-cycle phases as they are contributing to local jobs. Meanwhile biodiesel (rapeseed) production may outside of Sweden compete with other more urgent land uses and thereby violate SP4. The electric and hybrid alternatives contribute to SP4 reducing noise level and air quality. Violations for diesel are mainly in SP2 due to emissions, but also in SP3 due to infrastructure and risks of environmental impacts. Batteries within electric and hybrid bus alternatives violate SP1 due to scarce materials such as Lithium. At last, hybrids violate SP2 as powertrains include both combustion engines and electric drives, which increase the production material flows and transport emissions.

<table>
<thead>
<tr>
<th>Sustainability Principle</th>
<th>Life-cycle phase</th>
<th>Biogas</th>
<th>Biodiesel</th>
<th>Diesel</th>
<th>Electric</th>
<th>Hybrid</th>
<th>Plug-in Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production</td>
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<tr>
<td></td>
<td>Transport</td>
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<td></td>
<td>Use phase</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waste</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP2</td>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Production</td>
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</tr>
<tr>
<td></td>
<td>Waste</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP3</td>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Production</td>
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<td></td>
<td>Transport</td>
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<tr>
<td></td>
<td>Use phase</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waste</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SP4</td>
<td>Raw material</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Production</td>
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<td>Use phase</td>
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<tr>
<td></td>
<td>Waste</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Indicators: negative, slightly negative, neutral, slightly positive

Electric powertrains are the most efficient and biodiesel the least efficient during the whole life-cycle. Biogas uses most energy of all energy carriers during the use phase, but is the second best after the 15 times smaller electric energy carrier in the extraction to
The emissions to air depend upon the type of energy carrier and powertrain (Börjesson et al., 2010; Gode et al., 2012) Emissions from hybrids (including Plug-in) are calculated based on energy savings. Within all these results, biofuels are considered carbon dioxide neutral in the use phase according to the Swedish annual Greenhouse Gas reporting to the UN (Swedish Environmental Protection Agency, 2012). The electric alternative emits the least per km and biodiesel together with diesel emits the most (Figure 3), but the hybrids would emit much less if they would run on biogas.

If the EU fuel directive (The European Commission, 2009a) calculation model is used instead of the UN GHG approach, the biodiesel carbon dioxide emissions would be halved and the biogas carbon dioxide emissions reduced by about 20 % compared to diesel in the use phase. When calculating GHG-emissions in the use phase, biodiesel will emit 60 % less than the diesel alternative, and biogas about 75 % less. Biodiesel would then emit a few percent more GHG (life-cycle) than diesel.
3.2 Current Economic potential

When calculating Total Cost of Ownership by the Net Present Value method and a real interest rate of 1%, the results shown in Figure 4 reveals that there is already today an economic advantage to chose electric propulsion (from wind power) in city buses instead of fossil fuels. The highest initial investment cost in year 2013 is for an electric bus (3.7 MSEK), and the lowest for a diesel and biodiesel bus (2.3-2.4 MSEK) (Table 3 and Figure 4). This could from a traditional economic calculation seem to suggest that it is beneficial to select the diesel bus as a short term investment. Still, the energy use is relatively high for fossil fuelled buses (0.4-0.5 liter/km or 4 kWh/km) and relatively low for electric buses (1.4 kWh/km). Moreover, the diesel bus generates the most external environmental costs such as air, land and sea pollution.

Table 3. The difference in life-cycle cost between combinations of energy carriers and bus powertrains for the year 2013

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Biogas</th>
<th>Biodiesel</th>
<th>Diesel</th>
<th>Electric</th>
<th>Hybrid</th>
<th>Plug hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus investment cost (MSEK)*</td>
<td>3.0-3.1</td>
<td>2.3-2.4</td>
<td>2.3-2.4</td>
<td>3.5-5.0</td>
<td>3.05</td>
<td>3.05</td>
</tr>
<tr>
<td>Energy usage per km (kWh/km)</td>
<td>5.50</td>
<td>4.65</td>
<td>4.50</td>
<td>1.40</td>
<td>3.10</td>
<td>4.00</td>
</tr>
<tr>
<td>Energy price excl. VAT (SEK/kWh)*</td>
<td>1.31</td>
<td>1.34</td>
<td>1.20</td>
<td>0.85</td>
<td>1.47</td>
<td>0.71</td>
</tr>
<tr>
<td>Energy cost (SEK/km) *</td>
<td>6.70</td>
<td>6.30</td>
<td>5.95</td>
<td>1.20</td>
<td>4.23</td>
<td>2.50</td>
</tr>
<tr>
<td>Energy usage kWh/yr</td>
<td>512 610</td>
<td>432 450</td>
<td>416 830</td>
<td>130 200</td>
<td>290 000</td>
<td>372 650</td>
</tr>
<tr>
<td>Fuel station cost (MSEK)*</td>
<td>25</td>
<td>2.5</td>
<td>7.5</td>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Facility cost (MSEK)*</td>
<td>55</td>
<td>2.5</td>
<td>-</td>
<td>30 (Wind)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maintenance cost (SEK/yr)</td>
<td>69 000</td>
<td>49 300</td>
<td>49 300</td>
<td>56 695</td>
<td>61 625</td>
<td>61 625</td>
</tr>
<tr>
<td>Helping maintenance (SEK/yr)</td>
<td>128 000</td>
<td>123 300</td>
<td>111 000</td>
<td>127 650</td>
<td>138 750</td>
<td>138 750</td>
</tr>
<tr>
<td>Production fuel/electr.(SEK/kWh)*</td>
<td>0.30-0.70</td>
<td>0.68-0.74</td>
<td>0.59</td>
<td>0.05-0.10</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Upgrading to gas (SEK/kWh)</td>
<td>0.15-0.20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Additive cost (SEK/kWh)*</td>
<td>-</td>
<td>0.072</td>
<td>0.05-0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Distribution (SEK/kWh)*</td>
<td>0.10-1.10</td>
<td>0.005-0.01</td>
<td>0.005-0.01</td>
<td>0.1-0.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Selling cost (SEK/kWh)*</td>
<td>0.8-2.40</td>
<td>0.025-0.03</td>
<td>0.025-0.04</td>
<td>0.02-0.01</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Data from bus manufacturers, bus operators (maintenance cost), energy suppliers, biofuels supplier, and facility station in Sweden
Recalculated from reference (Börjesson et al., 2010)

MSEK=Million of Swedish Kronor; SEK=Swedish Kronor; l/km=litres/kilometre; Nm³/km=Normal cubic meter / kilometre; l/yr=litres/year; kWh/km=Kilowatt-hour/kilometre; kWh/yr=Kilowatt-hour/year; SEK/l=Swedish Kronor/litres; SEK/kWh=Swedish Kronor/kilowatt-hour

Average energy price exclude VAT (Eon Sweden, 2013; Svensk Energi, 2013; Svenska Petroleum och biodrivmedelinstututet, 2013).

When using the LCC approach, other costs are also included (e.g. maintenance, helping maintenance, energy consumption, overhead cost, depreciation value and battery costs for buses with electric propulsion). In this calculation, the energy price increases annually by about 6%, based on the history of energy price development in the last 10 years. Investment costs are assumed to be constant overtime. Several uncertain factors also indicate that fossil fuelled buses are probably not desirable from a life-cycle cost perspective in the long run. This can for example be seen from the total energy demand in Sweden that is expected to increase from almost 380 Million ton oil equivalents (Mtoe) in 2012 to 437 Mtoe in 2030 (The European Commission, 2009b). This is also related to the geopolitical situation, new technologies, depleting reserves of fossil fuels, volatility in the price of crude oil, inflation rates volatility, taxation and increasing concerns about environmental pollution and greenhouse gas emissions.

Figure 4. Total Cost of Ownership (SEK/km) 2013-2020
3.3 Priority listing of bus types – both for EU fuel directive and form a strategic sustainability perspective

The EU fuel directive would favor the buses with the lowest current life-cycle costs. On the other hand, the Strategic Sustainable Development perspective prioritizes the buses from the most to the least sustainable (Figure 5). The electric bus then moves from being the lowest life-cycle costs to the most sustainable.

![Bus priority lists based on result of current life-cycle costs vs. sustainability](image)

4. Concluding discussion

This study is the first part of the longer study on buses outside of major cities and the results are therefore preliminary. However, the results suggest that the priority shifts from diesel buses to electric buses when we move from a traditional EU fuel directive calculation approach to a strategic sustainability perspective that includes economic, environmental and social issues - both now and in the future. More specifically, the authors have found indications that:

- Even though current European electricity to a large degree is generated from fossil fuels, an electric powertrain powered by new renewable electricity would be the most energy efficient and sustainable.
- Compared to diesel, the Total Cost of Ownership distributed over 8 years for Electric bus (with 1 extra battery and 1 fast charger) is more than 20 % lower, and the electric bus (with 1 extra battery and 2 fast chargers) is 17% lower. Future battery and fast charger uncertainties generate high costs in this study, but electric bus would be even more competitive if the cost could be spread out over nine years instead of the eight years that were stipulated by the
procurement period of this case. Also compared to diesel, the hybrid is 7% lower and Plug-in hybrid is 17% lower.

- The fossil diesel, within a traditional combustion engine powertrain, is a poorer solution than an electric powertrain powered by green electricity in terms of energy efficiency, life-cycle emissions and costs, as well as resource management for future generations. It can compete in the use phase with biofuel buses regarding energy efficiency, and with biodiesel regarding the emission categories acidification and eutrophication.
- The hybrid powertrain would in average reduce life-cycle emission with almost 40%, and the plug-in hybrid with around 70%, compared to diesel. Plug-in Life-cycle energy efficiency is almost 60% better than Diesel.

This paper relies heavily on the FSSD and related tools like SLCA. This could be seen as a potential shortcoming, but these tools have earlier been successfully applied at senior management levels in several companies (Broman et al., 2000; Everard et al., 2000; Nattrass, 1999; Robèrt, 2002). The main difference between the authors’ sustainability and life-cycle approaches and the traditional focus on energy efficiency or carbon dioxide reductions in the use phase, can be related to the strategic shift from reducing currently known impacts to covering the remaining gap to full socio-ecological sustainability. In line with this, the authors suggest that the EU fuel directive, to become a tool for sustainable development of bus transport, needs to be integrated with more progressive initiatives, as well as include both vision and a robust definition of sustainability.

Even if the authors favor the idea of electric bus powertrains, that concept still needs to develop to be the ‘silver bullet’ for bus transport regarding sustainable development. Careful recycling using a regenerative approach might in the short run solve the issue of scarce materials like Lithium in batteries, but it would be more strategic to use materials that are easier to manage in a sustainable way (like Sodium or Graphene). Another challenge is the marginal effect of electricity, which can lead to more usage of fossil fuels in other parts of Europe as a response to the extra demand of electricity caused by for example charging of electric vehicles (Trygg & Karlsson, 2005). One solution to deal with this is to use charging facilities powered by stand-alone solar/wind-power units delivering surplus to the upcoming smart electricity grid.

Two comparable studies searched for a practical way to use an LCA approach to compare biogas and electric buses. An LCA on car systems (Hawkins, Singh, Majeau-Bettez, & Strømman, 2012) showed comparable result for electric powertrains regarding life-cycle emissions and environmental impacts including batteries. Another study in Borlänge, Sweden (Andersson & Norman, 2012) concludes that an electric bus is a less expensive alternative in spite of high initial costs.
The electric bus has been put forward as a potential contributor to sustainable growth in the transportation sector. If this claim can be concretized, the time may soon come for a commercial scale up around Sweden. This study aims to support this development with a new suggested assessment approach that can integrate efficiency, carbon emissions and other socio-ecological sustainability issues with the economic potential for public bus transport systems. Unfortunately there are uncertainties in the timing and strength of many important influencing factors. The fossil fuel price is not only depending on the demand of different supply and demand conditions, but also including the geopolitical situation, import diversification, network costs, severe weather conditions, and taxation (The European Commission, 2013). Renewable electricity, on the other hand, is likely to decrease in price but depending on the technologies selected this development may be delayed by resource constraints as electric generators contain many rare metals. Meanwhile, the electric power sources and powertrains are currently in early stages of the learning curve and costs are likely to decrease substantially as these solutions are scaled up. On top of this there are uncertainties of governmental and legislative support for transport system transformation towards sustainability. The authors therefore see a need for further refinement of the suggested approach and its initial results, through simulation scenarios, and testing in practice.

<table>
<thead>
<tr>
<th>Nomenclature</th>
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<tbody>
<tr>
<td>European Union</td>
</tr>
<tr>
<td>Green House Gases</td>
</tr>
<tr>
<td>Framework for Strategic Sustainable Development</td>
</tr>
<tr>
<td>Life-cycle assessment</td>
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<tr>
<td>Life-cycle costing</td>
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<tr>
<td>Normal Cubic meter</td>
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<tr>
<td>Strategic life-cycle assessment</td>
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<tr>
<td>Sustainability Principles</td>
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</tbody>
</table>
Acknowledgements

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PAPER B

A sensitivity analysis of total cost of ownership for electric public bus transport systems in Swedish medium sized cities
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A sensitivity analysis of total cost of ownership for electric public bus transport systems in Swedish medium sized cities

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Abstract

To reach Swedish national climate change reduction targets, organizations collaborate for a sustainable development to improve energy efficiency, reducing pollution and noise in public bus transport. This follow-up study continues to strengthen the previous study by deepen the economic comparisons of two electric buses with different driving range and different type of chargers. The study aims to emphasize on sensitivity analysis for the total cost of ownership (TCO) to reduce uncertainty by identifying which factors of interest that most likely cause the estimated cost values for the electric bus. The result shows that the percentage change of line distance (km/year), operational years, and investment cost would be the most influential and significant factors on TCO.

Keywords: Electric bus; Sensitivity analysis; Total cost of ownership; Sustainable development; Climate Change; Emissions

1 Introduction

1.1 Background

The Swedish Government has set targets for greenhouse gas neutrality by 2050 and a fossil fuel independent vehicle fleet by 2030 (International Energy Agency Organization 2013). To reach these targets, regional, local government, and organizations work together to transition towards sustainability, which includes the decision to change public bus transport to become more energy efficient and to emit less pollution and noise (The European Commission 2005; The European Commission 2011).

A previous study (Nurhadi, Borén, and Ny 2014) has built and tested a new assessment approach that could enhance decisions on bus transport powertrains and energy
carriers for Swedish medium-sized cities with less than 100,000 citizens. The comparison was made on different energy carriers such as diesel, biodiesel, biogas, hybrid, plug in hybrid, and electricity. The study relied on a framework for strategic sustainable development (Robért 2000; Ny et al. 2006) and tools such as strategic life-cycle assessment (Ny et al. 2006), life-cycle assessment (International Standardization Organization 2006), and life-cycle costing (International 2004; The International Standard Organization 2008). The preliminary result suggested that the priority should be to move from diesel buses to electric buses to shift from the traditional fuel directive approach to a strategic sustainability perspective that included economic, environmental and social issues - both now and in the future. Moreover, that study (Nurhadi, Borén, and Ny 2014) was supported with findings such as:

- An electric powertrain with new renewable electricity would be the most energy efficient and sustainable choice, although the current European electricity is sourced from fossil fuels.
- The diesel bus was among the poorest solutions for energy efficiency and costs, and the poorest for life-cycle emissions. Since the cost for energy usage was much higher in fossil fuelled buses than in electric buses.
- The hybrid powertrain would in average reduce life-cycle emission by almost 40%, and the plug-in hybrid with around 70% reduction, compared to diesel. Where for plug-in hybrid, its life-cycle energy efficiency is almost 60% better than diesel.
- Compared to diesel, The Total Cost of Ownership (TCO) distributed over 8 years for an electric bus (with 1 extra battery and 1 fast charger) was 20% lower, and an electric bus (with 1 extra battery and 2 fast chargers) was 17% lower. The cost for the plug-in hybrid was 17% lower and the hybrid that was 7% lower compared to a diesel bus.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCO</td>
<td>Total cost of ownership (SEK/km)</td>
</tr>
<tr>
<td>PW</td>
<td>Present worth or present value</td>
</tr>
<tr>
<td>FW</td>
<td>Future worth or future worth</td>
</tr>
<tr>
<td>%</td>
<td>Percentage</td>
</tr>
<tr>
<td>SEK</td>
<td>Swedish Kronor</td>
</tr>
<tr>
<td>Km</td>
<td>Kilometer</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-hour</td>
</tr>
<tr>
<td>IC</td>
<td>Investment cost</td>
</tr>
<tr>
<td>OY</td>
<td>Operational Year</td>
</tr>
<tr>
<td>MSEK</td>
<td>Million Swedish Kronor</td>
</tr>
<tr>
<td>B</td>
<td>Battery</td>
</tr>
<tr>
<td>EC</td>
<td>Energy cost</td>
</tr>
<tr>
<td>MC</td>
<td>Maintenance &amp; helping maintenance cost</td>
</tr>
<tr>
<td>EBC</td>
<td>Extra battery cost</td>
</tr>
<tr>
<td>CC</td>
<td>Chargers cost</td>
</tr>
<tr>
<td>CT</td>
<td>Carbon tax</td>
</tr>
<tr>
<td>HC</td>
<td>Heating cost</td>
</tr>
<tr>
<td>LD</td>
<td>Line distance (km/year)</td>
</tr>
<tr>
<td>r</td>
<td>Real Interest rate (%)</td>
</tr>
<tr>
<td>tSEK</td>
<td>Thousand of Swedish Kronor</td>
</tr>
</tbody>
</table>
1.2 The focus of the study

This study aims to follow up on the previous bus study (Nurhadi, Borén, and Ny 2014) and check its validity by continuing to deepen the economic part of the life-cycle costing (LCC) comparisons for two electric buses with different driving range and different type of chargers. This new study also adds emphasize on a sensitivity analysis for the total cost of ownership (TCO) in section 2.1. The same assumptions are used as in the previous study. Five city-buses (line 1 and 7 in Karlskrona) with average speed profiles (25 km/h) and average load profiles, with a stop in almost every bus stop that was based on drive cycles of 93 000 km/bus/year. A timeframe of 8 years was used, as this was stipulated by Swedish procurement of public bus authority. In relation to that, 8 years is not the technical lifetime of the bus, which the bus can be used longer time. For TCO, the energy price was assumed to increase annually by about 6%, based on the history of energy price development in the last 10 to 15 years (Svenska Petroleum och biodrivmedelinstutitet; pool 2012) and with a real interest rate of 1%.

The study focuses on 2 main objectives with three questions (Q1-Q3):

1. A sensitivity analysis for the TCO to identify which factors of interest those most likely cause the estimated cost values for the electric bus. This could also help to reduce the uncertainty factors that may impact the TCO, since economic factors such as future investment costs, operating expenses, fuel cost, and others may not be known with great precision.

Q1: Which factor is the most influential and significant when the TCO is determined?

2. The study uses “what if” analysis and captures this in a spider plot graph to understand the responsiveness of each factor on the outcome of the TCO. Each factor is indicated as percentage deviation in several factors using a specific measure of present worth.

Q2: This involves a whole series of “what if” questions, such as: What happens to the TCO of an electric bus if the...

...future investment cost is overestimated by 10%, 20%, or 30%?
...travel line distance is decreased by 10%, 20%, or 30%?
...number of operational years is increased by 10%, 20%, or 30%?
...energy cost is increased by 5%, 10%, 20%, or 30%?
...maintenance cost (or fast charger cost) is reduced by 10%, 20%, or 30%?

Q3: Which of the described factors above are more important for the TCO where the effect of each factor is compared to all others - two by two (pair analysis)? This would make a stronger decision making to save more on TCO of electric bus if two variables are paired; also identify uncertainty factors that could be avoided in decision making process.
1.3 Limitation

A limitation of this study is that the input of the costs may vary depending on bus manufacturers and the specifications of the electric buses. Moreover, sensitivity analysis does not aim to quantify risk but rather to detect factors that are risk sensitive (Flanagan and Norman 1993). No salvage value or value of asset in the end of the whole investment period for this calculation.

2 Methods

The study begins with the comparison between two different types of electric buses (figure 1). Bus ‘A’ has a normal charger and bus ‘B’ a fast charger. The sensitivity analysis (Flanagan and Norman 1993) then calculate the present worth (Leland and Anthony 2012) as the present discounted value for an 8 year period from 2013-2022. Then model input data of three scenarios are used in the calculation of present worth to be captured in a spider plot. In response to that, the base scenario is used to represent the actual conditions of the public bus procurement in Sweden. The other low and high scenarios set the assumed minimum and maximum range that could work as probability of occurrence for variation of each factor. Low Scenario is where the probable choice and increment variation for higher cost-effectiveness of electric bus could occur, and high scenario is where the probable choice and increment variation could occur for lower cost-effectiveness of electric bus. Finally, a tornado graph is used to analyse the relative impact on the TCO as all factors are compared against each other - two by two factors.

Figure 1. Sketching the sequence of how methods of the study are used

2.1 Total Cost of Ownership (TCO)

Total Cost of Ownership is used to calculate the cost experienced during the entire life-cycle. The term of economic assessment has several similar names including the similarity term for TCO and life-cycle costing (Mälkki 2010).
\[ TCO = \frac{\sum ICn + Bn + ECn + MCn + EBCn + CCn + CTn + HCn}{\sum LDn + OYn} \] (1)

Where, \( n \) = average value from year 2013-2020, IC is Investment Cost, B is Battery Cost, EC is Energy Cost, MC is Maintenance & helping Cost, EBC is Extra Battery Cost, CC is Chargers Cost, CT is Carbon Tax (or emission cost), HC is Heating Cost, LD is Line Distance, and OY is Operational Years

### 2.2 Present worth (PW)

Present worth is widely used in business and economics to compare cash flows at different time periods. It is used here as present discounted value (present worth) in (SEK/km), where the future value of money has been discounted (Leland and Anthony 2012). The present worth is indicated as usually less or equal to future worth (FW) because the money has an interest rate and indicated as time value of money. The time value of money can then in principle be described as 1 dollar today is worth more than 1 dollar tomorrow. Writing the life-cycle cost or TCO in the form of a present worth,

\[
PW \text{ of } TCO = \frac{\sum_{i=1}^{n} IC + B + EC + MC + EBC + CC + CT + CC}{(1 + r)^i} \left( \frac{1}{1 + r} \right) \\
= \frac{\sum_{i=1}^{n} LD + OY}{(1 + r)} \tag{2}
\]

Where, PW = present worth from 2013-2020, FW= future worth from 2013-2020, \( r \) = real interest rate of 1% where \( i \) = year \((1 \leq i \leq 8)\) years.

### 2.3 Spider plot graph

Perry and Hayes (1985) have suggested the spider plot as a particular effective graphical presentation of sensitivity analysis. It is used to analyze many inputs and get the outcome of each single factor (Eschenbach, Ted G 1992), (Peter McNamee 2008). The study uses spider plot to indicate which elements of the TCO are the most sensitive and how they may behave. In engineering economy terms, the algorithm for sensitivity analysis is calculated with PW (of TCO), where the costs for investment, line distance, operational years, and maintenance would vary with real interest rate, is described in equation 3 to 6 below.
(P/F, 1%, 8) below indicates Present Worth of TCO divided by Future Worth of TCO, with real interest rate of 1% in 8 years operational of the bus. Where \((1 \pm p \% /100)\) indicates \(1 \pm \) percentage of Present Worth.

If the investment cost \((IC)\) varies by \(\pm 10\) to \(30\%\), with real interest rate of \(1\%\), then:

\[
P_W (\pm 10 \text{ to } 30\%) \frac{[ (1 \pm \frac{p}{100}) \left( \frac{P}{F}, 1\%, 8 \right) (IC) + (B) \left( \frac{P}{F}, 1\%, 8 \right) 
+ (EC) \left( \frac{P}{F}, 1\%, 8 \right) + (MC) \left( \frac{P}{F}, 1\%, 8 \right) 
+ (EBC) \left( \frac{P}{F}, 1\%, 8 \right) + (CC) \left( \frac{P}{F}, 1\%, 8 \right) 
+ (CT) \left( \frac{P}{F}, 1\%, 8 \right) + (HC) \left( \frac{P}{F}, 1\%, 8 \right)]}{(LD) \left( \frac{P}{F}, 1\%, 8 \right) \ast (OY) \left( \frac{P}{F}, 1\%, 8 \right)} \]

(3)

If the line distance \((LD)\) varies by \(\pm 10\) to \(30\%\), with real interest rate of \(1\%\), then:

\[
P_W (\pm 10 \text{ to } 30\%) \frac{[ (IC) \left( \frac{P}{F}, 1\%, 8 \right) + (B) \left( \frac{P}{F}, 1\%, 8 \right) 
+ (EC) \left( \frac{P}{F}, 1\%, 8 \right) + (MC) \left( \frac{P}{F}, 1\%, 8 \right) 
+ (EBC) \left( \frac{P}{F}, 1\%, 8 \right) + (CC) \left( \frac{P}{F}, 1\%, 8 \right) 
+ (CT) \left( \frac{P}{F}, 1\%, 8 \right) + (HC) \left( \frac{P}{F}, 1\%, 8 \right)]}{\left( \frac{1 \pm \frac{p}{100}}{100} \right) \left( \frac{P}{F}, 1\%, 8 \right) (LD) \ast (OY) \left( \frac{P}{F}, 1\%, 8 \right)} \]

(4)
If the operational year \((OY)\) varies by ±10 to 30%, with real interest rate of 1%, then:

\[
P W (\pm 10\text{ to } 30\%) \\quad \left[ (IC) \left( \frac{P}{F}, 1\%, 8 \right) + (B) \left( \frac{P}{F}, 1\%, 8 \right) + (EC) \left( \frac{P}{F}, 1\%, 8 \right) \right. \\
+ \left. (MC) \left( \frac{P}{F}, 1\%, 8 \right) + (EBC) \left( \frac{P}{F}, 1\%, 8 \right) \right. \\
+ \left. (CC) \left( \frac{P}{F}, 1\%, 8 \right) + (CT) \left( \frac{P}{F}, 1\%, 8 \right) \right. \\
+ \left. (HC) \left( \frac{P}{F}, 1\%, 8 \right) \right] \\
= \left[ (LD) \left( \frac{P}{F}, 1\%, 8 \right) \times \left( 1 \pm \frac{p}{100} \right) \left( \frac{P}{F}, 1\%, 8 \right) (OY) \right]
\]

(5)

If, the maintenance cost \((MC)\) varies by ±10 to 30%, with real interest rate of 1%, then:

\[
P W (\pm 10\text{ to } 30\%) \\quad \left[ (IC) \left( \frac{P}{F}, 1\%, 8 \right) + (B) \left( \frac{P}{F}, 1\%, 8 \right) + (EC) \left( \frac{P}{F}, 1\%, 8 \right) \right. \\
+ \left. (1 \pm \frac{p}{100}) \left( \frac{P}{F}, 1\%, 8 \right) (MC) + (EBC) \left( \frac{P}{F}, 1\%, 8 \right) \right. \\
+ \left. (CC) \left( \frac{P}{F}, 1\%, 8 \right) + (CT) \left( \frac{P}{F}, 1\%, 8 \right) + (HC) \left( \frac{P}{F}, 1\%, 8 \right) \right] \\
= \left[ (LD) \left( \frac{P}{F}, 1\%, 8 \right) \times (OY) \left( \frac{P}{F}, 1\%, 8 \right) \right]
\]

(6)

Where, \(PW\) is Present Worth, \(IC\) is Investment Cost, \(B\) is Battery Cost, \(EC\) is Energy Cost, \(MC\) is Maintenance & helping Cost, \(EBC\) is Extra Battery Cost, \(CC\) is Chargers Cost, \(CT\) is Carbon Tax (or emission cost), \(HC\) is Heating Cost, \(LD\) is Line Distance, and \(OY\) is Operational Years.

2.4 Two-factor tornado graph

The tornado graph is used to show the potential combination of two factors to generate potential highest cost reduction in TCO. It would also possibly show the cost effectiveness while analyzing many uncertain factors that could be avoided from decision making in economic perspective for public bus procurement.

The study uses a two-factor tornado graph concept (Eschenbach, Ted G (1992), (Peter McNamee 2008). The graph considers each pair of input variables and if \(N\) is the number of variables, then \(N*(N-1)/2\) pairs will be evaluated. For each pair of two
variables, all nine combinations of the low scenario, base scenario, and high scenario input variables are used. Likewise for each pair, the calculation shows the combination of input values that produces the lowest and highest output values and the pairs are sorted by bounds of variation.

### 2.5 Comparison of two different electric buses

The electric buses have two alternatives, which involves different driving range (battery capacity) with different type of chargers. The electric bus A refers to an electric bus provided with a normal charger for 2.5 to 4 hours, while the electric bus B refers to an electric bus provided with a fast charger (10 minutes charging time). The comparison can be seen in table 1 where the data is gathered from bus manufacturers in Sweden.

#### Table 1. Comparison of two different types of electric buses with different driving range and chargers

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus*</td>
<td>Custom made 100% electric, 12 m long</td>
<td>3.3 MSEK</td>
<td>Custom made 100% electric, 12 m long</td>
<td>3.42 MSEK</td>
</tr>
<tr>
<td>Battery capacity*</td>
<td>242kWh or 311 kWh</td>
<td>0.45 MSEK</td>
<td>80 kWh</td>
<td>0.4 MSEK</td>
</tr>
<tr>
<td>Battery type*</td>
<td>Lithium iron phosphate</td>
<td>0.09 MSEK</td>
<td>Lithium iron phosphate (2 extra battery)</td>
<td>2.8 MSEK</td>
</tr>
<tr>
<td>Charger*</td>
<td>Normal charger (2.5-4 hours full charge)</td>
<td></td>
<td>Fast charger (10 minutes to fully charge)</td>
<td></td>
</tr>
<tr>
<td>Charger lifetime (technical)*</td>
<td>10 years</td>
<td>10-30 years</td>
<td>100kWh/h</td>
<td></td>
</tr>
<tr>
<td>Charging rate*</td>
<td>0.9kWh/km</td>
<td>200-300kWh/h</td>
<td>1.14kWh/km</td>
<td></td>
</tr>
<tr>
<td>Bus energy usage*</td>
<td>200-300 km</td>
<td>60-70 km</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data from bus manufacturer in Sweden

### 2.6 Scenario description

The sensitivity analysis is used to test the most influential factor for the change of TCO of electric buses. Three scenarios below are included to give the variation to the probable range in the analysis.

1. **Low scenario** where the purpose is to assume the minimum values and get the lower bounds that could work as probability of occurrence. In the low scenario set to the line distance to 65 000 km, 6 years of operational years, and real interest rate of 0.5%, also where investment cost is 2.8 MSEK and energy cost per year is 0.78 MSEK.

2. **Base scenario** as the baseline of the model data input to generate the calculation of the algorithm to be plotted in the spider plot. This is based on the actual data from a bus manufacturer and bus operator in Sweden. Electric bus A and B has the similar numbers for maintenance cost of 1.53 MSEK per
year, line distance 93000 km per year, 8 operational years, and real interest rate of 1%, and carbon tax. The investment cost and energy cost of electric bus B is higher than for electric bus A, as an electric bus that can use fast chargers is slightly more expensive than an electric bus for a normal charger.

3. **High scenario** consists of an investment cost of 4.17 MSEK, energy cost of 1.02 MSEK per year, line distance of 121 000 km per year, 10 operational years, and real interest rate of 2%. These are assumed to be the same between electric bus A and B, and with the purpose to generate the upper bounds of possible values as the maximum values. The battery and charger costs are set with different numbers between electric bus A and B to get the reasonable maximum values since current normal charger cost of 0.25 MSEK per bus and per charger is much lower cost than current fast charger of 1.2 MSEK per bus and per charger.

### 2.7 Model Input data

This study uses input variables that are expected to vary over the probable range as shown in table 2 and 3. The measure of present worth (PW) (section 2.2) is calculated using three parameters: high scenario, base scenario, and low scenario. The input variables are considered to bring impact to the change of electric buses Total Cost of Ownership (TCO) in section 2.1.

<table>
<thead>
<tr>
<th>Input variables in present worth (2013-2020)</th>
<th>High scenario</th>
<th>Base scenario</th>
<th>Low scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Change of investment cost including battery (MSEK)(^a)</td>
<td>4.17</td>
<td>3.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Energy cost per year (MSEK)(^a)</td>
<td>1.02</td>
<td>0.72</td>
<td>0.86</td>
</tr>
<tr>
<td>Maintenance cost &amp; helping maintenance per year (MSEK)(^a)</td>
<td>1.65</td>
<td>1.53</td>
<td>1.20</td>
</tr>
<tr>
<td>Extra battery cost (MSEK)(^a)</td>
<td>0.58</td>
<td>0.44</td>
<td>0.30</td>
</tr>
<tr>
<td>Carbon tax per year (tSEK)(^a)</td>
<td>2.8</td>
<td>0.86</td>
<td>1.20</td>
</tr>
<tr>
<td>2 Normal chargers cost (tSEK)(^a)</td>
<td>3.7</td>
<td>0.30</td>
<td>121 000</td>
</tr>
<tr>
<td>Line distance per year (km)(^a)</td>
<td>65 000</td>
<td>93 000</td>
<td>6</td>
</tr>
<tr>
<td>Operational year (years)(^a)</td>
<td>2%</td>
<td>1%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

\(^a\) Input variables for high scenario and low scenario are assumed, while base scenario is expected values from bus manufacturer in Sweden.

\(^b\) Input variables for high scenario and low scenario are assumed, while for average real interest rate for base scenario is known from Swedish banks.
Table 3. Model input data for electric bus B (with 1 extra battery and 2 fast chargers)

<table>
<thead>
<tr>
<th>Input variables in present worth (2013-2020)</th>
<th>High scenario</th>
<th>Base scenario</th>
<th>Low scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Change of investment cost including battery (MSEK)*a</td>
<td>4.17</td>
<td>3.82</td>
<td>2.8</td>
</tr>
<tr>
<td>Energy cost per year (MSEK)*a</td>
<td>1.02</td>
<td>0.9</td>
<td>0.78</td>
</tr>
<tr>
<td>Maintenance cost &amp; helping maintenance per year (MSEK)*a</td>
<td>1.65</td>
<td>1.53</td>
<td>1.20</td>
</tr>
<tr>
<td>Extra battery cost (MSEK)*a</td>
<td>0.48</td>
<td>0.39</td>
<td>0.30</td>
</tr>
<tr>
<td>2 Fast chargers cost (MSEK)*a</td>
<td>1.2</td>
<td>0.98</td>
<td>0.75</td>
</tr>
<tr>
<td>Carbon tax / year (tSEK)*a</td>
<td>29.2</td>
<td>14.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Line distance / year (km)*a</td>
<td>65 000</td>
<td>93 000</td>
<td>121 000</td>
</tr>
<tr>
<td>Operational year (years)*a</td>
<td>10</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Real interest rate*b</td>
<td>2%</td>
<td>1%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

*a Input variables for high scenario and low scenario are assumed, while base scenario is expected values from bus manufacturer in Sweden.

*b Input variables for high scenario and low scenario are assumed, while for average real interest rate for base scenario is known from Swedish banks.

3 Results

3.1 The TCO comparison between 2 different types of electric buses with different number of extra battery and type of chargers compared to hybrid bus

In figure 2 below, the electric bus (with 1 extra battery and 1 normal charger) has the lowest TCO, 15% lower compared to other electric buses and 25% lower compared to hybrid buses. This could be appropriate for driving in the city area where there might be a fully charged electric bus as a back-up, if electric bus A has been driving for 200-300km in a day. The reason is that the normal charger uses 2.5-4 hours to be fully charged. A hybrid bus has the highest TCO (11.23 SEK/km) among the electric buses, where energy cost of fossil fuel generates high TCO compared to electric alternatives, even though the investment cost is lower. The second highest TCO is electric bus B (with 2 extra battery and 2 fast chargers) that is generated from the current high cost of fast chargers. During the lifetime of the 8 years, electric bus B needs 2 batteries, while electric bus A only needs 1 battery. This is mainly because the battery capacity is more in bus A, and it does not necessary charge as many times as the battery in bus B.
3.2 Answer to Q 1: The spider plot of electric bus A

The spider plot shows how the result of estimated TCO varies depending on percentage change of individual parameter (-30%, -20%, -10%, 0, +10%, +20%, +30%). The present worth (PW) of different factors of electric bus A would also change depending on the changes (%) of each input variable. The steepest line in the spider plot represents the most influential and significant factors, which have significant impact on the change of TCO. The PW of TCO of electric bus A with 1 extra battery and 2 normal chargers is 8.44 SEK per km. The spider plot (figure 3) shows the most influential and significant factors, which are line distance per year and operational year. Where these two variables have the greatest impact on the change of TCO. In relation to that, the PW of TCO would be significantly lower if the electric bus drive would be more than 100 000 km per year and operate for more than 9 years. Similarly, the investment cost also plays a significant role of lowering the TCO if it is reduced by more than 5%. Where maintenance cost also give a slight impact to the change of TCO. On the other hand, the cost of normal charger and extra battery does not impact the result of TCO significantly since it gives a low contribution to the change of TCO. A carbon tax does not give any significant impact to the change of TCO for the electric bus. However, it would give significant impact on TCO for fossil fuel buses, given by their carbon dioxide emissions (Nurhadi, Borén, and Ny 2014).
3.3 Answer to Q 1: The Spider plot of electric bus B

The present worth (PW) of different factors of electric bus B would also change base on those percentage changes of its individual parameter. The PW of TCO of electric bus B with 2 extra battery and 2 fast chargers is 10.56 SEK per km. The results (figure 4) shows almost similar findings for bus B as for bus A above (figure 3). The steepest line in the spider plot represents the most influential and significant factors, which have impact on the change of TCO. In relation to that, the most influential and significant factor is line distance per year, the second most influential factor is operational year, then the third most influential factor of the investment cost and maintenance cost. Similarly to the fast charger cost brings quite substantial impact to the change of TCO since it contributes quite high values especially if it includes two of fast chargers. The summary of the most influential factor is captured in figure 5 below.
Figure 4. How TCO of electric bus B (with 2 extra battery & 2 fast chargers) varies with changes (%) in different parameters.

From figure 3 and 4, a summary of the most influential factors are captured as a result from the spider plot that ranked from the most to the least influential factor in electric A and B, as shown in figure 5 below.

<table>
<thead>
<tr>
<th>Rank.</th>
<th>Influential factors in Electric bus A</th>
<th>Influential factors in Electric bus B</th>
<th>The factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Line distance / year (km)</td>
<td>Line distance / year (km)</td>
<td>The most</td>
</tr>
<tr>
<td>2</td>
<td>Operational year</td>
<td>Operational year</td>
<td>influential</td>
</tr>
<tr>
<td>3</td>
<td>Investment cost including battery &amp; helping maintenance per year</td>
<td>Investment cost including battery</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Maintenance cost &amp; helping maintenance</td>
<td>Maintenance cost &amp; helping maintenance</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Energy cost per year</td>
<td>Fast chargers cost</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Extra battery cost</td>
<td>Energy cost</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Normal chargers cost</td>
<td>Extra battery cost</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbon tax / year</td>
<td>Carbon tax / year</td>
<td>Insufficient</td>
</tr>
</tbody>
</table>

Figure 5. Summary of the most influential factors that cause the change of TCO
3.4 Answer to Q 2: a whole series of “what if” questions that generate answers such as:

The result is shown in figure 3 and 4, with the following figure 6 that answers the question: what happens to TCO of electric bus A or B if…

<table>
<thead>
<tr>
<th>The most influential factor</th>
<th>% Change</th>
<th>TCO of Electric bus A</th>
<th>TCO Electric bus B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future Investment</td>
<td>+(10-30%)</td>
<td>5 – 14%</td>
<td>5 – 13%</td>
</tr>
<tr>
<td>Travel line distance</td>
<td>-(10-30%)</td>
<td>13 – 30%</td>
<td>12 – 30%</td>
</tr>
<tr>
<td>Operational year</td>
<td>+(10-30%)</td>
<td>8 – 34%</td>
<td>7 – 33%</td>
</tr>
<tr>
<td>Energy cost</td>
<td>+(10-30%)</td>
<td>2 – 4%</td>
<td>0 – 3%</td>
</tr>
<tr>
<td>Maintenance and helping maintenance</td>
<td>-(10-30%)</td>
<td>2 – 5%</td>
<td>2 – 5%</td>
</tr>
</tbody>
</table>

Figure 6. What happens to TCO of electric bus A or B if…change

The PW of TCO is 8.44 SEK per km for bus A, and 10.56 SEK per km for bus B. From figure 6 shows more detail below:

…the future investment cost is overestimated by 10% to 30%? TCO for bus A will increase from 5.2 to 14%, while TCO for bus B will increase by 4.8 to 13%.

…travel line distance is decreased by 10 to 30%? TCO for bus A will increase from 13 to 30%, and TCO for bus B will increase from 12.3 to 30%. The result reveals that it would be profitable to drive longer distance as it lowers the TCO, especially if the distance is more than at least 75 000 km. but even when 100,000 km per year is passed.

…number of operational year is increased by 10 to 30%? TCO for bus A will be reduced by 8 to 34%, and TCO for bus B will be reduced from 7 to 33%. This reveals that the most profitable to drive more than 8 years operational life, since the 6 years would give much higher TCO. It is not cost effective to drive less than 8 years. The most desirable is 10 years of operational life that bring much lower TCO.

…energy cost is increased by 10 to 30%? TCO for bus A and B will increase from 1.8 to 4%, and TCO for bus B will increase from 0.4 to 3%, if electricity cost increase by 10 to 30%. Energy cost, normal charger cost, and carbon tax are quite substantial but it is not significant enough to affect the change of TCO.

…maintenance cost and helping maintenance cost (or fast charger for electric bus B) is reduced by 10 to 30%? TCO for bus A and B, and fast charger cost for electric bus B, will be reduced from 2.2 to 5%. If the maintenance cost of electric bus is not lower than maintenance cost for diesel bus, then it will impact much on the increase of TCO of electric bus. Fast
charger cost also influences a lot to TCO since the cost of fast charger is still high today.

### 3.5 Answer to Q 3: What are the important factors when making a pair analyses for TCO of bus ‘A’?

The result has $N = 8$ input variables, so there are $N*(N-1)/2 = 8*(8-1)/2 = 28$ pairs to evaluate as shown in the figure 7 below. This also shows what would happen to TCO of electric bus if the two variables are paired and what are the minimum and maximum values. This would make stronger decision making to save more on TCO of electric bus if two variables are paired. The two-factor analysis shows that a line distance of 121,000 km per year and 10 operational years could generate the lowest PW of TCO. On contrary, the highest cost is caused by low line distance 65,000km per year and 6 operational years.

Figure 7. A tornado graph that shows how minimum and maximum value of TCO of bus ‘A’ depends on pair analyses
4 Concluding discussion

The present worth (PW) of Total Cost of Ownership (TCO) for electric bus A (with 1 extra battery and 2 normal chargers) is 8.44 SEK per km, and 10.56 SEK per km for electric bus B (with 1 extra battery and 2 fast chargers). The result suggests that the electric bus A would be more preferable in term of cost effectiveness since the normal chargers are cheaper and allows a longer battery life. This might be a good solution for a city or suburb where a fully charged electric bus can be available as a back-up after a bus has been driving for 200-300km. Electric bus B could be an intermediate solution for a city that run on tight schedule since it charges within 10 minutes. This study aims to make previous study more credible by showing the ‘what if’ analysis of the most influential individual parameters to be considered in the TCO for an electric bus. This is supported with findings such as:

- The TCO of electric bus A will get 13 to 30% more expensive while the TCO of electric bus B will increase 12 to 30%, if the travel of line distance (which is the most influential factor in the change of TCO), is decreased by 10 to 30%.
- The TCO of electric bus A will decrease by 8 to 34% while the TCO of electric bus B will decrease by 7 to 33%, if the total number of operational years (which is considered as the second most influential factor in the change of TCO), is increased by 10 to 30%.

The previous study of that recommended the electric powertrain, is strengthened by this study, where the result could be used to avoid many economic uncertainty factors from the decision-making process for public bus procurement. A potential shortcoming of this study is the lack of real life testing of the assumptions and scenarios. Also the numbers presented depend on the reliability of the sources might not in great precision that may affect the result, however it gives a good indicator to show the most likely TCO and its influential factors.

The validity of the approach of this paper is however strengthened by another study (Ong et al. 2012) that used a similar approach to identify life-cycle costs of palm biodiesel production. They also made a sensitivity analysis. In their case, they could examine how uncertainty in international prices could alter project outcomes. Another study of marine renewable energy (MacGillivray et al. 2013) was done with a similar purpose. It displayed that even small changes of input assumptions can have a dramatic effect on the overall investment required for a sector to reach uniformity with benchmark technologies in marine renewable energy.

The paper also considered the implications of cost reduction to these uncertainties for marine energy innovation management. The electric buses have been expected as a potential solution to sustainable growth in the transportation sector. If this can be concretized, this aims to support the development for public bus transport systems with the economic analysis to potentially foresee uncertainty factors and bring cost effectiveness. A next expected step is real-life testing of electric buses around South of
Sweden as an attempt to validate the assumptions and approaches used in this and the previous bus comparison study.

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References


Preferences of Electric Buses in Public Transport?
- Conclusions from Real Life Testing in Eight Swedish Municipalities
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Preferences of Electric Buses in Public Transport? - Conclusions from Real Life Testing in Eight Swedish Municipalities

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Abstract

From a theoretical perspective, Electric buses can be more sustainable and can be cheaper than fossil fuelled buses in city traffic. The authors have not found other studies based on actual urban public transport in Swedish winter climate. Further on, noise measurements from buses for the European market where found old. The aims of this follow-up study was therefore to test and possibly verify in a real-life environment how energy efficient and silent electric buses are, and then conclude on if electric buses are preferable to use in public transport. The Ebusco 2.0 electric bus, fitted with a 311 kWh battery pack, was used and the tests carried out during November 2014 to April 2015 in eight municipalities in the south of Sweden. Six tests took place in urban traffic and two took place in more of a rural traffic setting. The energy use for propulsion was measured via logging of the internal system in the bus and via an external charging meter. The average energy use turned out to be 8 % less (0.96 kWh/km) than assumed in the earlier theoretical study. This rate allows for a 320 km range in public urban traffic. The interior of the bus was kept warm by a diesel heater (biodiesel will probably be used in a future operational traffic situation), which used 0.67 kWh/km in January. This verified that electric buses can be up to 25% cheaper when used in public transport in cities for about eight years. The noise was found to be lower, primarily during acceleration, than for buses with combustion engines in urban bus traffic. According to our surveys, most passengers and drivers appreciated the silent and comfortable ride and preferred electric buses rather than combustion engine buses. Bus operators and passenger transport executives were also positive to start using electric buses for public transport. The operators did however point out that procurement processes need to account for eventual risks regarding this new technology, along with personnel education. The study revealed that it is possible to establish a charging infrastructure for almost all studied bus lines. However, design of a charging infrastructure for each municipality requires further investigations, including electric grid capacity analysis, smart location of charging points, and tailored schedules to allow fast charging. In conclusion, electric buses proved to be a preferable alternative for all stakeholders involved in public bus transport in the studied municipalities. However, in order to electric buses to be a prominent support for sustainable development, they...
need to be charged either by stand-alone units or via an expansion of the electric grid, and the electricity should be made from new renewable sources.

Keywords: Sustainability, Electric Bus, Noise, GreenCharge

I. Introduction

1.1 Background

Many politicians in Europe are interested in more sustainable road transport solutions that contribute to societal goals such as greenhouse gas neutrality, energy use reduction, fossil fuel independence, and reduction of health problems related to emissions. Planning for sustainable development within complex areas such as transportation, which is greatly affected by development within other areas, calls for a structure that allows for a wide enough perspective to prevent sub-optimizations within certain areas, and where the development is guided by a robust definition of sustainability. The Framework for Strategic Sustainable Development - FSSD (Robèrt et al., 2013) is designed for such purposes and has been used on several occasions for development of transport towards sustainability (Alvemo et al., 2010; Borén, 2011; Cars et al., 2012; Robèrt et al., n.d.). In these and other studies, Electric Vehicles (EVs) are found to be a possible long-term solution for sustainable development, mainly because of high energy efficiency, very low emissions during drive, lower noise in city traffic, and the possibility to use renewable electricity for propulsion.

Meanwhile several European companies have started to manufacture electric cars and buses, some public authorities support projects aimed at increasing the share of EVs. GreenCharge, led by Blekinge Institute of Technology, is such a project in which municipalities, county boards, county councils, regions, companies and the Swedish Energy Agency collaborate to increase the share of EVs in a sustainable way. Electric buses powered by batteries have been available for public transport for decades and used in some cities worldwide to slow down erosion on old buildings and improve air quality. Research within GreenCharge has previously found that electric buses in urban public transport, when compared to combustion engine powered buses, are preferable not only from a sustainability perspective, but can also reduce the total cost of ownership with 25 % when charged with new green electricity (Nurhadi et al., 2014). That study was based on simulations, but not real life data, of bus lines in Karlskrona, Jönköping, and Sundsvall. Assumptions were based on older vehicles, where the energy use was assumed to be 1,04 kWh/km. This excluded interior heating and did not account for Swedish climate. Moreover, available noise measurement studies were old. Stakeholders and researchers within GreenCharge therefore wanted to try out electric buses under realistic Swedish weather conditions and in real public bus transport systems. The need for charging infrastructure was also of interest, as well as opinions from passengers, drivers and other stakeholders.
1.2 Purpose of the Study

The purpose of the study was to test and possibly verify earlier assumptions and results (Nurhadi et al., 2014), and assess whether key stakeholders find electric buses preferable to use in public transport.

2. Methods

2.1 Real-life Bus Testing Methodology

To get as real data and opinions as possible, the real-life testing required measurement of energy use and stakeholder opinions during a significant test period. Verification of the simulation study also required special focus on energy use in Karlskrona regarding line 1 and in Jönköping regarding line 1 and 3. Line 7 in Karlskrona that was part of the simulation study is today merged with line 1, and was therefore excluded from this follow up study.

2.2 Electric Bus Specifications

The tested Ebusco 2.0 battery powered electric bus measured 12 meters, and was manufactured in China in 2014 on commission of Ebusco Ltd in the Netherlands. According to the website (Ebusco, 2013a), the battery capacity was 311 kWh (160 kWh/kg) and energy use 0.9 kWh/km, allowing a range of 300 km in urban traffic with 50 % passenger load. The interior was heated by a diesel-powered heater, and cooled by air-conditioning that was powered by the 311 kWh battery pack. The test in Falun was an exception and was carried out with the older version Ebusco YTP-1. That older 12-meter bus had slightly lower passenger capacity, lower energy density in batteries, and thereby allowing for a range of only 250 km (Ebusco, 2013b).

2.3 Energy Measurements

A literature review and an enquiry among bus operator stakeholders identified some main influencing factors on the energy use of an electric bus. These factors were:

- Topography,
- Number of bus stops and other traffic related stops,
- Urban/rural traffic,
- Average speed,
- Passenger load,
- Driver’s experiences,
- Climate,
- Outdoor temperature (as the batteries where not stored in a temperature controlled environment inside the bus).

This study investigated which of the factors that seems to contribute most to the differences in energy use.

The bus was charged during nights in bus depots and the charging meter recorded how much electricity the batteries were charged with. This included losses related to charging and the batteries’ ability to keep the charged energy over time. This was double-checked by an internal energy meter in the bus. Energy use measurements were done on a daily basis and the distance meter was logged before the bus was leaving the depot each morning. To account for variations in the above-mentioned influencing factors the energy use figures from the simulation study were assumed to be verified if comparative figures could be measured as an average value over at least three days. Logging of mileage and amount of refueled diesel for the diesel powered interior heater was done at each refueling. The energy content of diesel was set to 9,96 kWh/liter. Recording of GPS-data was made for line 1 in Karlskrona to track the topography and verify the number of stops and the average speed.

The range was verified during real-life testing, but with a safety margin to avoid unwanted stops due to empty battery. Experiences from earlier testing by Ebusco revealed that driving during very cold days with less than 20 °C below zero with heavy passenger load could require a maximum energy use of about 1,2 kWh/km, while very favorable conditions could require as little as 0,75 kWh/km. Lower energy use is probably caused by faulty logging of mileage or charging. The energy use from the simulation study was 1,04 kWh/km while Ebusco assume 0,9 kWh/km with 50 % passenger load (Ebusco, 2013a). Measured daily energy use averages, which were not between 0,75-1,2 kWh/km, were therefore excluded.

2.4 Noise Measurements

This study measured and compared noise from diesel and hybrid buses currently in operation in Karlskrona and from the electric bus from Ebusco (Section 0). The diesel bus was a Mercedes Citaro, and the hybrid a Volvo 7900, both meeting the requirements of Euro 6. The study was defined by the UN standard ECE 51-02 (United Nations, 2013), and noise (dBA) was measured at constant speed 30 - 50 km/h, stationary mode, and during pressure release of compressed air by sound level meter type 1 RION NL-15 with microphone UC-53. The wind meter WS-10 recorded weather data during these noise measurements. The tires were not of the same type for the different buses, which could contribute to misleading results during constant speed measurements. The noise measurements did not include noise created during acceleration, but that was complemented by findings in a database from the Thomas D. Larson Pennsylvania Transportation Institute. These data came from the testing of buses for the US market since 1990, according to the United States of America vehicle noise measurement standard SAE J366 (SAE International, 2011). Three of the most
recent tested 12-meter buses for public urban transport powered by Electricity, Diesel, and Compressed Natural Gas (CNG) where averaged and compared to each other.

In addition to noise measurements, it is also important to listen to the passenger’s opinion of noise (Section 0).

2.5 Passenger and Driver Surveys

Surveys were created in English and Swedish to capture issues around noise and vibrations on-board, as well as noise and emissions outside the bus. A low inner temperature would reduce the total energy use and a control question was therefore asked about the perceived temperature on board to ensure that the interior heating had not been kept too low. Questions were also asked about the overall experience of riding an electric bus. Demographic control issues on gender, employment and bus travel habits were added. The drivers’ experiences during their work shifts were also important and questions were asked about weather, outside temperature, precipitation, driveability, passengers’ opinions, load, and the ability to follow the time schedule. The surveys where handed out during testing to both drivers and passengers on-board the electric bus.

2.6 Stakeholder Interviews

The opinions from other key stakeholders within this study, e.g. passenger transport executives, bus operators and municipalities, were collected via non-structured interviews.

2.7 Methods for Initial Investigation About Charging Infrastructure

In combination with testing in each municipality, the study made an initial investigation of possibilities to, and the need for, a charging infrastructure for the public transport systems in the municipalities. Mapping and documentation was based on interviews and literature reviews of official information regarding lines, vehicles, bus operators, and conditions for different charging systems. Public transport executives and traffic officers within municipalities were also interviewed to get a grip of decisions, strategies and plans about future local traffic systems that might influence the public transport in each municipality. This was intended to form a knowledge base for general proposals of charging systems.
3 Results

The electric bus was tested according to Table 1. The testing in Falun was restricted due to the change of bus type from Ebusco 2.0 to YTP-1, which would have provided the test with incomparable data. The first test period in Karlskrona was meant to include real-life testing, but was restructured due to administrative problems.

Urban traffic included speed limitations mainly up to 50 km/h, and rarely 70 or 80 km/h. In rural bus traffic, the speed was mostly limited to 70 or 90 km/h and had about 50 % less stops than in urban traffic. The real-life testing at Lerum comprised a blend of urban and rural traffic; meanwhile testing at Orust was entirely in rural traffic.

The real-life testing was conducted during a rather mild winter with few snowfalls but mostly rain, and temperatures between -6 to +13 °C (Lundgren, 2015).

Table 1: Real-life testing time schedule

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Period</th>
<th>Test focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karlskrona</td>
<td>17 Nov - 6 Dec 2014</td>
<td>Test drives, pre-testing, vehicle registration, maintenance.</td>
</tr>
<tr>
<td>Kalmar</td>
<td>7 Dec - 27 Dec 2014</td>
<td>Real-life testing in urban traffic.</td>
</tr>
<tr>
<td>Jönköping</td>
<td>29 Dec - 13 Jan 2015</td>
<td>Real-life testing in urban traffic, energy use line 1 and 3.</td>
</tr>
<tr>
<td>Borås</td>
<td>14 Jan - 28 Jan 2015</td>
<td>Real-life testing in urban traffic.</td>
</tr>
<tr>
<td>Lerum</td>
<td>2 Feb - 12 Feb 2015</td>
<td>Real-life testing in urban and rural traffic.</td>
</tr>
<tr>
<td>Falun</td>
<td>14 Feb - 1 Mar 2015</td>
<td>Real-life testing in urban traffic. No measurements or surveys.</td>
</tr>
<tr>
<td>Eskilstuna</td>
<td>3 Mar - 13 Mar 2015</td>
<td>Real-life testing in urban traffic.</td>
</tr>
<tr>
<td>Stenungssund</td>
<td>1 Apr - 2 April 2015</td>
<td>Test drives. No measurements or surveys.</td>
</tr>
<tr>
<td>Karlskrona</td>
<td>4 Apr - 10 Apr 2015</td>
<td>Energy use line 1, noise testing, real-life testing in urban traffic.</td>
</tr>
</tbody>
</table>

3.1 Energy Use Measurements

According to the assumed data requirements in the Section, some days of the testing had to be excluded from the data set as the data was outside the range 0.75-1.2 kWh/km. Some days in Kalmar where not measured at all due to resource shortage and maintenance. The testing in Jönköping at line 1 and 3 would have required at least another day to verify the simulation study and is therefore not described in detail. The real-life energy driveline testing results (Table 2) reveal that the bus used in average 0.96 kWh/km when tested in urban traffic, and 0.86 in rural traffic at the new line ‘Göksäterlinjen’ Orust. A mix of rural and urban traffic in Lerum resulted in an average of 0.93 kWh/km.
### Table 2: Average energy use results in each municipality and average results for use in urban traffic. Source: Appendix 1.

<table>
<thead>
<tr>
<th>Municipality</th>
<th>Period</th>
<th>Drivers *</th>
<th>Line</th>
<th>Outdoors temp. (°C)</th>
<th>Rain/ snow</th>
<th>Distance (km)</th>
<th>Average energy use (kWh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kalmar</td>
<td>17-18 Dec</td>
<td>5 b</td>
<td>401, 411, 412</td>
<td>+1 to +3</td>
<td>No</td>
<td>336</td>
<td>0,90</td>
</tr>
<tr>
<td>Jönköping</td>
<td>5-13 Jan</td>
<td>4</td>
<td>1, 3, 12, 18</td>
<td>-2 to +4</td>
<td>Some</td>
<td>1038</td>
<td>0,97</td>
</tr>
<tr>
<td>Borås</td>
<td>16-25 Jan</td>
<td>30</td>
<td>1</td>
<td>-1 to +3</td>
<td>Some</td>
<td>1235</td>
<td>1,02</td>
</tr>
<tr>
<td>Eskilstuna</td>
<td>3-5,10-12 Mar</td>
<td>3</td>
<td>1, 2, 4, 31</td>
<td>+1 to +10</td>
<td>No</td>
<td>900</td>
<td>0,90</td>
</tr>
<tr>
<td>Karlskrona</td>
<td>9-10 Apr</td>
<td>6</td>
<td>1</td>
<td>+10 to +12</td>
<td>No</td>
<td>514</td>
<td>0,96</td>
</tr>
<tr>
<td><strong>Sum urban traffic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>4023</strong></td>
<td><strong>0,96</strong></td>
</tr>
<tr>
<td>Lerum</td>
<td>2-11 Feb</td>
<td>1</td>
<td>525, 526, 532</td>
<td>-6 to +5</td>
<td>Some snow</td>
<td>1824</td>
<td>0,93</td>
</tr>
<tr>
<td>Orust</td>
<td>16-26, 28 Mar</td>
<td>1</td>
<td>Göksäterlinjen</td>
<td>0 to +5</td>
<td>Some</td>
<td>2123</td>
<td>0,86</td>
</tr>
</tbody>
</table>

* * According to number of survey responses  
* b Total number of drivers that answered the survey during the entire test period

### 3.1.1 Topography Related to Energy Use

There seems to be a correlation between topography and energy use. The tested bus lines in Kalmar and Eskilstuna were rather flat, while the lines in Borås and especially in Jönköping were hillier. Lines 12 and 18 in Jönköping had about 60 meters’ height differences and line 1 in Borås about 100 meters. The tested lines in Kalmar and Eskilstuna were on the other hand flatter and smooth had less than 20 meters’ height differences, with a few exceptions in Eskilstuna.

### 3.1.2 Drivers’ Driving Behavior Related to Energy Use

Another correlation seems to be related to the number of drivers in each municipality and the energy use. This is exemplified by testing in Lerum where a few drivers decreased energy use by about 10 % at the end of the test. There seems to be no differences in energy use due to the road conditions (wet/snowy/icy/dry) or temperature differences in the test. The latter is probably caused by the fact that air-conditioning was not used. The charging meter was not working in Kalmar, Eskilstuna, and Orust, but energy use was measured via logging of the energy meter inside the bus.

### 3.1.3 Driving Range and Battery Capacity Left

The range was tested several times, and the longest drive was done the last day in Karlskrona when the bus drove 272 km (Appendix 1), and the internal bus energy meter indicated 17 % battery capacity left. Ebusco test personnel estimated the charging losses to be 4 % for the whole test period.
3.1.4 Diesel Heater for Interior Heating System

Logging of the diesel heater fuel use from the 23rd of December to the 13th of January revealed a use of 93,6 litres. With the bus driving 1397 km during that period, this resulted in an average energy use of 0,67 kWh/km. According to SMHI (2015) the measured temperature and rain/snowfall for that period (Appendix 1) can be regarded as average winter conditions. This implies that the measured energy use should be representative. Passenger survey responses (Section 3.1.1 Topography Related to Energy Use), reveal that the interior temperature was by most passengers regarded as "ok" or "hot". This confirms that the diesel heater used enough energy and gave a satisfactory basis for energy measurements. The authors would like to highlight that the heater could use biodiesel to reduce CO₂ emissions.

3.1.5 Energy Use in Karlskrona

Line 1 between Saltö and Lyckeby in Karlskrona stretches 14,7 km and takes about 35-40 minutes to drive. The frequency is 10 minutes between each bus during peak time and this adds up to a total of 465000 km/year (93000 km/year/bus). The line has 38 bus stops in the longer of its two alternative routes. It has three traffic light stops, one railway crossing, and about 10 places where the bus has a duty to give way, which is slightly less than assumed in the simulation study. The average speed is 20-25 km/h and the topography (Figure 1) is less hilly than the most frequently tested lines in Jönköping and Borås. Still, it was not as flat as the ones tested in Eskilstuna and especially not as those tested in Kalmar.

![Figure 1: Topography of Bus Line 1 in Karlskrona.](image)

Only the last two days of real-life testing in Karlskrona, with an average of 0,96 kWh/km, gave energy use results (Appendix 1) within the requirements set up in this study. This energy use is about 8 % lower than assumed in the simulation study. These two days where similar regarding passenger load and climate, and can be considered as acceptable data for verification purposes. Differences in energy use seem related to how the driving was executed, as there were different drivers both days.
3.2 Noise Level Measurement

The first section describes the estimated noise for accelerating buses. The next comings sections are summaries of the technical report produced for this test (Haraldsson, 2015). All these sections cover the noise measurements in Karlskrona as described in the Section 2.2 Electric Bus Specifications, and thereby done accordingly to UN ECE 51-02.

3.2.1 Accelerating Vehicle Noise

As earlier mentioned, our tests do not include noise measurements during acceleration, but a test in Edmonton 2007 measured that an electric bus had 4 dBA lower noise level compared to a parallel diesel-hybrid bus when accelerating from 0 km/h and from 30 km/h (Checkel, 2008). In accordance with the Section 2. Methods, a summary of recently tested buses (Table 3) reveals that the electric buses had on average 9 dBA lower sound level than diesel buses and 12 dBA lower sound level than CNG-buses when accelerating from 0 km/h. When accelerating from 56 km/h, the electric buses had 6 dBA and 8 dBA lower sound levels, respectively.

Table 3: Differences in noise from tested electric, diesel, and CNG 12-meter buses within the Thomas D. Larson Pennsylvania Transportation Institute database.

<table>
<thead>
<tr>
<th>Bus model and year of measurements</th>
<th>Energy Carrier</th>
<th>Length (meters)</th>
<th>Passengers Seats/Total</th>
<th>Average acceleration noise (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BYD electric bus 2014</td>
<td>Electricity</td>
<td>12.2</td>
<td>36/49</td>
<td>59.8</td>
</tr>
<tr>
<td>Proterra BE40 2014</td>
<td>Electricity</td>
<td>12.8</td>
<td>41/79</td>
<td>65.6</td>
</tr>
<tr>
<td>Designline Enhanced El. 2012</td>
<td>Electricity</td>
<td>12.8</td>
<td>38/81</td>
<td>62.9</td>
</tr>
<tr>
<td>Average Electric</td>
<td></td>
<td>12.8</td>
<td>38/81</td>
<td>62.8</td>
</tr>
<tr>
<td>ElDorado ARRIVO 2014</td>
<td>Diesel</td>
<td>11.9</td>
<td>42/60</td>
<td>77.9</td>
</tr>
<tr>
<td>New Flyer NABI 40-LFW 2013</td>
<td>Diesel</td>
<td>12.5</td>
<td>38/72</td>
<td>67.7</td>
</tr>
<tr>
<td>New Flyer XD40 2012</td>
<td>Diesel</td>
<td>12.2</td>
<td>36/81</td>
<td>70.4</td>
</tr>
<tr>
<td>Average Diesel</td>
<td></td>
<td>12.2</td>
<td>36/81</td>
<td>72.0</td>
</tr>
<tr>
<td>ElDorado Axess HD 2014</td>
<td>CNG</td>
<td>12.5</td>
<td>38/61</td>
<td>76.7</td>
</tr>
<tr>
<td>New Flyer XN40 2014</td>
<td>CNG</td>
<td>12.5</td>
<td>39/71</td>
<td>74.7</td>
</tr>
<tr>
<td>Nova (Volvo) LFS 40 2013</td>
<td>CNG</td>
<td>12.2</td>
<td>35/65</td>
<td>72.6</td>
</tr>
<tr>
<td>Average CNG</td>
<td></td>
<td>12.2</td>
<td>35/65</td>
<td>74.7</td>
</tr>
</tbody>
</table>

\(^{a}\) (The Larson Institute, 2014a), \(^{b}\) (The Larson Institute, 2015a), \(^{c}\) (The Larson Institute, 2012a), \(^{d}\) (The Larson Institute, 2015b), \(^{e}\) (The Larson Institute, 2013), \(^{f}\) (The Larson Institute, 2012b), \(^{g}\) (The Larson Institute, 2014b), \(^{h}\) (The Larson Institute, 2014c), \(^{i}\) (The Larson Institute, 2014d)

3.2.2 Constant Speed Vehicle Noise

The constant speed noise measurements were done in Karlskrona on the 7th to the 8th of April at Klorgatan and Heliumgatan in Hattholmen, and on the 8th of April at Friluftsvägen in Bastajö since the ambient sound levels were lower there. Two microphones were placed to the left and right from the centreline of the bus track, and one wind meter was placed a few meters away from the microphone, as illustrated in
Figure 2. The results were adjusted to compensate for the ambient sound level, which was more than 10 dBA lower than the measured results.

A relatively small difference was found between the buses (Figure 3), but the electric bus was almost 2 dBA louder than the hybrid bus. It is uncertain if these differences stem from the bus driveline or something else like differences in tires.

3.2.3 Stationary Vehicle Noise

The noise from stationary vehicles was measured on the 8th 2015 of April in the bus depot in Torskors, where engines in the diesel and hybrid buses were revved to slightly more than 2000 rpm. The noise was measured behind the gas exhaust pipe as illustrated in Figure 4. The noise of the diesel bus peaked at 95.7 dBA and the hybrid bus peaked at 90.2 dBA. The electric bus did not exceed the ambient sound level, which was less than 60 dBA.

Figure 3: Results of constant speed noise measurements of electric, hybrid, and diesel bus
3.2.4 Compressed Air Noise

The buses sometimes release the over-pressure in the braking system at bus stops, which can be perceived as noise by passengers or people nearby. This compressed air noise was measured on the 8th of April 2015 beside the bus as illustrated in Figure 5. The levels were 69,2 dBA at the right side and 68,0 dBA at the left side of the diesel bus, 68,1 dBA at the right side and 65,7 dBA at the left side of the hybrid bus, and 64,7 dBA at the right side and 65,4 dBA at the left side of the electric bus. These results were adjusted to compensate for the ambient sound level that was more than 10 dBA lower than the compressed air measurements.

![Figure 5: Compressed air noise measurements of the hybrid bus. Photo: Sven Borén.](image)

3.3 Driveline related opinions

3.3.1 Passengers opinions

In total 1303 survey responses were collected from passengers during the entire test period (Borén, 2014) and the results are summarized in Figure 6a and 6b.

![Figure 6a: Passenger survey responses from the entire test period. Source: (Borén, 2014)](image)
Most of the survey responses came from Borås (84%). The question about comfort was included in an updated version of the survey before testing in Kalmar, but unfortunately the earlier version was used occasionally throughout the field test due to a misunderstanding. That resulted in 71% no-answers (n.a.) for that question. The conditions behind the 43 replies from November in Karlskrona are slightly different as the heating system was not working, and the bus was pre-tested with students who were curious to ride the electric bus. Other people were not picked up at the bus stops. The results clearly show that most passengers felt that the electric bus, in comparison to diesel buses or CNG buses in normal regular service, is quieter inside and outside at bus stops, produce less emissions at bus stops and is more comfortable (mainly regarding vibrations and ride comfort).

In addition to the questions in the surveys, passengers where asked to provide additional comments. The most common driveline related positive answers, in descending order, were that passengers...

... liked the bus,
... appreciated the environmental friendliness provided by the electric drive,
... appreciated that the bus had a low noise level,
... regarded the ride as a pleasant and comfortable experience, and appreciated a fresh and pleasant interior.

Some non-driveline related negative comments, in descending order, were about:

- sudden braking (which can be adjusted by software settings),
- narrower seats than usual and narrow passage backward from the driver,
- hard seats,
- only one space for wheelchair or stroller, and fogged windows when the heater did not work.
3.3.2 Drivers opinions

During the entire test, 77 drivers out of about a hundred answered the driver survey (Borén, 2014) and the number of respondents varied a lot in each municipality. Borås had 49 driver responses, but Orust and Lerum only one answer each. The comments from the drivers who drove the electric bus can be summarized as follows:

**Charging:** The majority of drivers did not charge the bus as the mechanics at the bus depots and/or Ebusco staff did this. A few of the drivers took part in the charging and felt that it worked well.

**Time schedule:** Almost all drivers answered that they managed to drive according to the timetable. A few of the drivers who drove only short distances expressed a fear that the electric bus would have problems to drive according to the timetable.

**Drive-ability:** Almost all drivers answered that they favor the electric bus drive-ability and some stated that the electric bus was even better to drive than other buses. Some drivers thought that the electric bus was quick at the start from standstill. About a third of the respondents mentioned that the bus brakes were hitting hard over 30 km/h, and that the bus was blunt, particularly in steep inclines. This is possible to adjust in the bus software, but can limit the range. In addition to the survey, direct conversations with drivers revealed that the electric bus was a bit weak when speeding over 50 km/h, which is also possible to adjust in the bus software, but might limit the range.

Most drivers have given positive feedback about the electric bus, but some have complained about things that are not related to the driveline, such as the absence of stop braking, poor rear visibility, a modest driver environment with few personal adjustment possibilities, the absence of rear mirror inside the bus, and misplacement of the door mirrors.

3.3.3 Stakeholders opinion

Discussions have been held primarily with the stakeholders in the study, the participating municipalities, passenger transport executives, and bus operators. The following comments emerged in meetings during the study with drivers and representatives from the bus operator Bergkvarabuss in Karlskrona, and representatives from Blekingetrafiken, Region Blekinge, Karlskrona municipality and the local energy company Affärsverken, (Borén, 2015):

- The electric bus from Ebusco was perceived as good and the use of hybrids was perceived as superfluous.
• The electric bus has the potential to fit into the operator’s business if the need for charging within one or two circulations of vehicles can be solved in a simple way for the driver, without involving high costs.
• For future use of electric buses in public transport, bus operators’ potential risk relating to the uncertainty about the new technology and expertise needs to be taken into special consideration. Several major European bus manufacturers have not started the production of electric buses yet, which some bus operators who have established cooperation with them consider to be a disadvantage. It is therefore important to make public procurement design specifications that are tailored for electric buses and the supporting charging infrastructure.
• The simulation study revealed a 25% lower total cost of ownership for electric buses compared to diesel buses for urban public transport. This is received with caution by stakeholders, but gives a positive impression of electric buses.
• The introduction of electric buses need to be preceded by some type of projects where electric buses are tested over a longer period to raise the level of competence for all parties.

Conversations with other stakeholders involved in the project confirmed the above views, as well as most of the comments from the passenger surveys. The issue of grid related capacity for depot charging of several electric buses during nights has been raised several times, as well as whether they should invest in electric buses with less battery and lower purchase costs, which would require a more advanced and expensive charging infrastructure. Once stakeholders have tested the electric bus and have seen how it can work in urban areas, the question of charging often appears, and how it could be solved in each municipality.

3.4 Initial charging infrastructure investigation

Interviews with representatives from municipalities and passenger transport executives revealed that they believe something has to be done to decrease transport emissions and lower noise levels within cities, and that use of electric instead of diesel buses has a great potential to contribute to such development. One problem they are facing when planning for such development is the palette of electric bus systems and which configuration of bus and charging system that would fit their local public transport. Should the buses have a large battery pack that allows long range and maybe only slow charging at depots, or a smaller battery pack that might require strategically placed fast charging equipment? These issues were studied, including charging stations powered by the electricity grid, which need to allow for charging without effecting existing and future nearby electricity grid users (an overhead fast charger needs about 350-600 kW AC, while a handheld slow charger needs about 25-100 kW AC).

It was found that most bus lines included in the study had a great possibility to host electric buses and charging stations at either line end stations or at line crossing points, depending on the bus lines traffic intensity and the choice of battery pack size. For
example, bus line 1 and 3 in Jönköping has a high traffic load and run with 18- meter buses each 10 minute. The end station in Råslätt beside a shopping mall, could host an overhead charging station, as there seems to be enough grid capacity and a possibility to host an electric charging station for cars as well. Another high traffic line example is line 1 in Karlskrona that ends at Saltö, which could be suitable to host an overhead fast charger because a grid substation is located about 20 meters from the bus stop. If electric buses with large battery packs (typically over 300 kWh) were chosen, it might instead be interesting to install a fast charger at the future common bus station located beside the train station at Blekingegatan, which could fast charge buses on most lines in Karlskrona. This second alternative might also be suitable for Kalmar at the bus station beside the train station for charging a part of the bus fleet that passes the city center. Even if fast charging seems feasible, slow charging at depots during nights should be the base for a local bus charging system, as it is the cheapest alternative and keeps the batteries in a better condition. Electric buses with large battery packs seems like an interesting alternative when traffic load is low as in Orust, where the rural traffic with low energy use allows longer ranges than urban traffic.

As stated in the simulation study, electric buses should use new sustainable generation electricity capacity to contribute prominently to sustainable development. This is possible and energy companies that deliver electricity to the charging infrastructures have some incentives from the government and the customers to buy shares in or build new renewable electricity production (based on flow-based energy such as wind, solar, and streaming water).

4. Discussion

4.1 Main message

The findings of this study indicate that it is preferable to use electric buses in public transport. The main reasons for this are:

- Almost all passengers perceived the electric bus to be more silent and comfortable than today’s diesel and CNG buses. Most of the drivers enjoyed driving the electric bus, and representatives from municipalities, passenger transport executives and bus operators were positive too.
- Electric buses tested in the USA have more than a 6 dBA lower noise level than diesel and CNG buses during acceleration, which is perceived as a 75 % noise reduction by the human ear. This indicates that noise levels in cities with bus traffic could be reduced significantly.
- The energy use turned out to be 8 % lower than assumed in the simulation study (Nurhadi et al., 2014), which supports the conclusion that electric buses used in urban public transport are up to 25 % cheaper when compared to diesel buses.
• Almost all of the studied bus lines can be operated by electric buses, and are possible to equip with charging infrastructure that is powered by new sustainable electricity generation capacity. Renewable fuels could also power the interior heater.

### 4.2 Critical assessment

Some issues that could have improved the real-life:

• Energy measurements would have included charging and battery losses during the whole test if the charging meter had been used regularly. This was unfortunately not possible as the charging meter broke down from time to time. The energy use (battery to wheel) was anyhow displayed at the drivers seat and thereby continuously measured throughout the test.

• Energy use for interior heating and cooling could have been measured for a longer period to get more accurate average data. The testing was limited to Swedish wintertime, and the southernmost part of the test area had typical winter conditions. The northernmost part less so. If the testing had included all seasons, an average of the whole year would have been achieved to also include the use of air conditioning during warm days.

• Testing in Jönköping should in line with the study ambitions have included at least one more day on line 1 and 3 in order to be able to fully verify the simulation study. Testing in Falun could have contributed better to the results if the Ebusco 2.0 would have been used.

• The noise measurements could have been done with more buses available for the Swedish market, if there had been more time and resources available. They could also have been tested during acceleration. An interior noise measurement would also have been valuable to see if there might be any difference between passenger’s perceptions and measured noise levels. A more thorough analysis of possible differences in noise performance during acceleration regarding the US or the European market for the tested buses would give the analysis more accuracy.

### 4.3 Comparison with other studies

Bus testing by the Thomas D. Larson Pennsylvania Transportation Institute (Section 3.2.1 Accelerating Vehicle Noise) applied the SAE standard, but this is slightly different to the UN standard used in this study (Section

2.4 Noise Measurements as the SAE standard includes noise measurements during acceleration. The tested electric bus from BYD is similar for the USA and European market, but the other tested buses cannot be purchased in Europe and it is therefore some uncertainty about the accuracy when using results from bus tests for the USA
markets in European cities. The same applies for a bus noise study in Edmonton (Checkel, 2008).

A study about feasibility of electric buses in small and medium-sized cities in the USA (Wang and González, 2013) uses less updated data from the same source as used in this study (Section 3.2.1 Accelerating Vehicle Noise). They found noise from accelerating electric buses to be surprisingly much lower than in this study, probably because they believe the ambient level can be excluded from the measurements, which is not in line with the UN standard used in this test and neither with the presented results via the above-mentioned reports from the Thomas D. Larson Pennsylvania Transportation Institute. In line with this study, Wang and González also believe that electric buses are ideal for use in small and medium-sized cities if the buses are charged with renewable energy.

4.4 Conclusions and further work

This study has clarified that electric buses have low energy use and low external noise levels, and receive positive opinions from passengers, drivers and other stakeholders in real-life use during wintertime in the south of Sweden. It also seems like the urban public transport system can rather easily host a charging infrastructure generated from renewable sources. An update of earlier studies about total cost of ownership (Nurhadi et al., 2014) confirms that electric buses are up to 25 % cheaper than diesel buses when used in public urban transport and charged with new renewable energy. In all, this supports the conclusion that electric buses are preferable for use in Swedish public urban and rural transport, which can probably be applied also to other European and especially Nordic areas with similar climate.

Further studies within should include testing throughout a whole year to get a yearly-based average energy use. To support the development of a business model tailored for electric buses in public transport, further studies should reveal data for likely costs, and also develop training of bus drivers, maintenance personnel, and planners to use the electric bus in an optimal way. In this context, deeper correlation analyses on what factors that are the most influential on energy use could be useful to increase the validity of our conclusions.
Appendix 1: Energy measurement and parameter logging per day

<table>
<thead>
<tr>
<th>Municipality, Date</th>
<th>Line</th>
<th>Passenger load a</th>
<th>Road surface</th>
<th>Temp (°C)</th>
<th>Rain/ snow</th>
<th>Distance (km)</th>
<th>Energy use (kWh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kalmar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17\textsuperscript{th} Dec</td>
<td>401, 412</td>
<td>Medium-low</td>
<td>Dry</td>
<td>+1 to +3</td>
<td>No</td>
<td>150</td>
<td>0.92</td>
</tr>
<tr>
<td>18\textsuperscript{th} Dec</td>
<td>401, 411</td>
<td>Low</td>
<td>Dry</td>
<td>+3</td>
<td>No</td>
<td>185</td>
<td>0.87</td>
</tr>
<tr>
<td><strong>Jönköping</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5\textsuperscript{th} Jan</td>
<td>Mix</td>
<td>Low</td>
<td>Dry</td>
<td>-2</td>
<td>No</td>
<td>147</td>
<td>0.88</td>
</tr>
<tr>
<td>7\textsuperscript{th} Jan</td>
<td>12, 18</td>
<td>Low</td>
<td>Dry</td>
<td>+3</td>
<td>No</td>
<td>224</td>
<td>0.99</td>
</tr>
<tr>
<td>8\textsuperscript{th} Jan</td>
<td>Mix</td>
<td>Low</td>
<td>Dry</td>
<td>+3</td>
<td>Rain</td>
<td>114</td>
<td>0.98</td>
</tr>
<tr>
<td>9\textsuperscript{th} Jan</td>
<td>12, 18</td>
<td>Medium</td>
<td>Wet</td>
<td>+2</td>
<td>Snow</td>
<td>159</td>
<td>0.92</td>
</tr>
<tr>
<td>10\textsuperscript{th} Jan</td>
<td>1, 3</td>
<td>Medium</td>
<td>Snow-dry</td>
<td>+4</td>
<td>Little Snow</td>
<td>131</td>
<td>1.05</td>
</tr>
<tr>
<td>12\textsuperscript{th} Jan</td>
<td>12, 18</td>
<td>Medium</td>
<td>Wet</td>
<td>+3</td>
<td>Rain</td>
<td>172</td>
<td>1.05</td>
</tr>
<tr>
<td>13\textsuperscript{th} Jan</td>
<td>18</td>
<td>Medium</td>
<td>Dry</td>
<td>+3</td>
<td>No</td>
<td>79</td>
<td>0.91</td>
</tr>
<tr>
<td><strong>Borås</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16\textsuperscript{th} Jan</td>
<td>Mix, 1</td>
<td>Medium-high</td>
<td>Wet-dry</td>
<td>0</td>
<td>Little Rain</td>
<td>100</td>
<td>1.06</td>
</tr>
<tr>
<td>17\textsuperscript{th} Jan</td>
<td>1</td>
<td>High</td>
<td>Wet-dry</td>
<td>2</td>
<td>Little Rain</td>
<td>150</td>
<td>0.92</td>
</tr>
<tr>
<td>18\textsuperscript{th} Jan</td>
<td>1</td>
<td>Medium</td>
<td>Wet</td>
<td>0</td>
<td>Rain</td>
<td>101</td>
<td>1.02</td>
</tr>
<tr>
<td>19\textsuperscript{th} Jan</td>
<td>1</td>
<td>High</td>
<td>Wet</td>
<td>1</td>
<td>Snow</td>
<td>154</td>
<td>1.09</td>
</tr>
<tr>
<td>20\textsuperscript{th} Jan</td>
<td>1</td>
<td>High</td>
<td>Wet</td>
<td>0</td>
<td>Snow</td>
<td>143</td>
<td>1.09</td>
</tr>
<tr>
<td>21\textsuperscript{th} Jan</td>
<td>1</td>
<td>High</td>
<td>Wet-dry</td>
<td>2</td>
<td>Little Rain</td>
<td>107</td>
<td>0.99</td>
</tr>
<tr>
<td>22\textsuperscript{nd} Jan</td>
<td>1</td>
<td>High</td>
<td>Dry</td>
<td>0</td>
<td>No</td>
<td>167</td>
<td>1.01</td>
</tr>
<tr>
<td>23\textsuperscript{th} Jan</td>
<td>1</td>
<td>High</td>
<td>Dry</td>
<td>-2</td>
<td>No</td>
<td>153</td>
<td>1.00</td>
</tr>
<tr>
<td>24\textsuperscript{th} Jan</td>
<td>1</td>
<td>Medium</td>
<td>Wet</td>
<td>-1</td>
<td>Snow</td>
<td>98</td>
<td>0.98</td>
</tr>
<tr>
<td>25\textsuperscript{th} Jan</td>
<td>1</td>
<td>Medium</td>
<td>Dry</td>
<td>-1</td>
<td>No</td>
<td>117</td>
<td>0.98</td>
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<tr>
<td><strong>Lerum</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2\textsuperscript{nd} Feb</td>
<td>Mix, 525</td>
<td>Low</td>
<td>Snow</td>
<td>-4</td>
<td>No</td>
<td>227</td>
<td>1.00</td>
</tr>
<tr>
<td>3\textsuperscript{rd} Feb</td>
<td>525, 535</td>
<td>Medium</td>
<td>Snow</td>
<td>-4</td>
<td>No</td>
<td>121</td>
<td>0.99</td>
</tr>
<tr>
<td>4\textsuperscript{th} Feb</td>
<td>525, 535</td>
<td>Medium</td>
<td>Dry</td>
<td>-4 to -5</td>
<td>No</td>
<td>220</td>
<td>0.97</td>
</tr>
<tr>
<td>5\textsuperscript{th} Feb</td>
<td>525, 535</td>
<td>Medium</td>
<td>Dry</td>
<td>-3 to -6</td>
<td>No</td>
<td>220</td>
<td>0.96</td>
</tr>
<tr>
<td>6\textsuperscript{th} Feb</td>
<td>525, 535</td>
<td>Medium</td>
<td>Dry</td>
<td>-2 to -5</td>
<td>No</td>
<td>220</td>
<td>0.93</td>
</tr>
<tr>
<td>9\textsuperscript{th} Feb</td>
<td>525, 535</td>
<td>Medium</td>
<td>Dry</td>
<td>5</td>
<td>No</td>
<td>234</td>
<td>0.88</td>
</tr>
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<td>Dry</td>
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<td>Dry</td>
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<td>3\textsuperscript{rd} Mar</td>
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<td>9</td>
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<td>1.03</td>
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### Acknowledgment

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### References


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PAPER D

Competitiveness and Sustainability effects of Cars and their Business Models in Swedish Small Town Regions
Paper D is submitted as:

Competitiveness and Sustainability Effects of Cars and their Business Models in Swedish Small Town Regions

Lisiana Nurhadi, Sven Borén, Henrik Ny, Tobias Larsson

Abstract

This article aims to develop and test a new approach for comparing sustainability effects (mainly approximated through CO2 emissions) and the total cost of ownership of various business models (Regular Purchasing, Car Pooling, Car Leasing, and Taxiing) applied to private cars with different energy carriers (Biogas, Ethanol, Gasoline, Plug-in Hybrid, and Electric). The results indicate that, out of all of the vehicles, electric vehicles are the most competitive—from both an ecological and economic perspective. Moreover, of all of the business models, Car Pooling is the most competitive when driving short to medium distances, reducing CO2 emissions by 20-40% compared with Regular Purchasing. Meanwhile, Car Leasing emits the same amount of CO2 emissions as Regular Purchasing if both are driven the same number of kilometers per year. The results also indicate that, from a cost effectiveness perspective, people who travel less than 2000 km per year should primarily consider using Taxis or similar services, while Car Pooling is most cost effective for those who travel from 2000 to 8500 km. For those who travel between 8500 and 13500 km per year, Car Leasing is the most cost effective, and Regular Purchasing is the best option above 13500 km per year. If most car owners were to accept and adapt to this identified need for a market move towards Car Pooling with Electric Vehicles, necessary transportation could be ensured while significantly reducing the number of cars on the road, whether from Regular Purchasing or Car Leasing, as well as those that run on fossil fuel. This, in turn, would result in less fossil fuel use, fewer emissions, and decreased negative effects on human health.

Keywords: Business modeling; Sustainable transport; Total Cost of Ownership; Electric car; Fossil-fueled car; Life-cycle costing
1 Introduction

1.1 Current challenges in personal transport and some early responses

Today, the road transport sector is used daily by people and businesses across the globe, and it generates nearly 2% of the European GDP (The European Commission, 2012). Road transport is therefore a vital part of the European economy. At the same time, road transport contributes to the increase in fossil fuel prices and unsustainability. It increases greenhouse gas (GHG) emissions and places a large amount of pressure on natural resources. There is a growing consensus that fossil fuel use in the automobile industry needs to be vastly scaled down from what it is today in an effort to reduce air pollution and carbon footprints (IVL Svenska Miljöinstitutet, 2009; Lööf et al., 2013; Staten Offentliga Utredningar-Government Official Reports, 2013; The European Commission, 2012; 2011; The International Energy Agency IEA, 2012a). Emissions from the transport sector also contribute to various other environmental and health effects, such as respiratory disease, allergies, and cardiovascular disease (Curtis et al., 2006; Robert J Laumbach and Howard M Kipen, 2012). To address this unsustainable development, the Swedish Government has agreed upon national goals, including GHG neutrality by 2050 and a fossil fuel-independent vehicle fleet by 2030 (Staten Offentliga Utredningar-Government Official Reports, 2013; The International Energy Agency IEA, 2013). Several Swedish projects are underway to respond to these challenges. The GreenCharge project (Greencharge, 2015) is currently working on a road map for fossil fuel independence and the sustainable development of Electric Vehicles (EV’s) by 2030 in Southeast Sweden, combining demonstrations of EV systems with strategic sustainability research.

GreenCharge utilizes a well-established approach to plan strategically for sustainable development: the Framework for Strategic Sustainable Development (FSSD) (Robért et al., 2013), which applies backcasting from a principled definition of sustainability. It is applicable to any system or organization that wants to plan for sustainability, and it has already been used in several transport-related studies (Borén et al., n.d.; Robért et al., n.d.). In line with several recent national personal transport investigations (Staten Offentliga Utredningar-Government Official Reports, 2013; The International Society of Sustainability Professionals (ISSP), 2008), the necessary Swedish steps towards sustainable road transportation at large are expected to be:

1. Plan cities to minimize the need for transport
2. Plan cities so that the remaining necessary transport can be shifted towards…
   a. …primarily, walking and biking, especially within a few kilometers from work or the grocery store
b. secondly, effective public transport (including electric buses and rail transport, such as trams and railroads)
c. thirdly, personal cars

3. Promote energy efficient vehicles, such as battery electric and hydrogen fuel cells, complemented with vehicles running on renewable fuels.

1.2 Common car motoring types

Current private car types can be classified by their motoring design as:

- **The Biogas car**, powered by an internal combustion engine (ICE) with energy from biogas. Biogas is the final product of fermentation processes, composed mainly of methane (CH₄) and carbon dioxide (CO₂), and is also known as digestion gas (Toyota Motor Corporation Mizuho Information Research Institute, Inc. 2004; The European Biogas Association 2013).

- **The Ethanol car**, powered by an ICE, which uses bioethanol, is already used in Europe with an ethanol/petroleum blend, and it has a high octane rating, which can improve performance (The Sixth Framework Programme 2007).

- **The Gasoline or Diesel car**, powered by an ICE with two types of engines (spark ignition for gasoline and compression-ignition for diesel), operating differently and with a general ICE efficiency of approximately 25-30% according to its average performance in 2005 (The International Energy Agency IEA 2012a).

- **The Plug-in Hybrid Vehicle (PHEV)** uses an electric motor in series or in parallel with an ICE and has a small battery that can provide a driving range of between 30 and 80 km. When the battery is depleted, the driveline uses an ICE as a range extension. PHEVs are an evolution of **Hybrid Electric Vehicles (HEVs)** and can, unlike the HEVs, be plugged into a grid socket to charge the battery (Faria et al. 2012).

- **The Battery Electric Vehicle (BEV)** is powered by an electric motor and has a large, chargeable battery that provides a driving range of up to 450 km depending on the car (Faria et al. 2012).

In the present situation, the most promising sustainable alternatives to fossil fuel cars seem to be PHEVs and BEVs charged with renewable energy (Faria et al., 2012; The International Energy Agency IEA, 2013). One of the obstacles to rapid market penetration, though, is the higher initial investment required compared with conventional combustion engine technologies (Tate et al., 2008). In addition, the current renewable electricity supply for the global car fleet is only in its infancy, which sometimes leads to critiques against switching towards electric and renewably fueled vehicles. Therefore, a more sustainable solution is to charge electric vehicles (EVs) with new, renewable electricity that would compensate for the current negative effects from the normal grid electricity used by EVs (Nurhadi et al. 2014).
1.3 Broadening traditional business models with Product-Service System (PSS) thinking

As product development has traditionally focused on the development of tangible products, there is a push in the industry towards the design of products and services together—often referred to as Product-Service Systems (PSS). Selling products (physical goods) used to be the normal way to do business. PSS, on the other hand, offers not only a product but also the provision of the “function,” where you pay for the result rather than the product (Alonso-Rasgado et al., 2004; Isaksson et al., 2009; Lindahl et al., 2014; Manzini and Vezzoli, 2003; Mont, 2002; Thompson, 2012; Thompson et al., 2010; Tukker and Tischner, 2004). PSS offers new business model designs, where companies might not offer any ownership in these PSS-models but are responsible for maintenance, repair, and control. Different users sequentially use the same product, and others can use the product at other moments (Tukker and Tischner, 2004). Car Pooling by Sunfleet (Ronzani 2014) and Move About, which focuses on electric Car Pooling (Jakobsson 2015) and Car Leasing, are examples of user-oriented combinations of physical products and services. Car Leasing has been around longer than Car Pooling and is another increasingly common option (Hagberg 2014). With the implementation of a PSS approach, it is possible for all major dimensions of sustainability to benefit (Tukker and Tischner, 2004). Such examples include:

- Environmental gains from holistic responsibility from suppliers, for example, with dematerialization that reduces a product’s consumption.
- Economic gains from the existence of new service-oriented market opportunities for companies where they can increase competitiveness. For example, a PSS approach is expected to improve customer loyalty due to the added service content that deepens and prolongs the customer interaction throughout the PSS lifetime.
- Social gains from strengthened stakeholder relations with a higher focus on the quality of the consumer experience and service.

1.4 Challenges and opportunities for some current business models

It is not only the types of cars and financial models that are different; the variations of how they are accessed and used by customers (“business models”) also bring their particular challenges and opportunities. Examples of new business models include Uber¹ Taxi and Total offerings including free charging that Tesla² gives to their


²
customers. In this study, though, we will focus on a few well-known and established alternatives for daily transport:

- **Regular Purchasing or Owning a car.** This means that the users are not locked into any limited ownership period, so the car is always available for their own use or to sell at any time. However, when the car is driven, the depreciation (reduction in value) burdens the car owner (Clark, 2015). As a private person, purchasing a car could include a "subscription" for service and maintenance. Privately owned cars must carry a high cost for parking, and the owner cannot bring the car to the city for parking during the workday.

- **Car Sharing or Car Pooling** exploits the strategy of a membership-based service that offers the user short-term access to a top quality, well-maintained, new car with a minimum of fixed costs and other obligations. Members can reserve a car from a fleet that is parked at central locations within a city, usually near metro and train stations (Baptista et al., 2014; Trafikverket-Swedish Traffic Authority, 2012). Companies such as Sunfleet and Move About in Sweden provide this type of service. Car Pooling means that people should plan their travel routes, which often results in decreased mileage by itself, where they could plan to use Car Pooling combined with the use of alternative means of transport, such as train, bike, or walking, to reach their final destination. A benefit of Car Pooling in bigger cities is the opportunity to park within the city at certain assigned free parking slots for Car Pooling cars. In smaller cities and towns like the ones in this study, though, this advantage is smaller due to the relatively high accessibility of parking slots.

- **Car Leasing** offers cars for an agreed amount of money at a fixed period where the cost of leasing depends on the driving range in the agreement. Leasing is often seen as an alternative way to finance the car rather than a new business model. Nevertheless, in this article, leasing means ‘operational leasing’ that includes a fixed monthly payment including a guaranteed residual value (within certain limitations), service, maintenance, etc. A car leased by a company often gets the parking cost paid by the employer, and this is included in the beneficial value that the driver pays tax (VAT) for. A residual value can also already be agreed upon when the car is purchased, corresponding to a type of private leasing without the possibility of deducting VAT, which is valid only for "legal" persons (e.g., companies) (Leaseurope, 2014). **For the buyers**, the leasing option provides lower individual payments, and its contract is often easier to qualify for than a car loan. Leasing allows the buyer to return the car and select a different model when the lease term is expired. It also allows a buyer to drive a new car for a few years without being exposed to the risks of selling a used car and allows them to buy the used car when the leasing period has ended. **For the seller**, leasing generates regular income for a longer period of time compared with a regular purchase and allows them to sell the car for the remaining value after the leasing period (Chemmanur et al., 2009).

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• **Taxiing** is a service that includes a car and a driver for a small group of passengers, quite often as a non-shared ride. The driver brings passengers from door to door with high flexibility. This also makes Taxiing a good complement to public transport (Aarhaug and Skollerud, 2014).

### 1.5 Purpose

This article aims to discuss the development and testing of a new approach for comparing sustainability effects and the total cost of ownership of various business models (Regular Purchasing, Car Pooling, Car Leasing, and Taxiing) applied to private cars with different energy carriers (Biogas, Ethanol, Gasoline, Plug-in Hybrid, and Electric). This article is also a contribution to the current reality assessment within the GreenCharge project’s roadmap regarding how electric vehicles could contribute to Southeast Swedish fossil fuel independence in the transport sector by 2030.

### 1.6 Scope and limitations

This study does not intend to describe in detail the behavior of car users depending on how they choose to access their car service (applied "business models"). The authors have chosen to report only the results of the analysis (e.g., Life-cycle assessment and Life-cycle Costing) without any deeper interpretation. Diesel cars are not included in the study because they, in this context, have almost the same characteristics as gasoline cars.

The assumed end-users for the TCO analysis are private car owners living in the Municipality of Karlskrona (67,000 inhabitants) in South East Sweden. In addition, the following conditions are assumed to apply:

- For Regular Purchasing: an end user living in Karlskrona in the Southeast of Sweden with a 45-km daily commuting distance, which corresponds to a yearly distance of 15,000 km and nine years of ownership.
- For Car Leasing: the same end user with the same driving range of 15,000 km/year but with three-year leasing periods.
- For Car Pooling and Taxiing: a person from Karlskrona with a driving range of 3,500 km/year.

The following is not included in the study:

- Specifics of the area of driving (e.g., whether it takes place in town or in the countryside)
- Parking costs
• Tax fringe benefits, other than the Swedish government subsidy called the ‘green car bonus’ (in Swedish: ‘supermiljöbilpremie’)
• Rental car services, as it is difficult to estimate a relevant number of kilometers driven to make it comparable with the other studied business model types.
• Utility cars
• Some of the transport mileage displaced from users moving into car pools that is assumed to be distributed into other modes of transport, such as biking or walking. The sustainability impacts of these are assumed to be negligible, as they are mostly low- or zero-impact transport modes.
• The time periods for ownership and use are based on the authors’ assumptions of typical normal cases. Future follow-up studies, though, could make deeper sensitivity analyses for different time periods (e.g., 3, 6, 9, 12 years) and/or different travel distances.
• There is no analysis for car users that are driving recklessly in any of the business models.

2 Methods

This study is focused on the analysis and redesign of business models. The Design Research Methodology (DRM) (Blessing and Chakrabarti, 2009) is an approach that aims to make the study of such naturally loosely held design processes more scientific by introducing additional distinctions between goals: a pre-state, experiments, and an after-state. DRM is therefore used to frame the research in this study (Figure 1), to structure the methods (section 2), and in the result (section 3) further below.

This study is also faced with the challenge of embracing the broad and complex challenge of sustainability. While there are many tools and approaches for sustainable development and design (Johansson and Sundin, 2014; Ny et al., 2006; Robért et al., 2013; Short et al., 2012), the above-mentioned Framework for Strategic Sustainable Development (FSSD) (Robért et al., 2013) facilitates both a holistic overview and a way to relate particular challenges to that overview (Ny et al., 2006).

The analysis of this study goes through the business models of current car systems with a focus on selecting those with the least expected socio-ecological sustainability impacts and compares the models economically within the total cost of ownership. The following general DRM steps are followed:

• Research Clarification (RD): to clarify the goals of the study and the aims for initial screening regarding how the FSSD will be used and to close the gap of ecological sustainability with the FSSD.
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- Descriptive Study I (DS I): map and differentiate current business models for car systems with Business Model Canvas (BMC), then screen for their sustainability consequences with Strategic Life-cycle assessment (SLCA) and, where necessary, go deeper into the sustainability and cost assessments with Life-cycle assessment (LCA) and Life cycle costing (LCC).

In future work, the authors plan to conduct a follow-up study on combinations of new business models and their sustainability effects. This is covered by the DRM steps Prescriptive study I and Descriptive study II (Figure 1).

2.1 Research Clarification: Setting goals with the Framework for Strategic Sustainable Development (FSSD)

The study relies on the Framework for Strategic Sustainable Development (FSSD) to provide not only a strategic sustainability perspective but also an integrated overview of sustainability, business models, technologies, and financial considerations. FSSD planning uses backcasting and starts from an imagined social-ecological sustainability vision. Then, the current reality is assessed in relation to the vision. Finally, strategies are explored to close the gap between the current reality and the sustainability vision. This planning is applied for electric cars in a parallel study (Borén et al., 2016.; Robért et al., 2016.) that uses the following Sustainability Principles (SP’s) Broman and Robért, 2015) to frame the sustainability vision:

“In the sustainable society, nature is not subject to systematically increasing…
1 …concentrations of substances extracted from the Earth’s crust;
2 …concentrations of substances produced by society;
3 …degradation by physical means; and in that society;
4 …people are not subject to conditions that systematically undermine their capacity to meet their needs.” These principles are also used in the below-described overarching FSSD-based sustainability assessment.

2.2 Descriptive Study I: business modeling with Business Model Canvas (BMC)

The term “business modeling” is used as a broad informal and formal description to represent core features of a business that includes offerings, strategies, infrastructure, operational processes, and policies. In line with that, business modeling describes the rationale of how an organization creates, delivers, and captures value (Osterwalder and Pigneur, 2009). It also gives the possibility of bringing distinctive ideas to the business for its stakeholders and car users. The authors believe that companies need to make fundamental decisions and choose a business model that supports key business purposes, sustainability values, and strategic goals.

A tool for mapping companies’ business models is the Business Model Canvas (BMC) template (Figure 2), which is a visual chart divided into nine building blocks (Osterwalder and Pigneur, 2009).

1. Key partners: refers to various activities that are outsourced and various resources that are acquired outside the company
2. Key activities: refers to performing a number of key activities inside the company
3. Key resources: refers to the assets required to offer and deliver the previously described elements
4. Value proposition: refers to the resolution of customer problems and the satisfaction of customer needs with value propositions
5. Customer relationships: refers to customer relationships that are established and maintained with each customer segment
6. Customer segments: refers to a company that serves one or several customer segments
7. Channels: refers to value propositions that are delivered to customers through communication, distribution, and sales channels
8. Cost structure: refers to what the most important costs inherent in the business model are and which key resources and key activities are most expensive
9. Revenue stream: refers to what values the customers are really willing to pay and how they actually choose to pay
2.3 Descriptive Study I: Sustainability screening through Strategic life-cycle assessment (SLCA)

As a first screening, the SLCA is a qualitative method to address social and ecological sustainability aspects (Ny et al., 2006). It quickly identifies the most important high-level sustainability challenges that can guide necessary decisions and activities. If needed, the analysis suggests complementary analyses for “hot-spot” issues that are particularly important for sustainable development. In SLCA, the sustainable impacts and contributions are identified within each life-cycle phase (e.g., raw material, production, packaging & distribution, use, and end of life), as exemplified in Figure 3. In this study, the SLCA will be used to compare cars and their energy carriers.
2.4 Descriptive Study I: Life-cycle assessment (LCA)

Life-cycle assessment (LCA) (ISO, 2006) is used as a further assessment for “hot-spots” identified by the SLCA (section 2.3) for the negative environmental consequences on society of different energy carriers for cars and their business model(s) during their lifetime.

<table>
<thead>
<tr>
<th>GHG emission compound</th>
<th>GWP effect or GWP 100-year factor (CO₂ e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>1</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>23</td>
</tr>
<tr>
<td>Nitrous Oxide (N₂O)</td>
<td>296</td>
</tr>
</tbody>
</table>

Table 1. Characterization factor (IPCC 2001) (Borjesson et al., 2010).

The environmental impact in the study is quantified by calculating emissions from the category of the global warming potential (GWP) indicator in gram CO₂ equivalent per kilometer (g CO₂ eq/km), including carbon dioxide (CO₂), nitrous oxide (N₂O), and methane (CH₄) (Table 1). Methane (CH₄), for example, contributes 23 times more to global warming than carbon dioxide (CO₂). For the LCA (g CO₂ e/km) of conventional/fossil-fueled cars, car manufacture, use, and end of life are included. In response to this, LCA approaches take this “well to wheel” efficiencies consideration of new vehicles in 2013 with 2.7% energy efficiency for the years 2005-2030 (The International Energy Agency IEA, 2012b). In this study, energy efficiency has also been incorporated in the GWP calculation for Car Pooling and Car Leasing. Moreover, the LCA for PHEV and BEV are included in car manufacture, battery manufacture, use, battery disposal, and end of life.
GWP indicator result (g CO₂ e/km/person)  
= Emission (g/km) * GWP effect (CO₂ e) * km/year  

2.5 Descriptive Study I: Life-cycle costing (LCC) through Total Cost of Ownership (TCO)

Life-cycle costing (LCC) has been adopted from the ISO 15686-5 standard on service life planning in buildings and constructed assets (The International Standard Organization ISO, 2008). Many other fields have worked with LCC since then (The Green Icon, 2010; The International Electrotechnical Commission, 2004). A related and sometimes synonymous term is TCO (Leland and Tarquin, 2012; The Green Icon, 2010).

An important concept in LCC is the Depreciation value. This captures the loss of value of a car over a certain period, and it is not known to a firm or employee before the car has actually been sold (The European Union, 2010). A general rule of thumb in the Swedish car market is a depreciation rate of 50% over 3 years of ownership, with a 10% annual depreciation rate in subsequent years (Hagman et al., 2014). Similar studies have been noted by Hagman, Ritzen, & Stier, 2014, due to uncertainties in calculating depreciation value estimations for BEV’s Swedish market (for example, uncertainties of the limited local history depreciation data, local market differences, uncertainty regarding the future development of price, performance, and battery lifespan). Therefore, the authors will assume a conservative depreciation rate of 40% for 3 years, within the range suggested by Hagman, Ritzen, & Stier, 2014 and Lööf et al., 2013 when the green car bonus has been included. The depreciation rate is not easy to calculate because it is affected by many conditions, such as kilometer mileage, and it varies greatly between different car models. The cars that are more fuel-efficient tend to depreciate more slowly because of the increased interest in cars that are cheaper to run. Likewise, older versions of cars may depreciate more slowly than new upcoming versions of cars (Leaseurope, 2014). The residual value after nine years for a Regular Purchase car for all types of cars is here assumed to be 10%. The reason is that, by the time a car reaches this age, the aggregated depreciation will have led to an almost complete loss of residual value and after that it decreases more slowly.

In this article, the TCO (Cost per Kilometer) uses the Swedish Kronor as the currency (Swedish Kronor per Kilometer (SEK/km)), with an exchange rate of Euro = 9,28 SEK (as of 25 November 2015). The TCO of Conventional cars listed below includes the initial purchasing cost, operational costs, emission costs, and end of life with the assumption of a 5% depreciation value accounted for biogas cars, ethanol cars, and gasoline cars, where n = the average value over the years 2014-2022 (nine operational years) with 15,000 km/ year. IC is Investment Cost, EC is Energy Cost, MC is Maintenance Cost, SC is Service Cost, EMC is Emission Cost, *CT is Car Tax
The money has an interest rate and determined as usually less than or equal to Future Worth (FW) because the money has an interest rate and is indicated as the discount value of money in the future. It is used here as a present discounted value (Net Present Value/NPV) in SEK/km/person, where the future value of money has been discounted (Leland and Tarquin, 2012). The life-cycle cost or TCO can be written in the form of an NPV, where NPV = net present value for 2014, FV= future value from 2015-2022, r = real interest rate of 1% [where i = year (1 ≤ i ≤ 9) years], and an operational range of 9 years.

**NPV of TCO, Conventional car**

\[
\text{NPV} = \frac{\sum_{i=1}^{n} IC + EC + MC + SC + EMC + CT}{\sum_{i=1}^{n} (LD + OY)}
\]

In this study, TCO is calculated by the NPV method that includes costs for investment, energy, maintenance, and service. The economic value of a car’s investment is determined, where the real interest rate is calculated as 1%; 6.25% is calculated for an annual increase of average energy price development over the last 10 years, and 6.28% is calculated for an annual increase of average electricity price development in the last 10 years.
NPV of TCO, PHEV & BEV

\[
NPV = \sum_{t=1}^{n} \frac{IC + EC + MC + SC}{(1 + r)^t} - \sum_{t=1}^{n} \frac{LD + OY}{(1 + r)^t}
\]

2.6 Descriptive Study I: Selection of case study companies and expert interviews

2.6.1 Case companies for Car Pooling and Car Leasing

Sunfleet\(^3\) started in the late 1990s as a development partnership between Volvo and Hertz. They saw that there was a gap to fill between permanent car ownership and car rental. The solution that they sought was a future-oriented and climate-positive solution for people's transport needs. They began with the traditional collective-owned car pools and developed an entirely new approach with a focus on flexibility and service (Ronzani 2014). They quickly became one of the first companies that could offer a climate-smart, simple, and sustainable alternative for people who do not want to own a car but still want access to a car for longer trips. Today, they are a fast-growing, independent service company, with Volvo as majority owner, and they operated within 37 cities in 2014. Sunfleet’s customers are, to a large degree, companies (50%), and they have 37000 individual users in their carpools. Their vision is to change the Swedish perspective on using and owning a car.

Miljöfordon Syd\(^4\) is an economic association in the south of Sweden and was formally started in 2002 by a few enthusiasts who were interested in reducing cars’ impacts on the environment. Members represent different stakeholders, such as car dealers, car rentals, car maintenance, fuel distribution, and sales operators, municipalities, counties, the Energy Agency for Southeast Sweden, and also individuals interested in cars and environmental issues. This

has led to concrete projects that are pushing the development of more environmentally friendly transport collaborations with GreenCharge, including the vehicle energy declarations that have been done since 2011, which is an analysis for vehicles to show energy-related costs and environmental impact (Lööf et al., 2013).

\(^4\) Miljöfordon Syd http://miljofordonsyd.se/om/[Accessed by 10 December 2014].
Move About\textsuperscript{5} is a company that has been developing customer-based products and services that combine Car Pooling and electric cars since 2008. They have developed a complete system of electric carpools for businesses and municipalities addressing the need for public electric car pools. Move About has more than 100 electric cars in operation in Sweden, Norway, Denmark, and Germany, with a special tailor-made booking system that plans the use of electric cars very efficiently as a means of reducing costs. They aim to contribute to sustainable transport by moving towards multimodality transport for different transport modes, which combines public transport with electric Car Pooling.

3 Results

3.1 Descriptive Study I: Applying Business Model Canvas (BMC) for current business models

The mapping of business models for Regular Purchasing, Car Pooling, Car Leasing, and Taxiing (Figure 4) was conducted by the authors through the Business Model Canvas—BMC (Osterwalder and Pigneur, 2009), and it is nine building blocks represented by a visual chart with elements describing its value proposition, infrastructure, customers, and finances. This was adapted from examples for typical Regular Purchasing or owning a car (as a customer buying the car from a car dealer). Data were gathered from a typical Car Pooling company (Sunfleet), from a Car Leasing expert (Miljöfordon Syd), and from a typical Taxi company (Taxikurir\textsuperscript{6}).

The value propositions for Car Pooling, Car Leasing, and Taxiing are increasing the cost competitiveness, the vehicle’s accessibility, and the service to the users, while not including the necessity of owning a car or maintaining it regularly. Taxiing also includes drivers as a service. Alternately, Regular Purchasing includes ownership and its benefits of constant access, control, etc.; however, it requires a high initial investment cost and regular maintenance with the costs that that entails. Here are the similarities and differences for Regular Purchasing, Carpooling, Car Leasing, and Taxiing that are found within BMC:

- The similarities are from their key partners and customer segments that are involved in business models, including car manufacturers, car dealers, insurance companies, service maintenance companies, and end customers, including business markets.

\textsuperscript{5} Moveabout http://www.moveabout.se [Accessed by 10 December 2014].

\textsuperscript{6} Taxikurir http://www.taxikurir.se [Accessed by 15 December 2014].
The differences that are shown in the BMC for their key activities, value propositions, customer relationships, customer segments, cost structure, and revenue streams depend on their product offerings (purchase a car or cars) and the services they offer (leasing or sharing the car or cars or riding in a taxi).

Figure 4. Applying current car business models (Regular Purchasing in yellow, Car Pooling in pink, Car Leasing in orange, and Taxiing in blue) within BMC.

3.2 Descriptive Study I: Strategic Life-cycle assessment (SLCA) for Regular Purchasing vs. Car Leasing vs. Car Pooling vs. Taxiing

The SLCA conducted in this study focuses on the life-cycles (including raw material extraction, production, transport, use, and waste management phases) of different cars and their business models. It shows similar results among current business models for fossil-fueled cars, so only the obvious differences are shown in Figure 5. Common negative contributions (red box) from all categories to SP1 (Sustainable Principle 1) are due to usage of fossil fuels (creates emissions such as CO₂, SOₓ, PM) and heavy metals in the extraction and production processes. For SP2, in the extraction and production phases, NOₓ emissions from combustion processes, POPs (Persistent Organic Pollutants) and Dioxins are released to the biosphere in all categories. Common
negative contribution to SP3 in the extraction phase is due to open pit mining for fossil oil, metals and other resources. Moreover, the use of scarce resources (Platinum in catalytic converters used in ICEVs and Lithium in batteries for BEVs) and open pit mining (causing negative health effects and forces people to move) give common negative contribution in the extraction phase to SP4. The following additional contributions to these mentioned above are shown in figure 5:

• Gasoline cars additionally contribute negatively to SP1 due to oil spills in the extraction phase and emissions from flaring in the extraction and production phase. Emissions from combustion of gasoline in the use phase negatively contribute to SP1, 2, and SP4 due to negative health effects.

• The main reason for the differences between electric cars for the various business models is that Car Pooling uses approximately five fewer cars than Regular Purchasing and Car Leasing.

• The negative contribution from electric cars is caused by the use of scarce materials in lithium batteries (SP4) and by charging from an electricity grid that is connected to the European electricity grid, which emits high levels of CO₂ from non-renewable generated electricity (SP1). Alternately, there would be no negative contribution (green box) if new wind electricity would be used as power for electric cars. Electric cars' negative impact on SP1 is also caused by extensive use of energy that emits high levels of CO₂ during the production of numerous battery cells, compared with fossil-fueled cars with a small battery for auxiliary systems only.

• There is a contribution to social sustainability (SP4) for the ethanol, biogas, and electric alternatives in the first life-cycle phases, as they are contributing to local jobs.

• The electric and hybrid alternatives contribute to meeting SP4, as they reduce the total noise level in especially dense city traffic.
The basic Global Warming Potential (GWP) comparison (g CO\textsubscript{2} e/km/ person) of different business models for Regular Purchasing, Car Pooling, and Car Leasing are used for further CO\textsubscript{2} emission calculation (Figure 6). This is to show the comparison based on kilometers, without further assessing the different people who might drive different distances per year. The following assumptions are used in this study for the CO\textsubscript{2} calculation:

- **Regular Purchasing** of a used car is nine years (15000 km/year). Average car mileage in the use phase is 15000 km/year (Hagberg 2014). Five individuals use five new cars.

### 3.3 Descriptive Study I: Data for TCO and CO\textsubscript{2} emissions

#### 3.3.1 The CO\textsubscript{2} assumption of Regular Purchasing of a car, Car Pooling, and Car Leasing

![Image of Table and Figure 5: SLCA for various cars (cars and fuels) with various business models (Regular Purchasing, Car Pooling, Car Leasing, Taxiing).]
• **Car Leasing** is used for three years, meaning the car is changed every three years (after years 0-3, years 3-6, and years 6-9). Five individuals use five new cars.

• **Car Pooling** for a car that uses 3500 km per person/year (17500 km/year/car), while the company changes its car every 18 months.

The service life of cars in the 2000s ranges between 150,000 and 200,000 miles (Baptista et al., 2014). Compared with Regular Purchasing, Car Pooling replaces four to eight vehicles in Europe (Koch, 2005; The state of European Car-Sharing, 2010).

This study assumes that five individuals use one car, even though it is assumed that the transport mileage from Car Pooling is reduced, as it is distributed to other modes of transport. However, in this study, the other transport modes’ mileages are not included. The authors’ assumption for **service life** of the car is 9 years, where it is 135,000 km (9 years x 15000 km) for a car in this study. The reason for this is to set the boundary of nine years of service life for Regular Purchasing, as it reaches the aging car, expensive to fix, not to own/switch car so many times. It would be compared with three of the three-year Car Leasing periods.

<table>
<thead>
<tr>
<th>Business models</th>
<th>Regular Purchase / Owning a car</th>
<th>Car Pooling</th>
<th>Car Leasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life cycle</td>
<td>15000 km / year /person</td>
<td>3500 km / year /person</td>
<td>17500 km / year /car</td>
</tr>
<tr>
<td>Manufacture</td>
<td>5X CO2</td>
<td>X CO2</td>
<td>5X CO2</td>
</tr>
<tr>
<td>Use</td>
<td>0-9 years</td>
<td>5Y CO2</td>
<td>5Y CO2</td>
</tr>
<tr>
<td></td>
<td>Use the same car from year 0 to year 9</td>
<td>5.16 Y CO2</td>
<td>5Y CO2</td>
</tr>
<tr>
<td>End of life</td>
<td>5Z CO2</td>
<td>Z CO2</td>
<td>5 Z CO2</td>
</tr>
</tbody>
</table>

Assumptions for calculating CO2 emissions:
- Regular purchase is using 1 car for 1 person = 15000 km/year /person
- Car Pooling is using 1 car for 5 persons = 3500 km/year x 5 person = 17500 km/year/car
- Car Leasing is using 1 car for 1 person = 15000 km/year/person
- Taxi is assumed 17500 km/year/car

Figure 6. How the business model Car Pooling uses less cars and causes less CO₂ than Regular Purchasing and Car Leasing.

### 3.3.2 Source of electricity

The electricity sources for powering BEV and PHEV in this study are based on two alternatives that EV users most likely will charge their vehicle with:
1. The European electricity grid mix EU 27 generated 357 grams CO$_2$ equivalent per Kilowatt-hour (g CO$_2$ e per kWh) electricity in 2012. CO$_2$ emissions from fossil fuels consumed for electricity generation, in both electricity-only and combined heat and power plants, divided by the output of electricity generated from fossil fuels, nuclear, hydro (excl. pumped storage), geothermal, solar, wind, tide, wave, ocean, and biofuels (The International Energy Agency IEA, 2012c).

2. According to the US National Renewable Energy Laboratory (NREL), wind electricity generates, on average, 12 g CO$_2$ eq per kWh. In another study, wind electricity emits 11 g CO$_2$ eq per kWh, which causes BEV to emit 1-2 CO$_2$ e/km (Nordelöf et al., 2013).

### 3.3.3 Car comparison with its related costs

There are many different cars available in different markets using biogas, ethanol, gasoline, plug-in, or battery technologies in the driveline. Examples of common vehicles in comparable sizes in each of the above-mentioned groups are compared in Table 2 and used throughout this study.

**Table 2. A comparison of prices and energy use for biogas, ethanol, gasoline, plug-in hybrid, and battery electric cars.**

<table>
<thead>
<tr>
<th>Car type</th>
<th>Car Name</th>
<th>Picture</th>
<th>Purchasing cost 2014 (SEK)</th>
<th>Bonus</th>
<th>Energy use</th>
<th>Energy cost (SEK/km) 2014</th>
<th>Maintenance and service cost (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas</td>
<td>Fiat Punto</td>
<td><img src="image" alt=" Fiat Punto Picture" /></td>
<td>170 000</td>
<td>No</td>
<td>0.6 Nm³/10 km</td>
<td>0.66</td>
<td>4800</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Volkswagen Golf TSI Multifuel BMT</td>
<td><img src="image" alt=" Volkswagen Golf TSI Multifuel BMT Picture" /></td>
<td>180 000</td>
<td>No</td>
<td>0.72 litre/10 km</td>
<td>0.72</td>
<td>4800</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Any kind of cars (similar cost and size)</td>
<td><img src="image" alt=" Any kind of cars Picture" /></td>
<td>150 000</td>
<td>No</td>
<td>0.6 litre/10 km</td>
<td>0.74</td>
<td>4800</td>
</tr>
<tr>
<td>Plug in hybrid (PHEV)</td>
<td>Prius plug in hybrid ZVW35</td>
<td><img src="image" alt=" Prius plug in hybrid ZVW35 Picture" /></td>
<td>360 000</td>
<td>40 000</td>
<td>0.25 litre / 10 km &amp; 0.77 kWh / 10 km</td>
<td>0.37</td>
<td>4800</td>
</tr>
<tr>
<td>Battery Electric (BEV)</td>
<td>Nissan Leaf</td>
<td><img src="image" alt=" Nissan Leaf Picture" /></td>
<td>340 000</td>
<td>40 000</td>
<td>1.6 kWh/km</td>
<td>0.13</td>
<td>3360</td>
</tr>
</tbody>
</table>

Data from (Gröna Bilister-The Green Motorist, 2014) and Miljöfordon Syd in Sweden (2014). Average energy cost (SEK/km) exclude VAT (OKQ8, 2013; Pool, 2012; The Swedish Petroleum Biofuel Institute, 2013).  

SEK = Swedish Kronor; SEK/km = Swedish Kronor per kilometer; SEK/year = Swedish Kronor per year; liter/km = liter per kilometer; Nm³/km = Normal cubic meter/kilometer; kWh/km = Kilowatt-hour/kilometer.
3.4 Descriptive Study I: LCA and LCC assumptions and results

The comparison parameters of the study include TCO and CO₂ emissions as shown below in Table 3. The results suggest that the priority shifts from a gasoline-powered Regular Purchasing car to an electric Car Pooling car from today, especially when the rising fuel prices come into play. The new suggested approach in this study is expected to help move towards a strategic sustainability perspective. This is indicated in the authors’ following findings regarding life-cycle emissions and the total cost of ownership in this study:

Regular Purchasing car:

- Compared with the other cars in this study, a gasoline car causes the most emissions from the manufacturing and use phases of the life-cycle.
- An ethanol car would reduce CO₂ emissions by 50% compared with a gasoline car if they generate the same amount of emissions during the manufacturing phase. This is because the use of ethanol reduces CO₂ emissions by 80% compared with Regular Purchasing of a gasoline car (Lööf et al., 2013).
- Alternately, assuming a biogas car generates the same emissions as a gasoline car in the manufacturing phase, it can generate a negative 110% CO₂ emissions reduction in the usage phase. This is because a biogas car reduces emissions by 80% compared with the Regular Purchase of a gasoline car (Lööf et al., 2013).
- Assuming the Regular Purchase of a BEV or PHEV uses EU-27 electricity mixes, they generate no CO₂ emissions reduction in their battery manufacture and usage. This results in 50-60% less CO₂ emissions, equivalent to a Regular Purchase gasoline car (Lööf et al., 2013).
- However, if the Regular Purchase of a BEV or PHEV is powered by renewable energy, e.g., wind power, this would result in an 80-90% reduction of CO₂ equivalents over the entire life-cycle compared with other Regular Purchases of fossil fuel cars. The least socio-ecological impacts come from the Regular Purchase of a BEV or a PHEV.
- As described in the TCO comparison of the Regular Purchase cars based on nine years of ownership (Figure 7), there is already an economic advantage to choosing a Regular Purchase car that uses biogas, ethanol, or electricity. A Plug-in Hybrid car has the highest TCO among the cars compared because it uses a small amount of gasoline and has a higher initial investment cost. The TCO of a biogas or ethanol car is 12-15% lower than a gasoline car, while a BEV car has a 10-14% lower TCO, and a PHEV car has a 5% higher TCO than a gasoline car.
Car Pooling:

- If more kilometers per year are driven because more people are Car Pooling (17500 km/year for five persons) compared with the Regular Purchase of a car (15000 km/year per person), then slightly more CO$_2$ emissions are generated in the use phase.
- However, there are five persons per one Carpool, so the resulting CO$_2$ equivalent per person in a Carpool would, in the manufacturing and waste management phases, be one fifth (1/5) of what it is for a Regular Purchase.
- **Gasoline** Car Pooling reduces emissions by 20% compared with a gasoline Regular Purchase.
- **Ethanol or biogas** Car Pooling reduces emissions by 30-40% (g CO$_2$ e/km/person) compared with their Regular Purchase cars. This is because Car Pooling companies exchange their cars for more energy-efficient cars every one or two years and sell the old models on the secondhand market. Thus, equal emissions distribution per user is generated, also making people drive 30% less (Trafikverket-Swedish Traffic Authority, 2012).
- **PHEV and BEV powered by EU-27 mixes** in Car Pooling reduce emissions by 50-70% when compared with business models of the Car Leasing and Regular Purchase cars of all car types. The concept of BEV and PHEV in Carpools is most beneficial in towns where it is easy to access public charging systems, especially when people need to travel short distances (3500 km/year) but do not want to own a car.
- **BEV and PHEV Car Pooling powered by wind power** has the lowest socio-ecological impact, with an almost 80% reduction compared with BEV and PHEV powered by EU-27 electricity mixes as mentioned in section 3.3.2. The challenge of this Car Pooling business model is to make people drive more (the more kilometers, the cheaper it is per km).
- The **cost of Car Pooling** is 20-40% higher than a Regular Purchase; however, the users do not need to worry about the maintenance of the cars, as it is taken care of by the Car Pooling companies (Appendix B3). Moreover, the cost of electric Car Pooling by Sunfleet is the same as for other cars to encourage people to use more electric cars in Car Pooling (Ronzani 2014).

Car Leasing:

- Car Leasing could be another alternative if it is really necessary to use the car for a longer term. Users do not pay for the full value of the vehicle, but only for the time they actually use it. There is no difference in CO$_2$ emissions between Biogas, Ethanol, Gasoline, BEV, and PHEV in Car Leasing compared with Regular Purchase cars when the users travel the same number of kilometers (15000 km/year) (Lööf 2014).
• Car Leasing has the lowest socio-ecological impact when using **BEV and PHEV** with wind power.

• **The cost of Car Leasing** is 20-40% higher than Regular Purchasing; nevertheless, the users do not need to spend extra money for the maintenance cost of the cars, as it is often included in the monthly payment for leasing (Appendix B4).

Taxiing:

• Assuming that a taxi drives 3500 km/year, the CO₂ emissions are equivalent to Car Pooling for the same distance.

• Taxiing for a normal range is assumed to have a similar cost regardless of its energy carrier (Biogas, Ethanol, Gasoline, Plug-in Hybrid, and Electric).

• Taxiing has a fixed starting fee, and the price then increases per kilometer. The price also depends on the time of the day and whether it is a weekday or weekend. A taxi trip is also charged per minute, making it relatively more expensive for congested short-distance trips and trips where the approach charge is relatively high. This might differ substantially for different cities, taxi companies, etc. Taxi companies charge different prices for their services (Appendix B5).
Table 3. How sustainability effects (CO₂ emissions) and TCO are mostly reduced when moving from Regular Purchasing, Car Leasing, Car Pooling, to Taxiing—especially for electric vehicles.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Sustainability (Kg CO₂ e/yr)</th>
<th>Use</th>
<th>Battery disposal</th>
<th>Life cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular Purchase</td>
<td>Car Pooling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ethanol car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug-in Hybrid car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric car</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the following: Studies from Gröna Bilister (Gröna Bilister-The Green Motorist, 2014), Sunfleet’s sustainability report in Sweden (2014), (Faria et al., 2012; 2013; Toyota Motor CorporationMizuho Information Research Institute, Inc, 2004).

Kg CO₂ e/year = Kilogram CO₂ equivalent per year; Km/ year = Kilometers per year; SEK/year = Swedish Kronor per year.

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3.5 Descriptive Study I: LCC for zooming into the details of the Regular Purchase of a car

According to section 2.5, this study calculates the TCO by using the NPV method for the Regular Purchase of a car driving 15000 km per year (within nine operational years), including a real interest rate of 1% where 6.25% is calculated for annual increases of average energy development, 6.28% is calculated for the annual increase of electricity prices, and investment costs are assumed to be constant over time (OKQ8, 2013; Pool, 2012; The Swedish Petroleum Biofuel Institute, 2013).

The result in Figure 7 reveals that gasoline cars have much lower investment costs but incur much higher energy costs compared with BEV or PHEV cars. The highest initial investment cost in the year 2014 was for the purchase of a Plug-in Hybrid (320 KSEK), and the lowest was for a diesel or gasoline car (150 KSEK). Traditional economic calculations seem to suggest that it is beneficial to purchase a gasoline car as a short-term investment. Still, the energy use is relatively high for conventional fossil-fueled cars (0.53-0.8 liters per km or 5.3-8 kWh per km) and relatively low for electric cars (1.6 kWh per km). Moreover, the gasoline car generates the most external environmental costs because of air, land, and sea pollution and is not desirable from a life-cycle cost perspective (Nurhadi et al., 2014; The International Energy Agency IEA, 2012b; Toyota Motor CorporationMizuho Information Research Institute, Inc, 2004). The emission costs are calculated with ASEK model (Bångman, 2014) (Figure 7), which is not calculated as the total emission costs.

![Figure 7. Zooming into the TCO breakdown of the Regular Purchase of a car (15000 km/year within nine years) depending on the energy carrier type.](image-url)
3.6 Descriptive Study I: The summary of cost differences from its business models and km travel

The results shown in Figure 8 reveal that an electric car for Car Pooling and an electric car for Car Leasing could be TCO competitive, compared with the Regular Purchase of an electric car. The Car Pooling TCO is different and depends on the membership conditions, kilometer price (on average, 3.30 SEK/km), and the time used (Sunfleet 2014). The TCO for Taxiing ranges from 7,5-11,90 SEK/km, depending on the usage during weekdays or weekends and the time of use, which is not included in the starter fee of 38-45 SEK (different cities in Sweden have different starter fees). Car Leasing depends on the type of car, kilometers driven, and number of months leased. It costs from 2.5-8 SEK/km without fuel (Autolease 2014). The input data for TCO calculation can be seen further in Appendix B.

The results indicate that people who drive less than 2000 km per year should, from a TCO perspective, primarily consider using a Taxi, while those who travel from 2000 to 8500 km should find Car Pooling most favorable. People who drive from 8500 to 13500 km per year should choose Car Leasing, and those who travel even longer distances should consider Regular Purchasing.

4 Concluding discussion

This article aims to discuss the development and testing of a new approach to compare the sustainability performance and costs of various business models (Regular Purchasing, Car Pooling, Car Leasing, and Taxiing) applied to cars with different energy carriers (Biogas, Ethanol, Gasoline, Plug-in Hybrid, and Electric). First of all, a
Strategic life-cycle assessment (SLCA) helped to compare the overarching social and ecological sustainability impacts of the alternative cars and business models. Then, an LCC and LCA were conducted, with the main comparison parameters of Total Cost of Ownership and CO\textsubscript{2} emissions, respectively. This article is also a contribution to the current reality assessment of the GreenCharge project’s roadmap for how electric vehicles could contribute to Southeast Swedish fossil fuel independence in the transport sector by 2030.

The newly suggested approach in this study is expected to help in moving towards a strategic sustainability perspective that includes economic and environmental issues—both now and in the future. The results of the study can be concluded as:

- Some key overview results from the SLCA were the identification of negative contributions to SP1 from CO\textsubscript{2} emissions – both from an electricity mix with a significant share of European fossil sources, and from the production of the batteries. A positive contribution to social sustainability was the added contribution to local jobs from the initiated replacement of fossil cars with ethanol, biogas and electric alternatives.
- According to the LCA, the least ecological impact came from a Regular Purchase BEV car powered with renewable energy, which results in 90% CO\textsubscript{2} equivalent reduction, while a PHEV generates 80% CO\textsubscript{2} equivalent reduction, biogas generates 80% CO\textsubscript{2} equivalent reduction, and ethanol generates 50% reduction of CO\textsubscript{2} equivalent over the life-cycle compared with small gasoline cars. Gasoline outputs the most emissions from its manufacturing and usage life-cycle phases.
- The TCO within nine years for the Regular Purchase of biogas and ethanol cars is 12-15% lower than for a gasoline car, while it is 10-14% lower for a BEV car and 5% higher for a PHEV car than for gasoline cars today.
- Car Pooling could be an alternative when driving short distances because it reduces emissions by 20-40% (g CO\textsubscript{2} e/km/person) compared with Regular Purchase cars.
- Car Pooling with electric cars and wind electricity generates the least socio-ecological impacts compared with Car Leasing and Regular Purchase cars, regardless of energy carrier. Meanwhile, BEV and PHEV Car Pooling powered by wind electricity have the lowest socio-ecological impacts compared with BEV and PHEV powered by EU-27 electricity mixes. Moreover, to encourage people to use more electric cars instead of gasoline cars, Sunfleet has set the price of electric Car Pooling to the same level as for other cars (Ronzani 2014).
- There is no difference in CO\textsubscript{2} emissions for Car Leasing compared with Regular Purchase cars when the users drive the same number of kilometers for both business models.
- When driving 15000 km per year, the cost of Car Pooling and Car Leasing is 20-40% higher than for Regular Purchasing; nevertheless, the users do not need to spend extra money for maintenance costs of the cars, as it is often included in the payment.
From a TCO effectiveness perspective, people who drive less than 2000 km per year should consider using a Taxi, while Car Pooling is more TCO-effective for those who drive from 2000 to 8500 km. Those who travel between 8500 and 13500 km should consider Car Leasing, and those who drive more than 13500 km per year should opt for Regular Purchasing. If most car owners would accept these changes, necessary transportation would be ensured while the number of cars needed for such transportation would be significantly reduced. Likewise, users’ consideration of their kilometer travel distance could influence them to choose the correct business models for themselves, including other complementary means of transport, such as public transport, biking, and walking. In the long term, this could also reduce the numbers of cars owned, indirectly causing, for example, a lower demand for supporting infrastructure.

Some shortcomings of this study are that the numbers from various cars are not consistently comparable (e.g., prices may vary between manufacturers of similar cars, prices may vary between dealerships of similar cars, and the price may vary between countries for similar cars). Additionally, the study can consider possible weaknesses in the current TCO calculations related to the assumptions that have been made. However, the authors believe the prices are representative enough for this overview study and give a reasonable indication of the most likely TCO and CO₂ equivalent per km driven. Similar numbers are consistently identified from several reliable key resources.

The validity of the approach used in this study is strengthened by another tandem publication for multi-stakeholder creation of a vision and development steps for sustainable electric vehicle systems (Borén et al., 2016b; Robért et al., 2016). That publication also uses the FSSD approach and suggests that the sustainable development of the traffic sector relies on the interaction between actors who have key roles within the transport sector and also that those who interplay within four essential transport planning perspectives (resource base, spatial, technical, and governance perspectives) should move towards the vision of sustainable transport solutions. The idea of comparing various business models for the same type of vehicle has also been tried elsewhere. A study called BeliEVe (Business model innovation for electric vehicles), by the Swedish ICT Viktoria (Willander and Stålstad, 2013), found that business models in the car industry have started to move beyond physical products to also include complementary bundled services. Similarly, Move About’s current business model focuses on exploring the electric Car Pooling market as their market niche. They believe that electric cars powered by electricity from renewable energy sources (e.g., wind and solar power) have the potential to become an important part of sustainable transport solutions and will therefore become cheaper to use than electricity from fossil energy sources. Moreover, the overall system perspective taken by this study when comparing car types is supported by the ELMOB project in Gothenburg in Sweden, which found that transport solutions are likely to go towards multi-modality. Their
planning for multimodal transportation includes not only cars but also electric bike sharing, electric Taxis, electric cars, one-way trips, etc. by using a "one-card-for-all" system and can be accessed from train stations as the main node.

In conclusion, the new comparison approach suggested in this study is expected to create high value for users when they will be able to choose the most suitable business model for themselves while fostering an effective transition towards sustainable transportation. This study also concludes that the TCO most likely contributes to giving useful information to assess the direct and indirect costs associated with the purchase of different cars for potential customers, rather than only looking into high initial purchasing costs. The implication is that this information could stimulate the sales of low emission cars and a switch to business models other than owning a car. Moreover, this could encourage common people to make wiser choices for their transportation solutions as an essential means to increase the share of more sustainable transport.

In future work, the authors plan to conduct a follow-up study regarding the sensitivity analysis in which we consider different years or different distances (e.g., 3, 6, 9, 12 years) from this current paper. In the future, work will also be an investigation of the sustainability effects of new combinations of business models and bundled offers (all in 1), to which the following DRM steps (Figure 1) can be added:

- Prescriptive Study I (PS I): use Blue Ocean Strategy and BMC to create a potential new combination of business models for electric car systems.
- Descriptive Study II (DS II): obtain feedback, verified with verbal communication, from experts in interviews.

Early stakeholder feedback on these continued plans has been positive (Ronzani 2014). In fact, Sunfleet already successfully offers a bundled offer for the semi-open hybrid car pool to the municipality of Trelleborg in Sweden, including maintenance and service. The authors also find it important that a similar study is done within business models for charging infrastructure.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BEV</td>
<td>Battery electric Vehicle</td>
</tr>
<tr>
<td>BMC</td>
<td>Business model canvas</td>
</tr>
<tr>
<td>DRM</td>
<td>Design research methodology</td>
</tr>
<tr>
<td>EV</td>
<td>Electric vehicle</td>
</tr>
<tr>
<td>FSSD</td>
<td>Framework for strategic sustainable development</td>
</tr>
<tr>
<td>LCC</td>
<td>Life cycle costing</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>SO₂</td>
<td>Sulphur Oxide</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>4 SP</td>
<td>Four sustainable</td>
</tr>
<tr>
<td>RC</td>
<td>Principles</td>
</tr>
<tr>
<td>DS I</td>
<td>Research Clarification</td>
</tr>
<tr>
<td>PS I</td>
<td>Descriptive study I</td>
</tr>
<tr>
<td>TCO</td>
<td>Total cost of ownership</td>
</tr>
<tr>
<td>PSS</td>
<td>Product service system</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid Vehicle</td>
</tr>
<tr>
<td>NOₓ</td>
<td>Nitrogen Oxide</td>
</tr>
</tbody>
</table>

Acknowledgement

The authors would like to express gratitude to Daniel Hagberg, Jonas Lööf, and Stefan Nilson from Miljöfordon Syd, Alexandra Ronzani from Sunfleet, Ulf Jakobsson from Move About, and Jens Hagman from Royal Institute of Technology (KTH) for their invaluable insights and feedback. Financial support from those involved in the GreenCharge project, including municipalities, counties, county councils, regions, companies, and the Swedish Energy Agency, are gratefully acknowledged.

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Appendix A. Interview questions at the inventory stage

A.1 Main interview questions:
Q1: What are your overarching business models to stand out from your competitors, and how do you involve different?
   a. Organizational levels (top management, middle management, and operational levels)?
   b. Time perspectives (short- and long-term)?
   c. Cost and investment perspectives?
Q2: How does the above-mentioned business model address sustainability problems?
Q3: If you wish, how can your company business model be improved?
Q4: How can your suggestion be transferred to top management?
Q5: What is your company’s definition of a sustainable society?
Q6: What are your main company challenges in relation to that definition?
Q7: How is your company doing at a strategic level to handle these challenges?

New proposed business model:
Q12: How do you think the new proposed business model (all in 1) would work in your company?
Q13: How are you going to implement it?
Q14: Do you intend to move towards intermodal transport? If so, what is your plan?

Appendix B. Input data costs for different business models

B1. An example of a new regular purchasing car (in Swedish Kronor or SEK).

<table>
<thead>
<tr>
<th>Regular Purchase Car</th>
<th>Biogas</th>
<th>Ethanol</th>
<th>Gasoline</th>
<th>PHEV</th>
<th>EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost incl. depreciation (incl. after 40000 SEK for PHEV and EV)</td>
<td>153 000</td>
<td>162 000</td>
<td>135 000</td>
<td>304 000</td>
<td>285000</td>
</tr>
<tr>
<td>Fuel/Electricity (excl. VAT)</td>
<td>11 842</td>
<td>13 030</td>
<td>11 388</td>
<td>6 691</td>
<td>2 303</td>
</tr>
<tr>
<td>Service, repair (per year)</td>
<td>8 400</td>
<td>8 400</td>
<td>8 400</td>
<td>8 400</td>
<td>7 500</td>
</tr>
<tr>
<td>Maintenance (per year)</td>
<td>2 000</td>
<td>2 000</td>
<td>2 000</td>
<td>2 000</td>
<td>1 500</td>
</tr>
<tr>
<td>Garage</td>
<td>3 600</td>
<td>3 600</td>
<td>3 600</td>
<td>3 600</td>
<td>3 600</td>
</tr>
<tr>
<td>Insurance, tax, inspection</td>
<td>7 400</td>
<td>7 400</td>
<td>7 400</td>
<td>7 400</td>
<td>7 400</td>
</tr>
<tr>
<td>Total SEK/year (NPV of 9 years incl. depreciation)</td>
<td>37 500</td>
<td>38 550</td>
<td>43 650</td>
<td>45 750</td>
<td>37 300</td>
</tr>
<tr>
<td>Total SEK/month incl. depreciation</td>
<td>3 125</td>
<td>3 212</td>
<td>3 700</td>
<td>3 812</td>
<td>3 100</td>
</tr>
</tbody>
</table>

Recalculated from many resources and Swedbank’s new car calculation, calculated within 15,000 km/year, with a gasoline price of 14,30 SEK/l, owned for 9 years.

<table>
<thead>
<tr>
<th>Any type of car</th>
<th>Membership</th>
<th>Student membership</th>
<th>Pay &amp; Go</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membership fee</td>
<td>395</td>
<td>395</td>
<td>395</td>
</tr>
<tr>
<td>Starter fee</td>
<td>25-40</td>
<td>25-40</td>
<td>25-40</td>
</tr>
<tr>
<td>Monthly fee</td>
<td>149</td>
<td>79</td>
<td>No</td>
</tr>
<tr>
<td>Timeprice (Daytime)</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timeprice (Evening)</td>
<td>29,25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Timeprice (Night time)</td>
<td>11,4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


B3. Car Pooling Move About (in Swedish Kronor or SEK).

<table>
<thead>
<tr>
<th>Electric car</th>
<th>Private person</th>
<th>Companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly fee</td>
<td>124</td>
<td>99</td>
</tr>
<tr>
<td>Timeprice per h (Daytime 6 am-5 pm)</td>
<td>99</td>
<td>99</td>
</tr>
<tr>
<td>Timeprice per h (Evening 5-11 pm)</td>
<td>169</td>
<td>169</td>
</tr>
<tr>
<td>Timeprice per half-day (6 am-5 pm)</td>
<td>324</td>
<td>259</td>
</tr>
<tr>
<td>Timeprice per one-full day (6 am-11 pm)</td>
<td>499</td>
<td>399</td>
</tr>
</tbody>
</table>

Source: [http://www.moveabout.se/Vad-kostar-det](http://www.moveabout.se/Vad-kostar-det)

B4. Car Leasing within 3 years (15,000 km/year) (in Swedish Kronor or SEK)

<table>
<thead>
<tr>
<th></th>
<th>Biogas car</th>
<th>Ethanol car</th>
<th>Gasoline car</th>
<th>PHEV</th>
<th>BEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment cost (purchasing)</td>
<td>170 000</td>
<td>180 000</td>
<td>150 000</td>
<td>320 000</td>
<td>300 000</td>
</tr>
<tr>
<td>Bonus</td>
<td>68 000</td>
<td>72 000</td>
<td>60 000</td>
<td>128 000</td>
<td>120 000</td>
</tr>
<tr>
<td>The depreciation value (40%)</td>
<td>12 300</td>
<td>12 300</td>
<td>12 300</td>
<td>7 560</td>
<td>7 560</td>
</tr>
<tr>
<td>Tax and Service</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of battery rent (3 years)</td>
<td>29 800</td>
<td>32 000</td>
<td>28 000</td>
<td>56 000</td>
<td>69 000 (includes battery)</td>
</tr>
</tbody>
</table>

Source: Recalculated from Miljöfordonsyd 2014

B5. Taxi (in Swedish Kronor or SEK).

<table>
<thead>
<tr>
<th>Taxi breakdown costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base fee (42 SEK) to ride a Taxi</td>
</tr>
<tr>
<td>Cost weekdays, time: 9 am-15 pm: +9,10 SEK/km</td>
</tr>
<tr>
<td>+434 SEK/h</td>
</tr>
</tbody>
</table>

| Cost weekdays, time: 15 pm-9 am: |
| 5 am-9 pm: +11,52 SEK/km |
| +434 SEK/h |

| Average cost, time: 5 am-9 pm: |
| 10,31 SEK/km |

Source: Taxikurir Stockholm
[http://www.taxikurir.se/orterisverige/stockholm/taxikurirstockholm/varapriser.4.7017056e11fcce66e6580002397.html](http://www.taxikurir.se/orterisverige/stockholm/taxikurirstockholm/varapriser.4.7017056e11fcce66e6580002397.html)
ABSTRACT

Between 1950 and 2013 the total amount of Swedish travelling has increased from about 20 billion to about 140 billion passenger kilometers. This included an increase in travelling with private cars from about 3 billion to about 105 billion passenger kilometers, and in bus travelling from about 2.5 billion to about 5 billion passenger kilometers. The European commission has indicated that public transportation (if powered by clean fuels) is a suitable way to reduce environmental and health problems.

This thesis focuses on sustainable personal road transport, and aims to develop and test a new approach to examining the economic and socio-ecological sustainability effects of various road vehicles for private travelling and related business models. A special focus is set on comparing various bus systems for public transport and ways (business models) for private people to access cars. The main comparison parameters are the total cost of ownership and carbon dioxide emissions of different energy carriers for buses and cars. The Design Research Methodology is used to guide the research approach. The approach also builds on the Framework for Strategic Sustainable Development, which includes, for example, principles that define any sustainable future and a strategic planning process. The approach first employs Strategic Life Cycle Assessment to give a quick overview of sustainability challenges in each bus life cycle stage from raw materials to end of life. Several analysis tools such as Life Cycle Costing, Life Cycle Analysis, Product Service System, and Business Model Canvas mapping are then iteratively used to "dig deeper" into identified prioritized challenges. Literature reviews, interviews, and simulations are used as supporting methods.

The results from a first theoretical test of the new approach suggest that a shift from diesel buses to electric buses (powered by renewable energy) could significantly lower carbon dioxide emissions, while also significantly lowering the total cost of ownership. The theoretical calculations were followed up by testing of electric buses in real operation in eight Swedish municipalities. The tests verified the theoretical results, and showed that electric buses are better than diesel buses both from a sustainability point of view and a cost point of view, and also that electric bus operation is a practically viable alternative for public transport. The new approach was tested also by comparing a variety of business models for private car travelling. The results indicate, among other things, that only people who travel more than 13,500 kilometers per year would benefit from owning a car.

In all, the thesis suggests a simultaneous shift from diesel buses to electric buses in public transport and, for the majority of the car drivers that drive less than 13,500 kilometers per year, switching from car ownership to car use services would be favourable for an affordable transition of the transport sector towards sustainability.