Agent-Based Analysis of Market Potential for Electric Vehicles in the Czech Republic

Bachelor thesis

Prague 2017
Author: Renáta Wojnarová
Supervisor: PhDr. Jiří Kukačka, Ph.D.

Academic Year: 2016/2017
Bibliographic note

WOJNAROVÁ, Renáta. *Agent-Based Analysis of Market Potential for Electric Vehicles in the Czech Republic* Prague 2017. 66 pp. Bachelor thesis (Bc.) Charles University, Faculty of Social Sciences, Institute of Economic Studies. Thesis supervisor PhDr. Jiří Kukačka, Ph.D.
Abstract

This study explores the economical, ecological, and social impact of potential rise of the number of electric vehicles in the Czech Republic. For this purpose, the methodology of agent-based modelling and cost-benefit analysis is used. Particularly, a simple agent-based model in the NetLogo software is created and calibrated to the Czech environment. It enables us to examine the impact of possible policies aimed at increasing electric vehicles’ market potential.

Results of the cost-benefit analysis suggest that under the current Czech conditions, over their whole life cycle, electric vehicles produce less CO₂ emissions in comparison to conventional internal combustion engine vehicles and thus, are more ecological. With the actual policy without any financial incentives, however, electric vehicles’ total costs connected to their purchase, usage and maintenance for an average Czech consumer are still higher compared to conventional vehicles. If the government would intend to significantly increase electric vehicles’ market share, both financial incentives and policies making their everyday usage easier are suggested to be implemented. Purchase discounts together with accessibility advantages are, according to this analysis, the most effective ways. Charging infrastructure development and electricity cost reductions are also important but they act more as a psychological tool.

Keywords

electric vehicles, electromobility, czech vehicle market, cost-benefit analysis, scenario analysis, agent-based modelling
Abstrakt


Výsledky cost-benefit analýzy ukazují, že za aktuálních českých podmínek produkují elektrická auta za svůj celý životní cyklus méně emisí CO₂ v porovnání s klasickými auty se spalovacími motory, a jsou tedy i více ekologická. Nicméně, s aktuální politikou bez jakéhokoliv finančních pobídek jsou náklady spojené s koupí, užíváním a údržbou elektrického auta pro průměrného českého spotřebitele vyšší než tytéž náklady na klasické auto. Pokud by česká vláda uvažovala o zřetelném navýšení počtu elektrických aut, je navrhováno zavedení pobídek jak finančních, tak také těch, které zjednodušují jejich každodenní užívání. Dle naší analýzy, nejefektivnější způsob, jak tohoto navýšení dosáhnout, jsou slevy na koupí vozidla a výhody v každodenním provozu. Rozšíření dobíjecí infrastruktury a snížení cen elektriny jsou také důležité, avšak slouží spíše jako psychologický prvek.

Klíčová slova

elektrická vozidla, elektromobilita, český automobilový trh, cost-benefit analýza, analýza scénářů, multiagentní modelování
Declaration of Authorship

I hereby proclaim that I wrote my bachelor thesis on my own under the leadership of my supervisor and that the references include all resources and literature I have used.

I grant a permission to reproduce and to distribute copies of this thesis document in whole or in part.

Prague, 26 July 2017

Signature
Acknowledgment

I would like to express my sincere gratitude to PhDr. Jiří Kukačka, Ph.D. for all his patience, comments, ideas, and for the enthusiasm he supervised me with throughout the entire work on this thesis. Further, my gratitude belongs also to my family for the support during my whole studies.
Contents

Thesis Proposal ...................................................... v
List of Acronyms ......................................................... ix
List of Tables .......................................................... x
List of Figures .......................................................... x

Introduction ............................................................. 1

1 EV design and their purpose ........................................ 3
   1.1 Global outlook ....................................................... 5
   1.2 EVs’ market share across the world: The case of Norway . . 7

2 Cost-benefit analysis of EV implementation ........................ 9
   2.1 Ecological and social impact .................................... 9
   2.2 Economical point of view for a Czech consumer .............. 12
      2.2.1 Purchase price, fuel costs and maintenance .......... 12
      2.2.2 Usage accessibility ........................................... 17

3 ABM model ............................................................. 19
   3.1 Methodology of agent-based modelling ......................... 19
   3.2 Model characteristics ............................................. 20
      3.2.1 Agents and their environment .................................. 20
      3.2.2 Main observed variables ...................................... 25
   3.3 Model calibration .................................................... 26

4 Sensitivity analysis .................................................. 32
   4.1 Overview ............................................................. 32
   4.2 Local sensitivity analysis ......................................... 35

5 Scenario analysis ................................................... 45
   5.1 Purchase subsidy and VAT exemption .......................... 46
   5.2 Electricity supply costs reduction ............................... 48
5.3 Waivers on tolls and parking fees .......................... 50
5.4 Development of charging infrastructure ..................... 53
5.5 Access to bus lanes and exclusive zones in the city ........... 55
5.6 Evaluation ......................................................... 57

Conclusion .......................................................... 59

References ......................................................... 61

Appendix A .......................................................... I

Appendix B .......................................................... IV
Thesis Proposal

**Author**  
Renáta Wojnarová

**Supervisor**  
PhDr. Jiří Kukačka, Ph.D.

**Proposed topic**  
ABM Scenario Analysis of the Market Share of EVs in the Czech Republic

**Topic Characteristics**

The future and potential of electromobility are very actual and controversial topics. Issues concerning the ecological impact of electric vehicles (EVs) and their effectivity are widely discussed. Proponents argue that emissions forgone by using electricity (if generated by a renewable resource) represent nearly zero environmental damage. However, the production of lithium-ion batteries used in EVs and their disposal could have a similar impact on the environment as using a vehicle with the internal combustion engine (ICEV). In addition, higher demand for electricity power resulting from EV usage can actually enlarge carbon footprint by extending the operating time of heat power plants. Whereas some countries as Norway or the United States have already implemented various successful programs in order to increase the market share of EVs, the Czech Republic is still holding back. First aim of this thesis is to find out, whether the low sales of electric cars are caused by well-founded economic incentives or only by different preferences of Czech consumers. The actual situation of the Czech vehicle market, together with the transport infrastructure and consumer behaviour will be taken into account. Another purpose of this thesis is to analyse and assess different policies aimed at increasing EVs’ market share by simple agent-based model, again calibrated to Czech background. We will try to examine direct financial incentives for car users like the purchase subsidies, exemption from taxes or no charging fees for EVs as well as non-financial incentives like the creation of exclusive zones in cities or building more public charging points which make the everyday usage of EV easier.
Hypotheses

1. CO$_2$ emissions produced in a whole life-cycle of an EV are lower than total emissions produced by an ICEV. Thus, carbon footprint can be reduced by using EVs.

2. EV is an economically optimal vehicle for the Czech consumer under actual conditions.

3. In the Czech background, overall costs of an EV concerning the purchase, maintenance and usage are lower than overall costs of an ICEV.

4. An agent-based model is a suitable method for analysing the effect of various policies on EVs’ market share.

5. Non-financial incentives are more effective in increasing EVs’ market share than financial incentives.

Methodology

Overall expenses and conveniences resulting from the purchase, maintenance and usage of an EV and its comparison with an internal combustion engine vehicle will be examined by the cost-benefit analysis. Next, the computational agent-based model describing simplified actual Czech vehicle market or its various individual aspects reflecting the transport infrastructure will be created in the NetLogo software. Consumers will be represented by heterogeneous agents acting in a market for vehicles. Different scenarios reflecting certain policies will be implemented and their effect observed in both short and long time horizons.

Outline

1. Introduction
   a. Design of EV technology and their purpose
   b. Implementation of EVs across the world
2. Cost-benefit analysis of EV implementation into the Czech Republic
   a. Ecological and social impact
   b. Economical point of view for the Czech consumer

3. Agent-based model in NetLogo
   a. ABM methodology
   b. Model characteristics
   c. Basic scenario
   d. Implementing different policies
   e. Evaluation

Core bibliography


Dong, Jing, Changzheng Liu, and Zhenhong Lin (2014). Charging Infrastructure Planning for Promoting Battery Electric Vehicles: An Activity-


List of Acronyms

**EV** electric vehicle

**ICEV** internal combustion engine vehicle

**BEV** battery electric vehicle

**VAT** value-added tax

**ABM** agent based modelling

**IEA** International Energy Agency

**CR** Czech Republic

**MPG** miles per gallon

**kWh** kilowatt-hours

**l/100km** litres per 100 kilometres

**kWh/100km** kilowatt-hours per 100 kilometres
List of Tables

1 General Comparison of costs ........................................ 14
2 Parameter values before the calibration .......................... 27
3 Calibration of Max motorway distance for EVs ................. 30
4 Overview of calibrated values ...................................... 32
5 Local Sensitivity analysis ............................................ 33
6 Overview of selected scenarios .......................... 46
7 Calculation of EVs’ consumption and fuel price .............. I
8 Calculation of EVs’ driving range .................................. II
9 Calculation of EVs’ price ............................................ II

List of Figures

1 Emissions over the life-time of the vehicle ....................... 11
2 Total costs for 1 km according to yearly distance, with pur- chase subsidy ........................................... 15
3 EV sales according to implemented policies ...................... 18
4 US Daily driven distance distribution of cars ................... 28
5 Motorway distance distribution for ICEVs ...................... 29
6 Histogram of Daily hours spent at home for EVs ............... 31
7 Contour plot of Daily hours spent at home ....................... 31
8 Development of dependent variables in time ................. 35
9 Sensitivity analysis of parameter $n_c$: Dependent variables as differences ............................................. 36
10 Sensitivity analysis of parameter $P_{2g}^{EV}$ and $P_{2g}^{ICEV}$ .................. 37
11 Sensitivity analysis of parameter $P_{1goal}^{AC}$ ..................... 38
12 Sensitivity analysis of parameter $P_{2goals}^{AC}$ .................. 39
13 Sensitivity analysis of parameter $P_{HCh}^{EV}$: Dependent variables as differences ............................................. 40
14 Sensitivity analysis of parameter $Maxd_{EV}^m$: Dependent variables as differences ............................................. 41
15 Sensitivity analysis of parameter $Maxd_{ICEV}^m$: Dependent variables as differences ................................. 41
16 Sensitivity analysis of parameter $s_{EV}$ and $s_{ICEV}$: Dependent variables as differences ................................. 42
17 Sensitivity analysis of parameter $P^E$: Dependent variables as differences ........................................... 43
18 Sensitivity analysis of parameter $p_{EV}$ and $p_{ICEV}$: Dependent variables as differences ........................................... 43
19 Sensitivity analysis of parameter $t_{EV}$ and $t_{ICEV}$: Dependent variables as differences ........................................... 44
20 Sensitivity analysis of parameter $f_{EV}$ and $f_{ICEV}$: Dependent variables as differences ........................................... 45
21 Scenario 1: Costs for 1 km ........................................... 47
22 Scenario 2: Costs for 1 km with the purchase price included ........................................... 49
23 Scenario 2: Costs for 1 km without the purchase price ........................................... 50
24 Scenario 2: Costs for 1 km with the purchase price included ........................................... 52
25 Scenario 3: Costs for 1 km without the purchase price ........................................... 52
26 Scenario 4: Time costs ........................................... 54
27 Scenario 5: Time costs ........................................... 56
28 NetLogo Interface ........................................... IV
Introduction

The first mention about electric motors usable in vehicles comes from the early 19th century when the Scottish inventor Robert Anderson made an electric-powered prototype of a crude carriage. Later on, in 1897, first commercial electric vehicles (EVs) entered the US market as passenger cars used by New York taxi service. After several booms and busts, with a contribution of intentions to reduce air pollution generated by internal combustion engine vehicles (ICEVs), their total sales and market share has been rapidly increasing since 1990s (Anderson and Anderson, 2004). Today, with rising demand for green and sustainable solutions, leading producers of EVs including Japanese Nissan and Mitsubishi, American Tesla Motors or Chinese BYD are actively investing in research and development. There is no doubt that these vehicles will have their substantial place in the future field of transportation.

Types of electrically-driven engines range from the gasoline hybrid vehicles over plug-in electric vehicles to fully electrically powered battery electric vehicles (BEVs) (Noori and Tatari, 2016). Concretely, BEVs and plug-in electric vehicles are both considered as types of EVs, gasoline hybrid vehicles are not. All of these should serve as a convenient and reliable mean of transport while saving energy and reducing greenhouse gas emissions. In the Czech Republic (CR), only 0.1% of newly registered passenger vehicles in 2015 were at least partly electrically-powered. This is almost ten times less than for the whole EU (European Automobile Manufacturers Association, 2015, 2016). One of the commonly known facts reasoning this low market share in this country is that the purchase and maintenance of an electric car is too expensive compared to conventional vehicles and with respect to average salary level. Other claims that the present availability of facilities needed for EVs’ usage is not sufficient. Another possible reason is that Czech consumers just do not want to comply with new trends. The often raised argument of possibly higher CO$_2$ emissions produced by EVs as a result of the electricity coming from the unsustainable source is also worth
to be mentioned. In this research, we thus evaluate possible benefits and disadvantages of EVs for the typical Czech consumer related to the ecological, social, and economical point of view to see if consumers’ decisions made when buying a car are driven by external economic incentives or just distinct preferences.

When speaking about policies promoting the use of EVs which many countries as Norway or Netherlands have already implemented, it is useful to analyse which of those policies concretely can be applied into the Czech framework if the government aimed at increasing EV market share effectively. Policies usually practised are the purchase subsidies, exemption from taxes, no charging fees for EVs as well as non-financial incentives like the creation of exclusive zones in cities or building more public charging points. For this purpose, agent based modelling (ABM) methodology proposed as a suitable instrument is applied. This method is based on investigating the individual behaviour of heterogeneous agents creating a complex system in a simple model. This system then reacts to the change in the environment where it is installed or change in the model characteristics (Railsback and Grimm, 2011). In our case, drivers act as individuals in a stylised traffic system where multiple scenarios representing government policies are implemented and final outcomes showing the resulting potential effectiveness of these policies are examined.

This bachelor thesis is organised as follows. In Chapter 1, the basics of EV purpose and technology, as well as global outlook, are introduced. Chapter 2 contains a cost-benefit analysis of EV ownership for the typical consumer acting in the Czech vehicle market. In Chapter 3, the simple agent-based model for analysing different policy scenarios is introduced and evaluated. The final Section concludes.
1 EV design and their purpose

This chapter presents the basics of electric vehicles’ technology together with their purpose to introduce to the reader the terminology of the cost-benefit analysis and scenario analysis in next chapters. Generally, EVs are vehicles that run completely or partially on electricity. There are more kinds of them and we now discuss three main types which are generally considered as the most popular ones.

Firstly, the majority of our attention is given to a completely electrically powered battery electric vehicle. Because BEVs do not use gasoline at all, they do not produce any tailpipe pollution so emissions from driving them are practically zero. Their electric motor is also more energy efficient (about 96%) in comparison to ICEVs whose energy efficiency is only 35%-40% (Volkswagen Group of America, Inc., 2013). Their motor turns off completely when a car stops and while the vehicle is braking, its battery is also partly recharging (‘regenerative braking’). BEVs can be comfortably recharged at home by using the classic electric outlet used for all other household appliances. Driving range varies usually somewhere about 170 km but some models can go even further. For instance, Tesla Model S 85D can do 400 km with one fully charged battery. BEVs’ acceleration is also higher thanks to their almost instant turning force resulting from no need for setting the pace (Union of Concerned Scientists, 2017a). Furthermore, electric power is a cheaper source of energy than gasoline so BEVs are not as expensive to use as ICEVs. International Energy Agency (2016) argues, that with 2016 taxes for electricity and fuel, the 100 km trip made by BEV costs about 75% less in Europe and one half less in the US than the same trip made by ICEV. BEV’s purchasing price is higher but in some countries, this is compensated by various government subsidies and tax exemptions especially in countries where EV market share is relatively high. In Norway for example, thanks to these subsidies, purchase of a BEV can be actually cheaper for consumers than a classic ICEV (International Energy Agency, 2016).
Secondly, the kind of EV highly related to the classic fuel car is the plug-in electric vehicle. According to Union of Concerned Scientists (2017d), its main characteristics is the parallel management of power flowing from both the gasoline (or diesel) and electric storage. Its motor is powered mainly by a rechargeable battery which can be renewed by plugging it into an electricity grid where a 120 V outlet is available. Thus, plug-in electric vehicles can actually run only on electric power. When its battery is depleted, the vehicle can switch automatically on its fuel source and recharge it while driving. The largest driving distance it can go only by running on battery is reaching 60 km.

Thirdly, there are conventional hybrid vehicles. Authors from the Union of Concerned Scientists (2017b) are pointing out, that these are though not recognised as EVs because they cannot by plugged-in to the network and recharged. So their only source of external energy is the gasoline. They run mainly on this source and additionally, they contain an electricity storage to power their motor at some specific times. That way, they are constantly changing the power from electric to gasoline and their battery is recharging while running on fuel. We can thus consider them as some kind of more energy efficient vehicles.

Lastly, there exists one type of EV which is not very widespread but is nowadays gaining decent market share, especially in California. That is hydrogen fuel cell electric vehicle. With a use of hydrogen gas for powering an electric motor while producing water as a by-product, driving them is, similarly to BEVs, not producing any pollution (if we do not take into account the electricity needed to produce the hydrogen gas). They are excelling through their fast refuelling ability which is about 10 minutes and their driving distance being similar to a conventional ICEV. The one and important disadvantage is that they need a special charging network providing them with hydrogen refuelling stations (Union of Concerned Scientists, 2017c).

Generally, concerning the ecological impact, BEVs and hydrogen fuel cell
vehicles are the ones having the highest potential to reduce tailpipe CO$_2$ emissions (by 100%). After that, there are plug-in electric vehicles with the potential of 50% reduction and then conventional hybrids with the ability of 25% emission reduction, according to the Volkswagen Group of America, Inc. (2013).

1.1 Global outlook

In this Section, we describe the main characteristic of global situation as well as some of the popular organisations focusing on electromobility. One of those institutions is the International Energy Agency (IEA). This organisation is promoting sustainable energy policies and energy security among its 29 member states, the CR is one of them. IEA is also conducting a research and analysing activity in the energy industry.

International Energy Agency (2016) reports that in 2015 the total number of EVs in the world climbed up to 1.26 million with the 80% of them in US, China, Japan, Netherlands, and Norway. The leader in the global stock of electric scooters and buses is China, in other countries electric passenger cars are more common. Together with rising worldwide sales of EVs, new policies and charging networks are being established, allowing these vehicles to travel longer distances even at the continental level, especially across the EU. Battery costs are now four times lower compared to 2008 costs. In addition, with higher battery density, it is now possible to squeeze more energy into one storage thus prolonging EV’s driving range. In December 2015, Paris Agreement with the aim of limiting the global temperature increment by 2°C was made at the UN Framework Convention on Climate Change. To achieve this goal, global CO$_2$ emissions of which 23% are produced by transport, have to be cut by 15 gigatons by 2050 (33 gigatons of CO$_2$ emissions were emitted in 2013). A stable rise in the global EV stock has to continue in order to meet this objective (International Energy Agency, 2016). However, EVs also need to be more ecological across their whole life cycle and the electricity generated to charge the battery has to be produced at least
partly by renewable resources, not only by fossil fuel plants typical for the CR. Nevertheless, for successful increase of EVs’ market share, it would be appropriate if the government would contribute with policies providing consumers with various economic and other usage incentives. These policies prioritise potential buyers of EVs as well as their current users. It usually begins with a purchase where some discounts or exemptions from registration, sale or value-added tax (VAT) are offered. Then, the circulation tax, toll, parking or electricity supply exemptions can be added together with other benefits such as an access to bus lanes or restricted traffic zones. More investment into the public charging network as well as fiscal advantages for private chargers (essential for each EV user) are also needed. Global stock of publicly available charging outlets for EVs reached 190,000 in 2015. 31% of them are in China, 17% in the US and 12% in Japan. Globally, there are 45 electric cars (of which 27 are BEVs) per each public fast-charging outlet and 7.8 electric cars per each public slow-charging outlet (International Energy Agency, 2016).

Besides the IEA agency, there exist many other organisations dealing with energy and electric cars specifically. In the EU, there is a European Green Vehicles Initiative launched as one of the public-private partnerships by the European Economic Recovery Plan established under the European Commission. Its aim is to promote and support research and development in the automotive industry in order to deliver green solutions for the European transport using renewable energy resources. In 2010 for instance, it chose to financially contribute to 30 projects focusing on road electrification, research on EV batteries and hybrid technologies (European Green Vehicles Initiative PPP, 2011). This effort should also help with one of the key targets of 2020 climate and energy package which aims to reduce greenhouse gas emissions by 20% in comparison to 1990 level (European Commision, 2012).

In the CR, one of the well-known initiatives for EV promotion is the project E-mobility established in 2009 by the ČEZ Group. It is testing the technology of EVs as well as optimisation of the process of building EV
chargers and doing research on the consumers’ side. Its main goal is to build sufficiently large and dense network of chargers across the CR. Nowadays, it is providing its customers with approximately 70 public chargers and it also offers the installation of home charging stations (‘wallboxes’) to EV users (ČEZ Group, 2017a). Some other public charger providers are for example Pražská energetika (PRE), E.ON energetic group and Innogy. All of them are major distributors of electricity in the CR.

1.2 EVs’ market share across the world: The case of Norway

As a typical example of how EVs took over to gain huge market share is Norway. “From the 1990s, electric vehicles have been high on the political agenda resulting in Norway being home to the largest per capita Electric vehicle market in the world.” (Figenbaum and Kolbenstvedt, 2013). This vehicle evolution happened in more phases. First efforts increasing incentives to buy these cars included exemptions from registration tax, toll road charges and annual vehicle license fee. In addition, free parking places for EVs were created at municipalities. Nevertheless, a limited number of those parking places is usually available so this action has only little influence unless this number is increased (Figenbaum and Kolbenstvedt, 2013). Later, in 2001, 25% VAT exemption was introduced. Generally, because EVs are more expensive to manufacture, their VAT is higher. But with the VAT exemption, Norwegian government made prices of EVs and ICEVs roughly equal. Bus lane access was granted in 2005. One could argue that this policy is negatively influenced by a limited amount of vehicles which would fit in those lanes. In 2009 however, this access was banned for minibuses making more area for buses and EVs. Finally, main road coastal ferries rates were also reduced. EVs share on new vehicle sales in 2012 achieved 3%. There were some registration tax exemptions established also for plug-in electric vehicles but not any other incentives for them were made. This led to only minimal sales of plug-in hybrids (Figenbaum and Kolbenstvedt, 2013).

According to authors, since 98% of electricity in Norway is produced by
hydro-electric power plants, EVs can be considered as almost emission free. Saving the environment is also the most frequent reason for Norwegians to choose an EV as their car for everyday use. The potential for their purchase is higher for households with more cars and for people with charging points available at work.
2 Cost-benefit analysis of EV implementation

This chapter discusses the benefits and shortcomings of the purchase, usage and maintenance of EVs as well as their general impact on society, with actual Czech conditions taken into consideration. At first, it is important to point out that even though the EVs' entrance to the market was successful and their expansion favourable in some of the countries across the world, the CR is now still in the early stage of a process of implementing these technologies. Therefore, the results should be interpreted with caution as the situation will be probably different in 5 to 10 years from now. Moreover, due to several data limitations, numbers presented here should be considered only as estimates. Nevertheless, this study could definitely serve as a decently accurate indicator of actual Czech EV market conditions and trends.

2.1 Ecological and social impact

Generally, emissions from car manufacturing are higher for EVs than for ICEVs. Emissions from driving depend on electricity generation mix being the source of fuel for EVs. According to Nealer et al. (2015), when having an EV instead of an ICEV, excess emissions produced by manufacturing the vehicle with battery are evened up after 6 to 16 months of driving. This applies for average consumer living in any region of the USA. Thus, inspired by their study, we use Czech data and develop a similar analysis to see where is a milestone at a time since the purchase when these excess emissions are offset. Given the actual situation in the Czech energy industry, concretely the structure of power plant production, our results considerably differ from those of Nealer et al. (2015).\(^1\)

For simplicity, we account only for fully electrically powered BEVs as representatives of EVs in this whole study. We use the methodology of Nealer et al. (2015) which is based on combining two types of CO\(_2\) emissions made

\(^1\)Some data for the Czech Republic are limited or missing, concretely the emissions from building of power plants, average emissions and average fuel consumption of ICEVs, and emissions from EVs manufacturing. For this purposes, US data are used.
over the vehicle life cycle. The first type is emitted by driving the vehicle, while the second one comes from vehicle manufacturing and disposal. We start with the operating phase. For an ICEVs, these emissions consist of those generated by (1) oil extraction, (2) transporting the crude oil to a refinery, (3) refining the oil into gasoline, (4) delivering the fuel to the gas station, and (5)combusting the fuel while driving. For EV representatives, they are generated only indirectly by (1) extracting raw materials such as coal or natural gas, (2) delivering them to power plants, and (3) burning the fuel in plants to produce electricity (Nealer et al., 2015). As a measuring unit, kg of CO$_2$/100km obtained from the information about energy consumption in litres per 100 kilometres (l/100km) for an ICEV and about energy consumption in kilowatt-hours per 100 kilometres (kWh/100km) for an EV is used. The lower the consumption in l/100km or kWh/100km, less emissions the car is producing. For an ICEV, these measurements are easily obtained, in the case of an EV, estimated emissions made by electricity generation in power plants have to be converted into kWh/100km.

For simplicity, we use only emissions produced by driving in the case of an ICEV and emissions made by producing electricity multiplied by vehicles fuel consumption when comparing the operating aspect of the ecological impact. For a charging emissions estimate, we take the combined BEV energy consumption of 13.3 kWh/100km which is the weighted average of energy consumptions based on 2014 Czech BEV sales.\textsuperscript{2} For an ICEV, combined gasoline consumption is 5.3 l/100km taken as the average of 2014 new car sales in the EU (Tietge et al., 2015). The resulting amount of emissions for an EV is then 8.38 kg of CO$_2$/100km.\textsuperscript{3} To compare, ICEV emissions estimate we calculated is 12.4 kg CO$_2$/100km.\textsuperscript{4} Thus, in the terms of only driving the vehicle, as our analysis shows, EVs are cleaner.

\textsuperscript{2}From 185 BEVs sold in the CR in 2014, major manufacturers were Volkswagen and BMW, followed by Nissan and others (Horčík, 2015a). A detailed overview is included in the Appendix A.

\textsuperscript{3}Total emissions from electricity and heat production (IEA Statistics, 2016) divided by the total electricity production of the CR for 2014 (IEA Statistics, 2017) times the calculated combined BEV energy consumption.

\textsuperscript{4}Average ICEV fuel consumption times gasoline consumption equivalent, which is 1 l of gasoline combusted = 2.34 kg CO$_2$ emitted, according to Tietge et al. (2015).
When looking at emissions produced by manufacturing and disposal of the vehicle, it is important to notice that while for an ICEV, these emissions account only for a small proportion of life-cycle emissions, in the case of an EV, battery manufacturing pollution is more significant. These emissions are produced by extracting raw materials such as lithium, cobalt etc. Projected lifetime for both mid-range BEV and similar size modelled ICEV is assumed to be 217 000 km and 15 years for consistency as in the analysis of Nealer et al. (2015). With data currently available and with continuous technology development, batteries’ lifetime can be only estimated. Nealer et al. (2015) made an additional analysis with multiplying battery manufacturing emissions by factor 1.5 and 2 and found that these deviations from total emissions are not seriously significant. As a result, we can assume that only one battery for the whole lifetime of an EV is used. Recycling some material used except batteries is also accounted for. Findings of Nealer et al. (2015) show that for a mid-size BEV, manufacturing emissions are approximately 1 tonne of CO\textsubscript{2} higher than those of an comparable ICEV.\textsuperscript{5} That translates into about 8 tonnes of CO\textsubscript{2} for manufacturing an ICEV and 9 tonnes of CO\textsubscript{2} for manufacturing an EV (Nealer et al., 2015). Figure 1 shows that with projected lifetime of 15 years, originally higher emissions of EV are offset after approximately 24 876 km or 1 year and 9 months of driving for the Czech consumer. Thus, carbon footprint can definitely be reduced by using EVs.

Figure 1: Emissions over the life-time of the vehicle

\textsuperscript{5}For this manufacturing phase estimate, US average electricity grid emissions were used.
Of course, this is only an approximation. However, in improving the efficiency and ecological impact of EVs, the government has a large opportunity to contribute substantially. Firstly, it can adopt policies in order to increase electricity production from renewable resources which in 2014 generated only 9.4% of electric power in the CR. The government is projecting to increase the share on total energy consumption up to 25% by 2040. In addition, expanding the nuclear capacity by building new reactors is also planned as another solution to reduce greenhouse gas emissions and to replace thermal power plants ending their operation phase (OECD/IEA, 2016). Next, the government could promote the EV accessibility which would also contribute to reducing emissions. More specific analysis of these policies is described in following chapters of the thesis.

2.2 Economical point of view for a Czech consumer

In this Section, we analyse costs and benefits connected to the vehicle purchase and usage and investigate final costs for Czech consumers who are divided into more categories depending on their yearly distance travelled. Again for simplicity, only BEV as the EV representative is considered, so we are not taking plug-in electric vehicles and hydrogen fuel-cells into account as their technology is more complex, their amount in the Czech vehicle market is very low, and results would be more difficult to interpret.

2.2.1 Purchase price, fuel costs and maintenance

We begin with the purchase price. We take several models of EVs with their basic facilities and calculate the weighted average according to their market share on total number of EVs sold in 2014 in the CR.\(^6\) This results in an average price of 878 000 CZK for a new EV bought in the CR.\(^7\) Because of data unavailability for average prices of ICEVs sold in this country only, we take the EU-13 average price of passenger cars sold in 2014, which is

---

\(^6\)Price overview is included in the Appendix A.

\(^7\)Rounded to thousands.
approximately 586 000 CZK (Statista Inc., 2017). Thus, what concerns the purchase, EVs are considerably more expensive. The main reason is not only their different technology but also the cost of batteries manufacturing. In addition, the government does not offer any purchase subsidy or VAT exemption yet. According to a study of Czech Ministry of Industry and Trade (2015), potential purchase subsidy of 200 000 CZK for a car would be enough to make EVs competitive. In addition, if also the VAT exemption would apply as in Norway (International Energy Agency, 2016), resulting EV average price would be approximately 526 000 CZK\(^8\) (VAT in the CR accounts for 21% of the car’s final price). That confirms our hypothesis that with these two financial incentives, EV’s price would be even lower than that one of an average ICEV. Nevertheless, none of these incentives for private consumers are yet planned.

Following with driving costs, the gasoline consumption for ICEVs we take into account is again 5.3 l/100km based on EU 2014 car sales (Tietge et al., 2015) which translates into approximately 164.3 CZK for 100 km ride.\(^{10}\) For EVs, electricity consumption is again 13.3 kWh/100km as the weighted average based on Czech 2014 EV sales. This translates into 49.2 CZK for 100 km ride.\(^{11}\) However, we have to take into account that some public chargers for EVs are free of charge, so actual driving costs can be even lower. That depends on how much electricity the driver takes is from unpaid source. According to online map from EVSELECT, s.r.o. (2017), the actual situation in the CR shows that there are 491 chargers owned either by energy companies (CEZ, E.ON, PRE, Innogy) or by private owners and there is no uniform price for electricity stated.

Other costs which drivers have to deal with are for the vehicle service maintenance. Czech Ministry of Industry and Trade (2015) claims, that

---

\(^8\)EU-13 consists of new members joining in 2004 or later: Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia and Slovenia. Mean 2014 cumulative exchange rate of 27.533 CZK/EUR was used, according to Česká národní banka (2017). Price rounded to thousands.

\(^9\)Rounded to thousands.

\(^{10}\)Average price of gasoline Natural 95 of 31 CZK per litre was used (Kurzy.cz, spol. s r.o., 2017).

\(^{11}\)Average price of electricity of 3.71 CZK per kilowatt-hours (kWh) was used (Energie123.cz, 2017).
according to the analysis used for its Clean Mobility plan, EV maintenance costs about 8 200 CZK/year in comparison with 11 800 CZK/year for a comparable mid-range ICEV. A general comparison of costs in CZK can be seen in Table 1.

Table 1: General Comparison of costs

<table>
<thead>
<tr>
<th></th>
<th>EV</th>
<th>ICEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase Price</td>
<td>878 000 CZK</td>
<td>586 000 CZK</td>
</tr>
<tr>
<td>Yearly Maintenance</td>
<td>8 200 CZK</td>
<td>11 800 CZK</td>
</tr>
<tr>
<td>Fuel price (for 1 kWh or 1 l)</td>
<td>3.71 CZK</td>
<td>31 CZK</td>
</tr>
<tr>
<td>Fuel Consumption for 100km</td>
<td>13.3 kWh</td>
<td>5.3 l</td>
</tr>
<tr>
<td>Price of 100 km ride</td>
<td>49.2 CZK</td>
<td>164.3 CZK</td>
</tr>
</tbody>
</table>

Now, we divide consumers into five categories according to the amount of yearly km driven and calculate their break-even points in time where total costs for 1 km of a ride with an EV are equal to those of an ICEV. Categories are following: 10 000, 20 000, 30 000, 40 000, and 50 000 km yearly. We use purchase prices, costs of gasoline and electricity and maintenance costs as given above. From all these figures, we calculate the price for 1 km driven which has a nonlinear decreasing trend in all cases. Costs for all groups are compared in Figure 2. According to our expectations, all drivers buying an EV have almost 50% higher costs in first few years of use. In the first group, for example, 1 km with an EV costs about 89 CZK in comparison with 61 CZK with ICEV in the end of the first year. Naturally, the higher amount of km driven, the lower costs for 1 km with both cars and the lower difference in costs between car types.Drivers in the fifth group pay only about 18 CZK with an EV and 14 CZK with an ICEV. After some specific time for each group, a break-even point occurs and costs for 1 km driven with an EV becomes less than 1 km with an ICEV. However, people driving yearly only 10 000 km or less should not consider buying an EV as more economical investment than buying an ICEV since prices for 1 km would equalise after 19 or more years of usage. Prospect for consumers from the second group is more feasible. EV would be more economical for them after 10 years or

Roland-Berger analysis
later. Break-even point in the third group occurs in the eighth year and in the fourth group in the sixth year. Finally, most money can be saved by people driving yearly 50 000 km or more as their costs for 1 km would be lower for an EV already in the fifth year of usage.

Figure 2: Total costs for 1 km according to yearly distance, with purchase subsidy

Thus, if we get back to our hypothesis whether having an EV is more economical for a typical Czech consumer, from the technical point of view, the answer is yes, after some specific time. Nevertheless, if we consider the fact that EVs’ driving range is still very limited and so they are used rather as city cars for driving lower distances, we reckon that their users would not drive more than 20 000 km a year. In order to make this investment more
profitable, the government would have to establish some purchase discounts or tax exemptions. We can certainly expect though, that with continuing technological progress in this field, producers will expand the capacity of batteries and manufacturing costs will decrease, resulting in more affordable and more time-flexible electric cars available in the market.

If we consider the establishment of purchase subsidy of 200 000 CZK for an EV (Czech Ministry of Industry and Trade, 2015), break-even points move down by the significant amount of years in every group. As shown in Figure 2, in the first group, for instance, it occurs even 13 years earlier, already in the seventh year of usage. In the second group, break-even point occurs 7 years earlier compared to the first situation, already in the fourth year. In the third group, the point moves into the third year and into the second year in the fourth and last group. Thus, we can conclude that after the establishment of this incentive, EVs would certainly become more economical for more drivers.

Next, if we include also the exemption of VAT decreasing initial price by 21% as was the case of Norway (Figenbaum and Kolbenstvedt, 2013), average EV becomes even cheaper to buy than an average ICEV as its mean price would be approximately 526 000 CZK. Hence, most of the drivers would benefit from lower costs already in the first year of usage. The cost of 1 km at the end of the first year with an EV would be about 7.5 CZK less in the first group and 2.4 CZK less in the last group than with an ICEV.

As a result, we conclude that an EV is not more economical for the typical Czech consumer driving lower mileages under the actual conditions because of higher aggregated costs for purchase, usage, and maintenance. The main reason is 1.5 times higher initial price than the price of an average ICEV. Specific policy as government subsidies and tax exemptions could resolve the issue and make these vehicles more attractive to consumers.
2.2.2 Usage accessibility

Related to the government involvement, Czech Ministry of Industry and Trade (2015) developed few possible scenarios how government policies can influence EVs’ accessibility and convenience and thus, their market implementation. The basic scenario which is in the accordance with actual conditions is that the charging infrastructure would be completed by 2025 to sufficiently serve all EV users, battery manufacturing costs will have substantial decreasing trend and that no monetary or accessibility incentives will be established. First possible policy useful to increase EV market share is to make the parking in city centres for EVs free of charge, reserve some amount of parking places only for EVs and permit them to use road lanes for buses and taxis. Their study analysed the effect of this incentive to be about 5 000 CZK saved every year by each EV driver.\(^\text{13}\) Second thing for EV implementation is the sufficient charging infrastructure which significantly increases vehicles’ driving range and erases drivers’ worries about limited distance they can travel. Nevertheless, returns from the investment into the charging station is uncertain as it is influenced by the present EV market share as well as by costs connected to the building of the chargers and to land-holding rights. Thus, the government could motivate investors either by monetary subsidies for building new charging stations or by providing them with a possibility of installing the stations on the state-owned land (property of The Road and Motorway Directorate, The Railway Infrastructure Administration etc.). Ministry expects that for charging network to be sufficiently dense, there should be about 500 to 1000 charging locations in the whole country. Third, the government could provide purchase subsidies as discussed earlier, decrease the toll on motorways and decrease the price of electricity at home for EV users.

If we look at scenarios examined by Czech Ministry of Industry and Trade (2015) with the aim to minimise costs for government while decently increasing EVs’ market share, the most effective scenario turned out to be the

\(^{13}\text{Quantification is based on average time spent on public parking (Czech Ministry of Industry and Trade, 2015).}\)
free parking policy and support for investors building the charging network. These tools have an economical effect by decreasing overall costs for users and also the psychological effect by erasing main accessibility borders. Additionally, monetary support as tax exemptions or purchase subsidies could reinforce effects of previous policies on demand for EVs, especially in the combination with both previous scenarios. As Figure 3 shows, without any supporting policy (Basic scenario), yearly EV sales in the CR are estimated to be about 5,000 cars in 2020. This is a result of general technology development, decreasing manufacturing costs and more models available in the market. Free parking and bus lane policy would increase these sales by another 5,000 resulting into 10,000 EVs sold in 2020. The same policy combined with charging network support would lead to sales of approximately 17,000 cars/year. Lastly, with monetary subsidies added, EV sales could be even 1,000 vehicles higher (Czech Ministry of Industry and Trade, 2015). Thus, if increasing EV market share would be the aim of the Czech government, this kind of combined support could be very effective.

Figure 3: EV sales according to implemented policies

Source: Czech Ministry of Industry and Trade, 2015
3 ABM model

3.1 Methodology of agent-based modelling

To fully understand our intention of using the ABM methodology and developing a model in NetLogo, we start with a brief introduction of this concept of modelling. From the history, scientists were usually limited by mathematical approaches so they had to keep models simple in order to be able to use calculus. With technology development, more complex problems closer to world reality can now be addressed with a variety of different tools and methods (Railsback and Grimm, 2011). Nevertheless, traditional general equilibrium theory is widely accepted in the majority of economic problems (LeBaron and Tesfatsion, 2008). Although these models are simple and easy to interpret, they rather represent how the whole system as a unit behaves. Entities in these systems have identical goals subject to constraints and act under strict assumptions. The result of their effort to maximise their utility is then a general equilibrium valid for the whole market. There is no emergent behaviour of entities who would react with each other. The main drawback of these models is that they often can not represent the real-world situation. That is the reason why new approaches as ABM were developed. Nowadays, they are on their rise and further evolving. ABM approach is based on a unique behaviour of individuals (agents) who interact with each other and/or with the environment. Agents have their own objectives and act independently. Additionally, they adjust these actions to the current state of themselves, other agents or the environment and therefore use adaptive behaviour. ABM models can thus deal with emerging situations where more complex system dynamics arises. We can study what happens to agents because of the system behaviour and also what happens to the system because of what individuals do. That means we can look across more levels. ABM is used in social sciences, biology, economics, finance and many other scientific fields. Another important characteristic of these models is that when we create them, we still have to observe their functioning and learn how to understand the behaviour of systems they represent. Most of the
model assumptions are experimental and models thus have to be tested and their assumptions analysed.

We develop a model in NetLogo which is a software widely used for individual-based modelling by economists as well as in many other fields. We explore the behaviour of drivers of EVs and ICEVs as agents acting in the stylised Czech environment under conditions calibrated to a simplified reality of the CR. Vehicles are influenced by external factors affecting their usage accessibility, time-consumption and monetary costs. As these agents are individually adapting their behaviour to external conditions and pursue their own objectives, thus interacting with their environment without any convergence to general equilibrium, we state that the ABM method we chose is appropriate to observe these outcomes of the system. Based on our analysis, we compare different characteristics of EVs and ICEVs, how it may influence consumers’ choice and we also explore the effect of various policies aimed at increasing EV’s market share discussed earlier.

This Section is divided into four parts. At first, we introduce the structure of the model and its principles (file with the program code is included in the external electronic attachment). Parameter calibration and sensitivity analysis follow. After the model is set up, we observe and present its emergencies and specific features. Then we run a scenario analysis and present the results together with our evaluation.

3.2 Model characteristics

3.2.1 Agents and their environment

For an analysis of effects of various scenarios on EVs’ market potential in the CR we use a simple model made in the NetLogo software. General Interface with model environment and all adjustable parameters is depicted in the Appendix B in the Figure 28. We created the “world” for our agents (vehicles) which consist of 2-dimensional square space. It is built from 31 x 31 patches, where 1 patch represents 1 km of real-world distance. These dimensions approximately correspond to the area of Prague which is about
500 km\(^2\) (approximately 22 x 22 km) plus its surroundings of about 5 km at each side. This parameter can be adjusted so the model can be calibrated to any different city. We, however, are doing analysis in the stylised Czech environment so we keep this parameter fixed. There are 6 straight roads in both vertical and horizontal direction creating a grid of main city “roads” for vehicles. This number was chosen in order to have sufficient number of opportunities for vehicles to move while keeping the model’s appearance clear.\(^{14}\) In this environment, 500 vehicles of two breeds (EVs and ICEVs) which are our independently behaving agents are created. That way, we have a sufficiently large sample to observe while the model can run quickly during an analysis. EV share is set up to 0.5 so we have two samples of the same size and so we can compare them statistically properly. Besides the city itself, one patch representing the motorway between two cities was created in the lower right corner of the square space, thus virtually expanding the model’s environment. Motorway distances and a number of cars using the highway are calibrated and approximately distributed according to the study of Van Haaren (2011) based on the US national survey data (Santos et al., 2011) on daily driven distance. Minimum motorway distance for both ICEVs and EVs is 10 km. Maximum for ICEVs is 370 km as we want to observe the system in the modelled Czech environment. It corresponds to the distance between the cities Prague and Ostrava which is, based on our consideration, the reasonable maximum which could a vehicle go forth and back in a day regularly. Maximum motorway distance for EVs is calibrated to be 200 km in order to obtain more realistic results as these cars are rather used only for the city and the usability of longer motorways for EVs drivers is not very convenient. A detailed discussion about the calibration process is presented in the next Section.

Next, some of the road patches are at the same time charging points available for EVs to recharge. As the reference value, we chose the num-

\(^{14}\)To make this grid, we inspired ourselves by the model Traffic Grid (available in the NetLogo Models Library) which observes general traffic in the city and problems arising on crossings with traffic lights or the creation of traffic jams.
ber of chargers to be 30 based on the approximate average of Prague and smaller Czech cities (EVSELECT, s.r.o., 2017). Besides chargers randomly distributed in our modelled city, there is additional one in the middle of the motorway for EVs to have the option to recharge themselves also when commuting. Vehicle capacity of these chargers is unlimited as we could reason by actual situation in the country and that is a very low amount of EVs in general.

One of the NetLogo’s typical features is that model’s running time is measured in ticks. One tick represents one time step specified by the modeller who decides which actions are taken by agents or what happens to the environment. In our case, tick corresponds to a car movement by 1 km in the city or by 2 km on the motorway. That results in the constant city speed of 50 km/h and a constant motorway speed of 100 km/h for both breeds of agents to simplify the model and again, to keep the comparability between the breeds. Following this setup, ticks are recalculated into hours, days (24 hours), months (30 days) and years (12 months) which are monitored. That way, our modelled measures can be compared to the real-world ones.

Before each run during the model setup, two or three patches lying next to the road are randomly assigned to each vehicle as its destinations. These can overlap between any two vehicles but not for the vehicle itself so it has always some distance to go between them. These three patches are named as house, goal1 and goal2. Every day, cars have to make their trip from home to their goal1, which can represent for example going to work. Here in the goal1, vehicles have to pay the one-off parking fee (this is set up to be 0 by default but is examined more in detail later in the analysis). Then, if the attribute of having two goals have been assigned to them by the observer, they go to goal2, and back home. When their trip is done, they wait at their homes until the next day begins. If the total distance is so long that a vehicle cannot finish it within one day, it has to do the whole journey anyway and then waits until the end of the day when it is back home. To avoid this situation as much as possible, the model was calibrated with the
aim to minimise this occurrence of not getting home in time. Some cars have all their destinations in the same town, some are commuting to other towns which makes them having to go to their goal and then back home through a motorway. The observer can setup probability of having two goals and probability of commuting to another town and thus regulate the number of EVs and ICEVs which have these specific characteristics. That way, we model a real-world situation of everyday usage of cars for common purposes as going from house to work and back or additionally doing a longer trip.

The behaviour of EVs and ICEVs is established separately by default. Because ICEVs use gasoline as their fuel, we assume that time spent on petrol stations to refuel is negligible as well as a geographic distribution and density of stations. Thus, ICEVs do their assigned trip once without any stop every day. On the other hand, EVs have their driving range set up only for 164 km. Thus, before each ride to their next destination (house, work, highway), they recalculate their distance there and if they do not have enough electric power, they head first to the closest charger where they recharge until full. After that, they recalculate the remaining distance. If their energy is enough, they drive without any other stop to their next destination. If not, they stop on the first charger available on their way and recharge again until full. There is one exception for EVs when having a possibility of charging at home. If the car is heading home and stops on a charger, it recharges itself only for a distance needed to achieve their home, plus a reserve of 20 km. The same applies if it is going home through the motorway, so when it stops on a motorway charger when heading home, only needed distance plus the reserve is recharged. We consider this behaviour as a reasonable representation of drivers’ decisions. It can happen that despite all these precautions, EV can discharge itself completely. Thus, when its energy is 0 it is moved to its house where it recharges itself or, if there is not any home-charging possibility, it is given an energy for 50 km. Then

\[15\text{Weighted average of EVs' driving ranges based on Czech EV sales for 2014. Detailed calculation in the Appendix.}\]

\[16\text{We count with driving distance reserve of 20 km.}\]
it waits until the next day to make its trip as usual. This situation can be understood as an occasional intervention of an assistance service. We assume that all public chargers have standard speed of operation for all EVs and that is 38 km recharged in 1 hour.\textsuperscript{17} If EV drivers have the possibility of recharging their car at home (also the feature assigned by the observer), vehicle recharges itself at the end of each day after it finished its trip. We assume that drivers who decide to buy an EV usually have this possibility as it is very common that most of the EV are mainly charged at home. Thus, 90\% of our EV agents have these home chargers available. Charging speed at homes is established to be 17.3 km recharged in 1 hour.\textsuperscript{18} For calibration and sensitivity analysis, we assume that all of the electricity recharged is for a constant price of 3.71 CZK/kWh.

Vehicles’ other attributes as purchase price, fuel consumption, the cost of yearly maintenance and prices for electricity and gasoline were taken from the part 2.2 from the Section 2. Every car has its own counter for money invested which consists only of its price right after the setup. Fuel costs are added after every tick when the car moves, making it cost for fuel used. At the end of every day, constant maintenance costs of 22.5 CZK for EVs and 32.3 CZK for ICEVs are added as calculated from the total yearly maintenance costs according to Czech Ministry of Industry and Trade (2015). Vehicles using the motorway have to also pay yearly Highway-toll, which is set up to be 1500 CZK by default.\textsuperscript{19} Thus, at the end of each day, fixed cost of 4.11 CZK is added to the counter of money invested for every vehicle which uses the motorway.

\textsuperscript{17}According to EVSELECT, s.r.o. (2017), most frequent public charger in the country is the Mennekes Type 2 with 22 kW, 32 A performance. With the assumption of its combination with most effective onboard chargers built in vehicles, it is able to recharge approximately 5 kW/h when applied to the average of three EVs examined in the analysis of Hybrid.cz (2014).

\textsuperscript{18}When using a classic home socket with 3.7 kW and 16 A performance (type SCHUKO), charging speed is about 2.3 kW/h when applied to the average of three EVs examined in the analysis of Hybrid.cz (2014).

\textsuperscript{19}In the CR, tolls for passenger vehicles are prepaid for a specific time. 1500 CZK is the price for motorway stamp valid for 1 year (for Transport Infrastructure, 2017).
3.2.2 Main observed variables

For calibration, sensitivity and scenario analysis, we observe following variables. First is Time, either in ticks or recalculated ticks into hours, days, months and years. One hour consists of 50 ticks. Recalculation was made based on constant car city speed 1 km/tick which makes it 50 km/h. For the ability to decide how much km our average EV or average ICEV drives, following variables are monitored:

\[
KM_v = \frac{\sum_{i=1}^{N_v} KM_{vi}}{N_v},
\]

\[
KM_v^{\text{day}} = \frac{\sum_{i=1}^{N_v} KM_{vi} * 1200}{N_v * \text{ticks}},
\]

where we calculate \( KM_v \) as Total km made for a vehicle of breed \( v \) and \( KM_v^{\text{day}} \) as Daily km made for average vehicle of breed \( v \). \( KM_{vi} \) stands for total km made by a vehicle \( i \) of breed \( v \) and \( N_v \) is the number of vehicles of this breed which equals 250 for both breeds in our case. To observe more specific daily behaviours of vehicles we monitor:

\[
h_{\text{Home}_v}^{\text{day}} = \frac{24 \sum_{i=1}^{N_v} THT_{vi}}{N_v * \text{ticks}},
\]

\[
h_{\text{Active}_v}^{\text{day}} = \frac{24 \sum_{i=1}^{N_v} TAT_{vi}}{N_v * \text{ticks}},
\]

where we calculate \( h_{\text{Home}_v}^{\text{day}} \) as Daily hours spend at home and \( h_{\text{Active}_v}^{\text{day}} \) as Daily active hours of average vehicle of breed \( v \). \( THT_{vi} \) stands for total home ticks made by a vehicle \( i \) and \( TAT_{vi} \) stands for total active ticks (when the vehicle is moving). Next, as our oversight of time costs for comparison of vehicle usage convenience are variables:

\[
Ticks_{EV}^{1\text{km}} = \frac{\sum_{i=1}^{N_{EV}} TAT_{EVi} + TCT_{EVi}}{\sum_{i=1}^{N_{EV}} KM_{EVi}},
\]

\[
Ticks_{ICEV}^{1\text{km}} = \frac{\sum_{i=1}^{N_{ICEV}} TAT_{ICEVi}}{\sum_{i=1}^{N_{ICEV}} KM_{ICEVi}},
\]
where we calculate Number of ticks for one km made by average vehicle of breed $v$. $TAT_{v,i}$ stands for variable Total active ticks which are ticks when a vehicle $i$ of breed $v$ was moving. $TCT_{EV,i}$ stands for a variable Total charging ticks which are ticks when an EV was charging (either in a public charger or at home). As a measurement of monetary costs, following variables are observed:

$$CZK_{v}^{1km} = \frac{\sum_{i=1}^{N_v} I_{vi}}{\sum_{i=1}^{N_v} KM_{vi}},$$ (7)

$$CZK_{v}^{1day} = \frac{1200 \cdot \sum_{i=1}^{N_v} I_{vi}}{N_v \cdot ticks},$$ (8)

where we calculate CZK invested for one km or for one day of average vehicle of breed $v$. $I_{vi}$ is total amount of money invested for a vehicle $i$ of breed $v$ from the beginning of a model’s run. Lastly, for calibration purposes following variables are controlled for:

$$EV_{nothome}^{1day} = \frac{\sum_{i=1}^{N_{EV_{nothome}}} EV_{nothome,i} \cdot 1200}{ticks},$$ (9)

$$EV_{O} = \frac{\sum_{i=1}^{N_{EV_{O}}} EV_{O,i} \cdot 1200}{ticks},$$ (10)

where we observe $EV_{nothome}^{1day}$ as Daily number of EVs failed to get home and $EV_{O}$ as Number of discharged EVs.

### 3.3 Model calibration

Some of the model’s parameters are not known or cannot be easily estimated without an additional research made in the Czech society. “Calibration is a special kind of parametrization in which we find good values for a few especially important parameters by seeing what parameter values cause the model to reproduce patterns observed in the real system.” (Railsback and Grimm, 2011). We thus do a calibration using the NetLogo Behavior Space tool which allows us to run the model multiple times with different settings and a combination of parameters’ values. We take an interval of feasible
parameter values and observe model’s behaviour while moving within those intervals. We then calibrate the parameters on their most feasible (reference) values. Unknown parameters needed to be calibrated are Probability of going to another city (for vehicles having one goal and for vehicles having two goals), Probability of having two goals (for EVs and ICEVs) and Maximal motorway distance for EVs. Table 2 shows an overview of our calibrated reference values of other parameters mentioned before. Calibration of parameters just introduced is done with following predetermined values in every run.

Table 2: Parameter values before the calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>World size</td>
<td>31 x 31 km</td>
</tr>
<tr>
<td>Number of cars</td>
<td>500</td>
</tr>
<tr>
<td>EV market share</td>
<td>0.5</td>
</tr>
<tr>
<td>EV driving range</td>
<td>164</td>
</tr>
<tr>
<td>Number of chargers</td>
<td>30</td>
</tr>
<tr>
<td>Probability of home-charging</td>
<td>0.9</td>
</tr>
<tr>
<td>Speed of public charging</td>
<td>5 kW/h</td>
</tr>
<tr>
<td>Speed of home charging</td>
<td>2.3 kW/h</td>
</tr>
<tr>
<td>City car speed</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Motorway car speed</td>
<td>100 km/h</td>
</tr>
<tr>
<td>EV price</td>
<td>878,000 CZK</td>
</tr>
<tr>
<td>ICEV price</td>
<td>586,000 CZK</td>
</tr>
<tr>
<td>EV daily maintenance</td>
<td>22,466 CZK</td>
</tr>
<tr>
<td>ICEV daily maintenance</td>
<td>32,329 CZK</td>
</tr>
<tr>
<td>Gasoline consumption and price for 100 km</td>
<td>5.3 l, 164.3 CZK</td>
</tr>
<tr>
<td>Electricity consumption and price for 100 km</td>
<td>13.3 kWh, 49.2 CZK</td>
</tr>
<tr>
<td>Paid electricity share</td>
<td>1</td>
</tr>
<tr>
<td>Parking fee EV</td>
<td>0 CZK</td>
</tr>
<tr>
<td>Parking fee ICEV</td>
<td>0 CZK</td>
</tr>
<tr>
<td>Motorway toll EV</td>
<td>1500 CZK</td>
</tr>
<tr>
<td>Motorway toll ICEV</td>
<td>1500 CZK</td>
</tr>
</tbody>
</table>

First parameters needed to be calibrated are probabilities of going to another city. We start with dividing all vehicles into two groups, one having one goal and second having two goals. To avoid possibly biased results, there is the same amount of EVs and ICEVs in each group with groups being mutually exclusive. In order to calibrate the average daily distance driven
within the city by each group, Probability of going to another city is now set up to zero. Average outputs of our model measured are approximately 40 km for vehicles in group 1 and 60 km for vehicles in group 2.\textsuperscript{20} We use a daily driven distance distribution from the analysis of Santos et al. (2011) based on a data from US National Household Travel Survey of Van Haaren (2011) (Figure 4) to calibrate appropriate value of Probability of going to another city for each group. In this figure, a distance of 0 to 40 km driven daily corresponds to 50% of all drivers surveyed and additional 20 km adds another 10% of drivers. Thus, we distribute all vehicles in the group 1 so that 50% of them will commute to another city. The value of the Probability of going to another city for vehicles having 1 goal (vehicles in group 1) is set up to 0.5. All vehicles in group 2 are distributed so that 40% of them will commute. That results in the value of the Probability of going to another city for vehicles having 2 goals (vehicles in group 2) being set up to 0.4. Generally, this commuting can correspond also to travelling from distant outskirts to the city.

Secondly, we need to calibrate a proper value of Maximal motorway dis-

\textsuperscript{20}If we take the average of 50 km, this would approximately correspond to driven mileages in the analysis in the Section 2.1. If we suppose people drive daily 50 km while commuting to work in 250 days in a year, plus some occasional trips on holidays, they would drive about 15 000 km yearly. In the analysis, yearly distances were 217000/15 = 14467 km.
tances for all vehicles and motorway distance distributions. Again, we inspired ourselves by the distance distribution of Santos et al. (2011). For ICEVs having Maximal motorway distance of 370 km as stated above, we used adjusted approximated distribution as shown in Figure 5. It is discrete and linearly decreasing with steps 10 km long until 100 km and with steps 50 km long after (70 for the last step) as the distribution in Figure 4 is rather flat for longer distances.

Figure 5: Motorway distance distribution for ICEVs

For EVs, maximal distance needs to be calibrated. To account for possible extremes which still have to be realistic, we run a calibration with the Probability of having two goals set up on 1 so we can explore those cases with longer distances besides the motorway length. We ruled out the option with 370 km as a maximum as our EVs’s driving range is only 164 km and we assume that they are not ordinarily used for longer routes. Again, adjusted distributions were calculated for maximal distances of 300, 250, 200 and 150 km with steps of 10 km length until 100 km and of 50 km length after. Means of final values of several variables (described in Section 3.2) are presented in Table 3. We needed to make sure that, according to Czech Ministry of Transport (2017), drivers do not drive more than 56 hours a week (8 hours a day). Thus, we monitored the maximal Daily active hours measuring the daily driving hours of EV which drives the most in total. We also checked for the mean value of the Daily number of EVs failed to get
home and a difference in Daily hours spend at home between average EVs and ICEVs. Naturally, the mean value of this difference is decreasing with decreasing Maximal motorway distance but only by a negligible amount. Lastly, we focus on minimal Daily hours spent at home of EVs which measures hours spent daily at home of EVs which is the shortest time at home in total.

<table>
<thead>
<tr>
<th>Max motorway distance (km)</th>
<th>$Maxh^{1\text{day}}_{\text{ActiveEV}}$</th>
<th>$E_{\text{nothome}}^{1\text{day}}$</th>
<th>$h^{1\text{day}}<em>{\text{HomeICEV}} - h^{1\text{day}}</em>{\text{HomeEV}}$</th>
<th>$Minh^{1\text{day}}_{\text{HomeEV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>7.43</td>
<td>0.58</td>
<td>1.68</td>
<td>2.88</td>
</tr>
<tr>
<td>250</td>
<td>7.21</td>
<td>0.06</td>
<td>1.57</td>
<td>4.22</td>
</tr>
<tr>
<td>200</td>
<td>6.88</td>
<td>0</td>
<td>1.44</td>
<td>6.24</td>
</tr>
<tr>
<td>150</td>
<td>5.81</td>
<td>0</td>
<td>1.23</td>
<td>10.91</td>
</tr>
</tbody>
</table>

Then, we calibrate the Max motorway distance to 200 km also by examining the approximate distribution of Daily hours spent at home for EVs in several runs (Figure 6). The histogram shows that only a few EVs (usually 1 to 3) spend at home on average less than 10 hours a day. These deviations do not concern us as this is possible in real world as well. Even though Max motorway distance of 200 km is not the best option from the point of minimising the value of a difference in Daily hours spend at home between EVs and ICEVs, it is minimising Daily number of EVs failed to get home which is again a decent indicator. In addition, we can still analyse the usefulness of EVs on longer distances. 200 km is also the distance between two largest Czech cities (Prague and Brno) which is one of the most frequent corridors. Nevertheless, 200 km is only an extreme value and because distances are proportionally distributed in the same manner as in the Figure 5, most EVs ride shorter distances.
Lastly, we need to calibrate appropriate value of Probability of having 2 goals for both EVs and ICEVs. For each combination of these two parameters, we observe mean values of the difference between average Daily hours spend at home between EVs and ICEVs. Parameters are varying from 0.1 to 0.9. Contour plot shows that there is not a significant relationship between the dependent variable and parameters (Figure 7). We can see a pattern suggesting lower values when Probability for ICEVs is high and Probability for EVs is low, which is the result we expect. Nevertheless, as values of dependent variable do not vary much (from 0.9 to 1.2 hours), we can conclude that the impact of changing these probabilities is not significant for model outcomes, so we calibrate both these parameter values on 0.5.
In the Table 4, we present an overview of all calibrated values.

Table 4: Overview of calibrated values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Calibrated value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of going to another city 1 goal</td>
<td>0.5</td>
</tr>
<tr>
<td>Probability of going to another city 2 goals</td>
<td>0.4</td>
</tr>
<tr>
<td>Max motorway distance EV</td>
<td>200</td>
</tr>
<tr>
<td>Max motorway distance ICEV</td>
<td>370</td>
</tr>
<tr>
<td>Probability of having 2 goals EV</td>
<td>0.5</td>
</tr>
<tr>
<td>Probability of having 2 goals ICEV</td>
<td>0.5</td>
</tr>
</tbody>
</table>

4 Sensitivity analysis

4.1 Overview

To verify the model’s operation and learn about its potential nonlinear behaviour which is the result of a complex output of various parameters’ settings and stochasticity, and to evaluate how sensitive the model is to parameters’ changes, local sensitivity analysis is conducted. Moreover, the model’s complexity does not allow us to describe its behaviour only by a closed-form equation. Some effects can be trivial and expected, and thus linear but it is important to check for those effects to be certain about the model’s accurate performance. The standard approach which we also follow is that within the sensitivity analysis, the model is eventually further modified if an abnormal situation occurs. Thus, a sensitivity analysis is an additional element of model’s development and not only a test of its features. We investigate all parameters from the Calibration Section above plus some additional ones which are of the main interest in Scenario analysis. These are Number of chargers, EV and ICEV price, EV and ICEV city speed, Parking fees, Motorway tolls and Paid electricity share. Other parameters are already fixed to fit the modelled Czech environment (Table 2). Our sensitivity analysis is based on recommended procedure by Railsback and Grimm (2011) and Domenico Delli Gatti and Stiglitz (2010). Authors suggest exploring the effects of parameters changing by +/- 5% about its reference value while
keeping other parameters fixed on their reference values. We use generally wider ranges as there are relatively high standard deviations in observed variables and also because of parameters’ nature. To examine the effect of changing parameters without any unnecessary disruptions, we sometimes keep some other parameters fixed on other than their reference values. The analysis is conducted as follows. First, we chose reference value of parameter $P$ (which we already know from calibration), then we determine the values within a specified range and also lower and upper values at the edges of this range: $P^-$ and $P^+$. We then observe a behaviour of several dependent variables reacting to parameters changing within the range. Monitored dependent variables are: $KM_{v}^{day}$, $Ticks_{v}^{km}$, $CZK_{v}^{km}$ and their differences between EV and ICEV as described in Section 3.2. Other dependent variables are either related to those three or were already examined in Section 3.3. At the end, we observe the behaviour of the model to see if dependent variables are responding to changes in a reasonable way and decide which parameters have the highest effects. Overview of all examined parameters and their ranges is depicted in Table 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>$P$</th>
<th>$P^-$</th>
<th>$P^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_c$</td>
<td>Number of chargers</td>
<td>30</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>$P_{2g}^{EV}$</td>
<td>Probability of having 2 goals EV</td>
<td>0.5</td>
<td>0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>$P_{2g}^{ICEV}$</td>
<td>Probability of having 2 goals ICEV</td>
<td>0.5</td>
<td>0.1</td>
<td>0.9</td>
</tr>
<tr>
<td>$P_{AC1goal}^{EV}$</td>
<td>Probability of going to another city 1 goal</td>
<td>0.5</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>$P_{AC2goals}^{EV}$</td>
<td>Probability of going to another city 2 goals</td>
<td>0.4</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>$P_{HCh}$</td>
<td>Probability of home-charging</td>
<td>0.9</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$Maxd^{EV}_{max}$</td>
<td>Max motorway distance EV</td>
<td>200</td>
<td>100</td>
<td>300</td>
</tr>
<tr>
<td>$Maxd^{ICEV}_{max}$</td>
<td>Max motorway distance ICEV</td>
<td>370</td>
<td>270</td>
<td>470</td>
</tr>
<tr>
<td>$s_{EV}$</td>
<td>City speed EV</td>
<td>50</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>$s_{ICEV}$</td>
<td>City speed ICEV</td>
<td>50</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>$p^E$</td>
<td>Paid electricity share</td>
<td>1</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>$p_{EV}$</td>
<td>Price of EV</td>
<td>878000</td>
<td>778000</td>
<td>978000</td>
</tr>
<tr>
<td>$p_{ICEV}$</td>
<td>Price of ICEV</td>
<td>586000</td>
<td>486000</td>
<td>686000</td>
</tr>
<tr>
<td>$t_{EV}$</td>
<td>Motorway toll EV</td>
<td>1500</td>
<td>0</td>
<td>2500</td>
</tr>
<tr>
<td>$t_{ICEV}$</td>
<td>Motorway toll ICEV</td>
<td>1500</td>
<td>0</td>
<td>2500</td>
</tr>
<tr>
<td>$f_{EV}$</td>
<td>Parking fee EV</td>
<td>0</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>$f_{ICEV}$</td>
<td>Parking fee ICEV</td>
<td>0</td>
<td>0</td>
<td>200</td>
</tr>
</tbody>
</table>
In our Cost-benefit analysis, we assume that both vehicles have their life time of 15 years (5475 days) and 217 000 km as discussed in the Section 2.1. In our model, however, average EVs has its total driven distance about 130 km daily and average ICEVs has about 143 km daily.\textsuperscript{21} ICEVs are driving more as a result of higher motorway distances based on the calibration. Generally, in this analysis, average daily driven distance is higher than in our Cost-benefit analysis. But we have to take into account that each car is used every day (regardless of weekends and holidays) and it also does not stop at its goals for a longer time, it only stays at home. With our modelled daily distances, 217 000 km made correspond to the time span of about 1500 days. Thus, we project the life time of all our agent vehicles only to 1500 days of nonstop operation.\textsuperscript{22} That way, we can think about our model as an “accelerated reality”. Because of these higher daily driven distances, we can project the results of our analysis into a longer time horizon. More concretely, our model operates faster with the “coefficient of acceleration” of 3.65.\textsuperscript{23} Thus, if each vehicle in the model would operate only every third or fourth day, we would get close to their operational time in reality. Finally, vehicles’ price is recalculated into fixed costs added daily as $\frac{Price_v}{1500}$ to the vehicle’s $I_{vi}$ variable (CZK invested of car $i$ of a breed $v$) and not as the whole one-off amount right after every model setup.

The length of one model run is fixed on 36 000 ticks (30 days). After this long time, observed variables of interest and model behaviour are already stabilised and produce consistent values (Figure 8) so we can consider 30 days as a sufficient length for obtaining representative results. With the coefficient of acceleration of 3.65, we can interpret the results visible after only 30 days of nonstop model operation into approximately 110 days in the real time.

\textsuperscript{21}With motorway usage included.
\textsuperscript{22}$\frac{217000}{143}$, rounded to hundreds. For comparability, we keep the same life-time also for EVs even though their driven distances are slightly lower.
\textsuperscript{23}Vehicles’ life time as approximated to be 5475 days in reality and 1500 days in the model. Coefficient of acceleration is then calculated as $\frac{5475}{1500}$. 
4.2 Local sensitivity analysis

We start with examining the effect of changing the Number of chargers. We set up the Probability of home-charging to 0, as well as the Probability of going to another city. Like this, we can examine the situation when EVs rely only on public chargers and we also lower the volatility of $K M_{E V}^{1 \text{day}}$ coming from the motorway distance distribution. Figure 9 shows the distribution of final values of $K M_{E V}^{1 \text{day}} - K M_{I C E V}^{1 \text{day}}$ and $T i c k s_{E V}^{1 \text{km}} - T i c k s_{I C E V}^{1 \text{km}}$ as results from multiple model runs with different settings of parameter $n_c$. White rectangles are depicting values within 25th and 75th percentile, horizontal lines inside those rectangles are the medians. Whiskers on upper and lower sides of rectangles define the values within $1.5 \times I Q R$ range\(^2\). Black points are outliers located outside this range. We can see that the effect of $n_c$ is nevertheless not very clear. Generally, $K M_{E V}^{1 \text{day}} - K M_{I C E V}^{1 \text{day}}$ is almost always positive meaning that with the same setup for EVs and ICEVs, EVs are

\(^2\)Where IQR = inter-quartile range which is the difference between lower and upper quartile.
driving more km daily as they have to search for chargers. There is a visible decrease in the amount of km made by EVs when changing the \( n_c \) from 1 over 5 to 10 and thus, shrinking the difference between ICEVs and EVs. Then, the effect is more random. We conclude that there is a significant change when moving within the lower range of parameter values but after some break-even point (\( n_c = 10 \) in our case), increasing \( n_c \) does not lead to noticeable results. Time costs depicted by \( \text{Ticks}_{1km}^{EV} - \text{Ticks}_{1km}^{ICEV} \) are not much affected by parameter values from 5 and more. This is probably the consequence of vehicles driving only in the city and thus, lower distances with the same speed so we cannot observe a clear relationship between the parameter and dependent variable. When there is only one charger, it happens more often that EVs’ battery gets depleted so vehicles are then transported to their home and given the instant recharge for 50 km which is not counted into \( TCT_{EVi} \) (Section 3.2). Based on equation 5, value of \( \text{Ticks}_{1km}^{EV} \) gets lower as a result.

Effect of Probability of having 2 goals is shown in the Figure 10. Here we set probabilities of going to another city to 0 so the effect can not be faded out by large highway distances with high deviations. We also examine dependent variables for EVs and ICEVs separately as we expect several differences, especially in the Time costs. Naturally, with higher \( P_{EV}^{2g} \), EVs are driving more. Same applies for ICEVs. EVs’ and ICEVs’ time cost for
1 km are not very responsive to this parameter as all cars still have the same speed. Moreover, with increasing $P_{EV}^{2g}$, there is not such a difference in driven distance so EVs can do their trip without any additional searching for chargers and additional public charging which would decrease their time costs (except those EVs without a home-charger).

Figure 10: Sensitivity analysis of parameter $P_{EV}^{2g}$ and $P_{ICEV}^{2g}$

For observing the effect of Probabilities of going to another city, dependent variables are again separate variables for EVs and ICEVs as they both move in the same direction. Maximal motorway distances for both breeds are now set up to 200 km so we can avoid disturbances coming from the fact that ICEVs are driving more in general. As shown in Figure 11, an average vehicle of both breeds is making approximately 10 km daily more with increasing value of the parameter $P_{AC}^{1 goal}$ by 0.1. When more vehicles are using the motorway, time cost decreases as they make more km with higher speed in comparison to the unchanged amount of km driven slowly in the city. For ICEVs, this effect is clear whether, for EVs, values of the dependent variable
are more widely distributed due to the fact that with more km driven, more charging time is also needed. Nevertheless, effect for ICEVs is smaller in absolute values as the numerator in the $Ticks^{\text{km}}_c$ equation is smaller.

Effect of increasing parameter $P^{\text{AC}}_{2\text{goals}}$ is very similar to that of parameter $P^{\text{AC}}_{1\text{goal}}$ (Figure 12). We can notice, that when $P^{\text{AC}}_{1\text{goal}} = x$ and $P^{\text{AC}}_{2\text{goals}} = x - 1$, values of dependent variables are almost equal. Because with 2 goals, vehicles are already driving more km in the city so the effect of increasing parameter $P^{\text{AC}}_{2\text{goals}}$ on Daily distance is almost identical to the effect of $P^{\text{AC}}_{1\text{goal}}$ but on a higher km range.
For the next analysis, we set up Probabilities of having 2 goals on 1 so vehicles have longer distances in the city to make and have to use chargers more in general. We also set Probabilities of going to another city on 0 to explore the effect only in the city environment as in the case of the parameter $n_c$. That way we eliminate disruptions coming from Motorway distance distribution. Again, EVs are driving almost always more because they need to search for chargers. With increasing amount of EVs having the charger at home, $K_{MEV}^{\text{day}}$ and so the difference in daily km made is getting slightly lower as seen from the Figure 13. This is caused by lower need of public charging and thus fewer situations when EVs have to search for chargers and drive few km more. With $P^{HCh} = 1$, EVs are driving nearly the same amount of km daily as ICEVs. Effect on Ticks for km made is clearly increasing. This is reasonable because home-charging is slower than public-charging making the time cost for 1 km of EVs higher. This effect of
slower charging clearly exceeds the time saved by less searching for public chargers and it has also a greater magnitude than effects in previous analyses (e.g. the parameter $P_{2goell}^{AC}$).

Figure 13: Sensitivity analysis of parameter $P^{HCh}$: Dependent variables as differences

For exploring the effect of changing Maximal motorway distances, we examine parameter values varying by 50 km with changing the whole distribution of Motorway distances for specified breed, again using a linear decreasing distribution with steps 10 km wide until 100 km and then with steps 50 km wide (70 km for the last step in case of ICEVs). As depicted in Figure 14, with higher maximal motorway distance for EVs and thus a higher probability of driving longer distances on a motorway, $KM_{EV}^{1day}$ and so the difference in km driven daily between EVs and ICEVs is lower. Also, the time costs for EVs are lower as vehicles are driving more km with higher speed in comparison to slower driving in the city. We can notice that EVs and ICEVs are driving almost the same distances daily when $Maxd_{EV}^{tm} = 300$. 
Figure 14: Sensitivity analysis of parameter $Maxd_{EV}^m$: Dependent variables as differences

For ICEVs, the relationship between the parameter and both independent variables is clear. Higher Maximal motorway distance translates into higher $KM_{ICEV}$ and lower $Ticks_{ICEV}$ because of a larger part of daily trip driven with higher speed (Figure 15). However, in absolute values, effect on $Ticks_{EV}$ for 1 km made is minimal in comparison with previous parameter $Maxd_{EV}^m$. Daily driven distance is the same for EVs and ICEVs when $Maxd_{ICEV}^m = 270$.

Figure 15: Sensitivity analysis of parameter $Maxd_{ICEV}^m$: Dependent variables as differences

When examining the effect of changing the parameter City speed, it is enough to observe only Difference in $Ticks_{EV}$ for 1 km made as vehicles are behaving still the same what concerns the distance and charging, only the time cost is affected. Moreover, Probabilities of going to another city are
again set to 0 as they would disrupt the ratio of slow to fast distance driven because the Motorway speed is set up to be 100 km/h by default. As expected, with increasing $s_{EV}$ and $s_{ICEV}$, ticks for 1 km made for each breed are decreasing (most significantly when changing the speed from 10 to 20 km/h) since the ratio of distance driven slowly to distance driven quickly is getting lower (Figure 16). It is important to notice that EVs are always slower due to additional charging time (resulting in a positive value of the dependent variable) except the situation when their city speed is 50 km/h (reference value of $s_{EV}$) and city speed of ICEVs is 10 km/h. That is the only situation when the value of the dependent variable is negative.

Figure 16: Sensitivity analysis of parameter $s_{EV}$ and $s_{ICEV}$: Dependent variables as differences

![Graph showing sensitivity analysis](image)

For last four parameters examined, we observe only CZK invested for 1 km as these are parameters affecting only the money invested and not the behaviour of cars. Moreover, we again set maximal motorway distances to 200 km for both breeds so their total distances driven are roughly the same (more for EVs because of charger searching). Except the case when we examine the parameters $p_{EV}$ and $p_{ICEV}$, purchase prices are setup to 0 CZK so we can see the effect of all other monetary incentives more clearly. Otherwise, many times higher initial price would apparently exceed those small changes in other costs after only 30-day model run.

Firstly, we examine the effect of changing the value of $P^E$. As shown in Figure 17, the dependent variable is increasing with increasing parameter as
the price for the unit of electricity gets higher. We can see that difference in money invested is negative as the fuel for ICEVs is more expensive and we keep other monetary parameters fixed on identical values for both EVs and ICEVs.

Figure 17: Sensitivity analysis of parameter $P_E$: Dependent variables as differences

When looking at changes in purchasing prices of vehicles, the trend in the dependent variable is clearly visible. Because of higher price of EVs than of ICEVs, the difference in costs between EV and ICEV is always positive. Generally, lower initial price means lower fixed costs and thus lower unit cost for 1 km (Figure 18).

Figure 18: Sensitivity analysis of parameter $p_{EV}$ and $p_{ICEV}$: Dependent variables as differences

For examining the effect of increasing Motorway toll for EVs and ICEVs, we set up the Probabilities of going to another city to 1 so we can explore
the effect more clearly without it being eliminated by vehicles not using
the highway and not paying the toll. We can see that costs for 1 km are
slightly increasing but only by about 0.005 CZK for every additional 500
CZK rise in the motorway toll (Figure 19). This is because the yearly toll in
comparison to e.g. vehicle purchase price is a very small amount. Thus, it
has practically no effect on money invested, especially when the amount is
divided by a number of kilometres made. In addition, ICEVs are now always
paying more because of more expensive fuel but same motorway distances.

Figure 19: Sensitivity analysis of parameter $t_{EV}$ and $t_{ICEV}$: Dependent variables as
differences

When looking at Parking fees as depicted in Figure 20, the effect of
increasing parameter value is positive. As this fee is only a small amount,
even though it is paid by all vehicles when achieving goal1, it does not
significantly influence the value of dependent variable. Increasing EVs’ or
ICEVs’ parking fee by 50 CZK raises their costs for 1 km only by about 0.4
CZK.
5 Scenario analysis

In this Section, we introduce various scenarios which we then implement in our NetLogo model calibrated to the Czech environment as described in Section 3.3. Based on results of this scenario analysis we evaluate effects on economy, usability and convenience of EVs for Czech consumers. That way, we can observe benefits and effectiveness of different policies aimed at increasing EVs’ market potential. Results are compared with the basic scenario which is together with its settings already described in the Section 3.2. With the ABM methodology, we are able to incorporate various attributes occurring in the real world as the individual behaviour of agents and general randomness. We are aware that our approach illustrates only a simple stylised model of reality which incorporates only the main real attributes like a regular city, motorways, charging and daily commuting into work. In the analysis, however, we keep the model settings fixed so these imperfections occur in every scenario and every model run. Thus, we can observe the clear effects of our scenarios and their modifications. In contrast with the Sensitivity analysis described in the previous Section, we are more interested in the magnitude of effects of changing parameter values and not only their trend. We also examine more in detail those variables’ particular values. When
deciding which scenarios to conduct, we inspired ourselves by the study of Czech Ministry of Industry and Trade (2015) which is already introduced in the Section 2 above. For each scenario, we first explain its features and our motivation for studying and implementing it in the model. Then we adjust model's parameters and do multiple runs with the same settings to simulate this particular situation under stylised conditions. Then we discuss the results and their potential applications in policy-making. Scenario overview is given in the Table 6.

<table>
<thead>
<tr>
<th>Scenario Description</th>
<th>Category of incentive</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Purchase subsidy and VAT exemption</td>
<td>Financial</td>
</tr>
<tr>
<td>2 Electricity supply costs reduction</td>
<td>Financial</td>
</tr>
<tr>
<td>3 Waivers on tolls and parking fees</td>
<td>Financial</td>
</tr>
<tr>
<td>4 Development of charging infrastructure</td>
<td>Usage and accessibility</td>
</tr>
<tr>
<td>5 Access to bus lanes and exclusive zones in the city</td>
<td>Usage and accessibility</td>
</tr>
</tbody>
</table>

5.1 Purchase subsidy and VAT exemption

Probably one of the most important and widely practised financial incentives, purchase discount of any type is positively accepted by all consumers considering buying an EV (International Energy Agency, 2016). Because these vehicles are much more expensive due to their different technology and especially higher costs emerging from battery manufacturing, their price is a crucial obstacle to purchase. As it was already discussed in the Section 1.1, in Norway, total discount is so high that EV are actually cheaper to buy than comparable ICEVs. In the CR, no purchase exemption has been introduced yet. So we implement a scenario of the potential introduction of the purchase subsidy and VAT exemption in our model and observe its potential to decrease total costs for a consumer. According to the research conducted by Czech Ministry of Industry and Trade (2015), the impact on consumers which would the purchase subsidy and complete VAT exemption have is the highest from all examined policies. Nevertheless, this solution is not considered as feasible for the government. Thus, we also examine the
situation with the VAT exemption only which is supposed to be less costly for government and the state budget.

What concerns the implementation of these policies to our model, we keep all parameters on their reference values (Table 2) or calibrated values (Table 4). Only the Price-EV attribute is changed from 878 000 CZK to 526 000 CZK. This reduction corresponds to complete (21%) VAT exemption and purchase subsidy of 200 000 CZK which is already discussed in the Section 2.2. Then we set the price to 726 000 CZK as a representation of only the VAT exemption. The price of our modelled ICEV is 586 000 CZK. Purchase price of the vehicle is recalculated into costs added daily. At the end of every day, we add $Price_v/1500$ to the vehicle’s $I_{vi}$ variable (CZK invested of car $i$ of a breed $v$) as discussed in the Section 4.1. To see the effect, we compare the value of CZK invested for 1 km. With basic scenario after 30 days of nonstop model operation, EV’s costs for 1 km are a bit higher than that of ICEVs because of higher fixed cost (price) added daily. What is more important however, is that with the establishment of both purchase incentives, because of lower fixed costs, EV costs for 1 km become lower by 34% in comparison to basic scenario and by 27% in comparison to ICEV as shown in Figure 21. This gives the EVs clear advantage above ICEVs. With the less radical scenario of only VAT exemption, costs reduction in comparison to basic scenario is 16% and 7% in comparison to ICEVs’ costs.

![Figure 21: Scenario 1: Costs for 1 km](image)

Thus, we conclude that these incentives really have significant effects on
total costs connected to purchase and usage of EV and so consumers’ decision. If the government would aim to increase EVs’ market share, this kind of policy would definitely help. Nevertheless, it would have to incur these additional expenditures into the state budget as well as forgo potential profits from VAT collection. Despite its high potential to increase EVs’ market share, in the CR this policy is rather considered as infeasible (Czech Ministry of Industry and Trade, 2015) because of higher costs for the government.

5.2 Electricity supply costs reduction

Another policy dealing with the financial allowance for potential and current EV users can be the reduction of electricity price. Even though the electricity is already cheaper than gasoline (49.2 vs. 164.3 CZK for 100 km) as described in Section 2.2, additional costs reduction is considered as a feasible way how to increase the market potential of EVs. According to the analysis of Czech Ministry of Industry and Trade (2015), discounted tariff on electric power supply would have a medium impact on consumers’ decisions but it would be actually easy to establish under actual Czech conditions. Nowadays, some large electricity providers in the country such as the ČEZ are already providing some kind of advantage for their customers having an EV, and that is daily discounted tariff from 6 p.m. to 8 a.m. Taking into consideration that drivers are charging their vehicles mostly at home at night, final electricity costs reduction can be about 50 % in total (ČEZ Group, 2017b). What concerns the public charging, the policy, in this case, is in fact not simple to implement as these chargers are built and owned by both large electricity distributors and private investors so prices are varying. Moreover, EVs drivers are not using public chargers that often as they use their home source which is a naturally more comfortable way.

For implementing this scenario into our model, we again keep all parameters fixed on their reference or calibrated values, only the paid electricity share is set up on 0.5 as the realisable cost reduction suggested by ČEZ
Group (2017b). The value of $P^E$ in the basic scenario is 1. We do not
distinguish between the electricity charged at home and the one at public
chargers as actual costs are added to the $CZK^m_{EV}$ counter when an EV
moves so we count the electricity used, not charged. One model run is again
30 days long and we observe only the time costs. Distances driven are ap-
proximately the same as in the Scenario 1. From the Figure 22, we can see
that potential establishment of this policy does not really change the total
costs of EV. As it was already mentioned in the Section 4.2, this is because
the unit electricity costs are already low in comparison to the price of gas-
oline. That means that variable costs which are added after every km made
are not sufficiently lower to generate a significant decrease in total costs.
Costs for 1 km of EVs are reduced by 14% in comparison to basic scenario
but are still higher than costs of ICEVs because of higher purchase price and
thus higher fixed costs. Thus, we run the scenario again but with purchase
prices set up to 0 so we can compare variable costs only.\footnote{Another fixed costs added daily is the maintenance of 23 CZK for EVs and 33 CZK for ICEVs and
highway tolls of 4 CZK. These amounts as well as their effect on total costs (fixed + variable), however,
are negligible in comparison to purchase prices.} In the Figure 23,
we see that with basic scenario, costs for 1 km of EVs are already 64% lower
than costs for ICEVs. This is a result of much lower variable costs coming
from the cheaper electricity than gasoline. After the policy establishment,
there is a 37% decrease in costs of EVs and 77% decrease in costs of EVs in
comparison to ICEVs.

Figure 22: Scenario 2: Costs for 1 km with the purchase price included
The final statement is that the policy of electricity supply cost reduction is not as costly to government or large electricity providers as direct purchase subsidies (Czech Ministry of Industry and Trade, 2015) and it certainly has at least a psychological effect on buyers. It could also help with the decision of public charger investors whether to make these chargers paid or not. As EV drivers would charge their vehicles mostly at home, it is likely that they would not mind paying for the electricity outside as it does not represent an especially large portion of the electricity consumed. Unless the battery technology improves so EV driving range prolongs substantially, no radical savings for Czech consumers could be done with this policy. But from the market side, we suppose that it could help to improve EV sales potential because if we look only at operating costs, there is a significant advantage for EVs resulting from the cheaper electricity than gasoline.

5.3 Waivers on tolls and parking fees

As the last incentive from the financial category, we observe the effect of tolls and parking fees reduction on potential economic savings for EV users. Drivers could also benefit from these incentives from the practical point of view. They do not need to care about buying motorway stamps (as is the case of the Czech toll system) or searching for the most convenient parking place in the city. That can make everyday usage of EV much easier. According to Czech Ministry of Industry and Trade (2015), free parking...
policy could be actually equally effective as the purchase discount and that means very effective. Additionally, it is also more feasible for the Czech government and the state budget. Effect of toll exemption is supposed to be slightly lower but still decent to increase EV market share (Czech Ministry of Industry and Trade, 2015).

We decided to examine these two kinds of policies together as it is usually done in similar analyses (e.g. in the research of International Energy Agency (2016)) and also because of relatively small quantitative changes in parameters and thus, dependent variables. The basic scenario now is slightly different. We set the parameter Parking fee for EVs and ICEVs on 240 CZK instead of 0 CZK.\footnote{According to spravneparkovani.cz (2010) and TSK hl. m. Prahy (2017), average parking fee in the CR for 1 hour is 21 CZK and 40 CZK in Prague centre, we use approximate average of these fees (30 CZK) and multiply it by 8 to represent a daily parking time in the city.} This fee is added to the vehicle’s counter of money invested $I_{vi}$ whenever the vehicle $i$ of breed $v$ arrives at its goal1. Motorway toll is set up to 4.11 CZK daily (1500 CZK yearly) according to actual prices in the CR (for Transport Infrastructure, 2017). All other parameters are setup on their reference or calibrated values. Then we set both Parking fee and Motorway toll for EVs on 0 to represent complete exemption from these fees as it was also considered in the analysis of Czech Ministry of Industry and Trade (2015). As shown in Figure 24, average costs for 1 km for an EV in the basic scenario are again higher than costs for ICEVs because of higher price and thus, higher fixed costs. After the policy establishment EVs’ costs are reduced by 14% in comparison with basic scenario and by 5% in comparison to ICEVs. This is a result of decline in costs added daily for EVs using the motorway (fixed costs) and also of decline in costs whenever they arrive at their goal1 (variable costs). In Figure 25, we again observe the policy establishment without taking the purchase prices into the account as they tend to increase fixed and thus total costs significantly. Here EVs’ costs are already lower in the basic scenario than those of ICEVs again because of significant fixed costs reduction. After the policy establishment, total costs of EVs are reduced by 72% in comparison to the basic scenario and by 81%
in comparison to ICEVs.

To conclude, even though that the establishment of this policy would not lead to immediate significant economic savings for EVs users, it could serve as a psychological incentive because of feasible outlook from the practical point of view. If we also consider the actual situation and market share of EVs in the CR, these several exemptions would not be very costly for the state or municipal budgets. Our scenario further shows that this combined policy would be slightly more effective than direct electricity cost reduction as was also the result of the analysis done by Czech Ministry of Industry and Trade (2015). Nevertheless, with a potentially elevated market share of EVs, a situation with free motorways and parking could become unsustainable in few years. Thus, it should not be considered as a permanent solution since marginal benefits would eventually fade out.
5.4 Development of charging infrastructure

The present situation of chargers availability in the CR is probably one of the most important arguments against an EV purchase. Sufficient infrastructure would eliminate consumers’ doubts about EVs’ practicability and limited driving range. Nevertheless, there is not any official support of charging infrastructure development from the government’s side. There are also some substantial risks connected with investments into the building of chargers since investors’ decisions depend on actual circumstances in the EV market (which is, on the other hand, influenced by existing charging infrastructure). Generally, current Czech charging network is considered as highly insufficient (Czech Ministry of Industry and Trade, 2015). What concerns the EV market share, based on the analysis of the Ministry, incentives for this infrastructure development would have almost the same consequence as the most effective purchase subsidy. Thus, we decided to include this scenario into our analysis to verify the results.

The reference value of the parameter Number of chargers in our basic scenario is 30. This is based on the EVSELECT, s.r.o. (2017) portal as an approximate average value between Prague and few smaller cities which are both represented by our modelled environment (when cars are using the motorway and commuting to different cities). Unfortunately, we could only guess by how many chargers the network would expand after the establishment of some kind of this supportive policy. So for the scenario, we increased the number by 20 which means the expansion of existing network by almost 70%. This seems already as huge increment but the resulting density is still quite low, for example, 3 times less in comparison to the Germany (German National Platform for Electric Mobility (NPE), 2015). Nevertheless, building a new EV charger is associated with high costs and so we could not consider some higher increment (more than 70%) as a feasible solution in the short-run as in absolute numbers, 20 is already a high amount. We observe only the time costs to see if EVs need to drive less and thus need less public charging after the policy establishment. As it was already mentioned in the
Section 4.2, increasing number of public chargers has no visible effect on the additional driven distance by EVs as one would probably expect. Time costs are reduced only by a negligible amount of 0.05% for EVs in comparison to basic scenario and they still remain higher than time costs for ICEVs. In addition, this negligible reduction is driven also by the deviation of the dependent variable.

Figure 26: Scenario 4: Time costs

Thus, if we look at possible investments into the charging infrastructure in the CR from the practical point of view, quantitative results are really unimportant. As we suppose that majority of EV drivers would charge their vehicles mainly at home (as it is usually practised and our model is accordingly calibrated), higher density would not result in significant decline in the number of km made because EVs do not have to drive larger distances to find a public charger. Thus, it does not generate significant time savings resulting from driving few km less and charging less. We can conclude that current density is big enough so drivers do not have to drive more km in order to use a public charger. Of course, it could be still more difficult on motorways, where drivers have to manage the limited driving range on occasional trips between distant cities (such as Prague and Ostrava) so they have to deal with additional time dedicated to recharging. As it was already mentioned, however, most of the currently sold EVs are primarily designed for everyday use in the city. We agree with Czech Ministry of Industry and Trade (2015), that supporting policy would definitely assure the drivers about more con-
convenient and accessible use of EVs even though the effect would be mainly psychological. As shown in our model results, significant time savings in everyday use are not made because of already sufficiently dense charging network. Nevertheless, from the different point of view, the problem with living and having an EV in the city is the availability of home-charging as many people park their cars on the street. More public chargers can be a non-negligible incentive especially for them since they could just charge their EV few times a week somewhere outside even though this solution is probably not that comfortable as charging in the own garage at night.

5.5 Access to bus lanes and exclusive zones in the city

The last scenario which we examine in our analysis is the priority access of EVs to bus lanes and some exclusive zones in the city centre which are under normal conditions unavailable for all motor vehicles. Even though the access policy is fully implemented only in a few countries in the world as Norway and partly France, Germany and UK (International Energy Agency, 2016), we think of it as an interesting idea of how to promote EV convenience and increase their market share. It does not save consumers’ money directly, but it can definitely save time, especially in large congested cities. Mainly the Prague traffic is very dense in comparison to other places in the country. Bus lanes are not that common in the CR (except Prague) because of mostly narrow streets and there are very few exclusive zones (e.g. Old Town district in Prague), where the access for vehicles would be limited. Establishment of low-emission zones was discussed several times but no law was yet adopted (Ministry of the Environment of the Czech Republic, 2017). According to the study of Czech Ministry of Industry and Trade (2015), these two policies would have rather a middle impact of increasing EVs’ market potential, but with relatively low feasibility because of reasons mentioned above.

The way how we try to implement this scenario into our model is rather simplified but it can serve well as the approximation. If we suppose that EVs could use the zones and bus lanes, they would move quicker in total than
other vehicles as they would not get into a traffic jam or make detours around the centre. In the basic scenario, city speed for both kinds of vehicles is now set to be 37 km/h as the average speed of vehicles in Prague, according to Olson and Nolan (2008), (reference value is 50 km/h). Motorway speed is set to be 100 km/h as in general model settings. Generally, time costs for EVs are higher because of longer refuelling time as discussed in the Section 3.2. We increase the city speed for EVs to 45 km/h as they benefit from higher accessibility. Time costs are being depicted by variable $Ticks_{Ev}^{1km}$ in the Figure 27. Naturally, they stay much higher for EVs because of significantly higher refuelling time. This is a well-known fact and unless the battery and fast-charging technology will develop more, this will always be their disadvantage. If we are however more interested in the change after the policy establishment, we can notice the decrease in the variable $Ticks_{Ev}^{1km}$ by 5% in comparison to basic scenario. This is a result of higher city speed which decreases $Ticks_{Ev}^{1km}$ as described in the Section 3.2.

![Figure 27: Scenario 5: Time costs](image)

Thus, it is clear that this policy would give an advantage to EV users in the ability to move within the cities. EVs would be much more practical to use. This policy represents important time savings for drivers. Specifically, after this establishment, EV drivers would save 0.13 min on every km made, that is 17 min daily in our model and approximately 5 min daily in reality in regular traffic.\textsuperscript{27} With congestions occurring in e.g. rush hours, time

\textsuperscript{27}Based on the fact that 1 tick equals 1.2 min (Section 3.2), modelled daily distance driven being 130
saved would be definitely greater. This policy is nevertheless, in the same manner as the Scenario 3 not sustainable in the long run, considering that EV market share would rise. After a sufficiently high amount of vehicles with these benefits, bus lanes would be similarly congested as the normal roads and city centres would be full of cars again creating higher risks for pedestrians. Moreover, it is not easily applicable in the Czech conditions because of a current state of the Czech traffic system, except some locations in Prague where bus lanes already exist. However, for people living for example in the Prague surroundings who daily commute to the centre to work, bus lanes access would represent a considerable incentive (as well as parking fee reduction).

5.6 Evaluation

From all different scenarios we have analysed, highly significant results could be seen in implementing Purchase subsidies and VAT exemptions which we can consider as the most effective financial incentive for increasing EV market potential. The advantage for consumers from this policy is that savings are done immediately with the purchase and are not directly dependent on a vehicle usage as opposed to electricity cost reduction and waivers on various fees. If we look at the operational costs reduction without taking the prices into account, waivers on tolls and parking fees are the most effective policies. From the usage accessibility point of view, the most effective policy seems to be providing access to bus lanes and exclusive zones as they save the drivers more time than for example denser charging network. Nevertheless, from this point of view, ICEVs seems to be still more time effective because of significantly lower refuelling time.

One could be surprised with the results of better infrastructure policy scenario which showed no clear improvement in the EV usage. This confirms an assumption, that these investments and building of new chargers serve more as a psychological tool for hesitating consumers. Similar logic
applies to reduced electricity supply charges which would also have a positive effect on consumers decisions but in the end, it would not represent high financial loss for electricity providers. Based on our analysis, we could state that with the current or potentially more dense charging network, providers can charge some fee for electricity to at least partly pay off the investments into the installation. Positive effect on consumers from better infrastructure is likely to exceed the additional negative one from the duty of paying for the energy. It is not easy to measure or decide if financial incentives would result in higher EV market share than non-financial ones as we are comparing financial savings with the practicability and convenience. However, we found that there exist some quantitatively highly effective policies from each category. For example the VAT exemption would result in costs which are 7% lower than those of ICEVs. With the purchase subsidy of 200 000 CZK in addition, costs would be even 27% lower than costs of ICEVs. Waivers on tolls and parking fees would result in 5% lower total costs in comparison to ICEVs but when looking on the operational costs only, they would be even 81% lower than costs of ICEVs. Non-financial incentives are not giving a clear advantage to EVs over ICEVs. Nevertheless, access to bus lanes and exclusive zones would be very attractive to drivers living in Prague and its surroundings. Finally, the combination of these policies from different categories could result in better outcomes if increasing EV market share would be the aim of the Czech government.
Conclusion

In this thesis, we inspired ourselves by an earlier US analysis of the ecological impact of EVs and we applied a similar methodology in the Czech stylised environment. We found out that even though the electricity grid mix in this country is relatively highly unsustainable and unecological, manufacturing and using an EV would subsequently result in lower CO$_2$ emissions over its whole life cycle in comparison to a conventional ICEV. Despite the higher emissions from vehicle manufacturing, initially greater pollution would be offset by EV’s more ecological driving after approximately 2 years of usage.

What concerns the economical point of view for the Czech consumer, EVs are relatively more expensive to buy but maintenance and refuelling costs are lower. Nevertheless, initial price gap between an average EV and average ICEV is so large that under the actual policy, most Czech consumers would probably not financially benefit from an EV usage, even after several years. Unless the government would provide these consumers with some material incentives or the costs of EV production would significantly decline, there is practically no possibility of financial savings made while having an EV instead of an ICEV. Unfortunately, the usage accessibility for EV drivers in the CR is still not sufficiently developed. This acts as another barrier against the choice for its purchase.

In case that Czech government would be interested in rising the market share of EVs, we conducted a detailed scenario analysis focused on various policies aimed at increasing EV market potential. We used the Agent-Based modelling methodology to construct a ABM model of the Czech vehicle market. We calibrated the model to actual Czech conditions and observed a quantitative effectiveness of the most popular policies practised in other countries. From our explored financial and non-financial incentives, the most effective ones seem to be the purchase discount and increased general accessibility as the permission to use bus lanes, free parking or access to exclusive zones in cities. It is important to notice, however, that policies as the investment into the charging infrastructure and reduced electricity
costs would have a substantial psychological effect, even though our analysis showed their total uselessness from the quantitative side.

To conclude, a future situation of the Czech EV market would heavily depend on possible implementation of policies as well as consumers’ preferences. Nevertheless, we could be certain that with the actual speed of vehicle technology development and also with trends coming from abroad, EVs’ usage accessibility will rise and their market potential will expand. EVs’ popularity is expected to increase, even within conservative Czech consumers.
References


European Automobile Manufacturers Association (2015, 12). New passenger car registrations by alternative fuel type in the European


German National Platform for Electric Mobility (NPE) (2015, 11). Charging infrastructure for electric vehicles in germany, progress report and recom-
mendations 2015. *German Federal Government, Joint Unit for Electric Mobility (GGEMO)*.


Appendix A

Additional calculations

For the Cost-benefit analysis section, following calculations and sources are used:

Table 7: Calculation of EVs’ consumption and fuel price

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Amount</th>
<th>Market share (%)</th>
<th>Consumption (kWh/100 km)</th>
<th>Price of 100 km (CZK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volkswagen E-golf</td>
<td>76</td>
<td>41.1</td>
<td>12.7</td>
<td>47.1</td>
</tr>
<tr>
<td>BMW i3</td>
<td>70</td>
<td>37.8</td>
<td>12.9</td>
<td>47.9</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>32</td>
<td>17.3</td>
<td>15</td>
<td>55.7</td>
</tr>
<tr>
<td>KIA Soul EV</td>
<td>2</td>
<td>1.1</td>
<td>14.7</td>
<td>54.5</td>
</tr>
<tr>
<td>Mercedes-Benz B ED</td>
<td>2</td>
<td>1.1</td>
<td>16.6</td>
<td>61.6</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>1</td>
<td>0.5</td>
<td>15.4</td>
<td>70.1</td>
</tr>
<tr>
<td>Mitsubishi I MiEV</td>
<td>1</td>
<td>0.5</td>
<td>12.5</td>
<td>50.1</td>
</tr>
<tr>
<td>Peugeot I-on</td>
<td>1</td>
<td>0.5</td>
<td>12.6</td>
<td>46.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>185</strong></td>
<td><strong>100</strong></td>
<td><strong>13.3</strong></td>
<td><strong>49.2</strong></td>
</tr>
</tbody>
</table>

The resulting Consumption and Price of 100 km in the row Total was calculated as weighted average of all listed vehicles:

\[
Consumption = \sum_{i=1}^{8} c_i \times ms_i, \tag{11}
\]

\[
Price^{100\text{km}} = \sum_{i=1}^{8} 3.71 \times c_i \times ms_i, \tag{12}
\]

where \( c_i \) is the combined fuel consumption of a vehicle \( i \), \( ms_i \) its market share and 3.71 equals average price of electricity in the Czech Republic in CZK (Energie123.cz, 2017).

\(^{28}\)Technical specifications of the newest models available in 2014 were chosen.

\(^{29}\)© Motoreu.com (2016); Kia Motors CZECH s.r.o. (2012)
Table 8: Calculation of EVs’ driving range

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Market share (%)</th>
<th>Consumption (kWh/100 km)</th>
<th>Battery size (kWh)</th>
<th>Driving range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volkswagen E-golf</td>
<td>41.1</td>
<td>12.7</td>
<td>24</td>
<td>189</td>
</tr>
<tr>
<td>BMW i3</td>
<td>37.8</td>
<td>12.9</td>
<td>18</td>
<td>140</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>17.3</td>
<td>15</td>
<td>24</td>
<td>160</td>
</tr>
<tr>
<td>KIA Soul EV</td>
<td>1.1</td>
<td>14.7</td>
<td>27</td>
<td>184</td>
</tr>
<tr>
<td>Mercedes-Benz B ED</td>
<td>1.1</td>
<td>16.6</td>
<td>28</td>
<td>169</td>
</tr>
<tr>
<td>Ford Focus Electric</td>
<td>0.5</td>
<td>15.4</td>
<td>23</td>
<td>149</td>
</tr>
<tr>
<td>Mitsubishi I MiEV</td>
<td>0.5</td>
<td>12.5</td>
<td>14</td>
<td>112</td>
</tr>
<tr>
<td>Peugeot I-on</td>
<td>0.5</td>
<td>12.6</td>
<td>14</td>
<td>111</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>13.3</strong></td>
<td><strong>22</strong></td>
<td><strong>164</strong></td>
</tr>
</tbody>
</table>

Driving ranges for individual vehicles can differ from actual manufacturer’s information as we used constant measurement for better comparability:

\[ dr_i = \frac{c_i}{b_i} \times 100, \]  

where the Driving range of a vehicle \( dr_i \) is calculated as its combined consumption divided by the battery size \( b_i \) times 100.

Driving range in the row Total is calculated as:

\[ \sum_{i=1}^{8} dr_i \times m_s_i. \]  

Table 9: Calculation of EVs’ price

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Amount</th>
<th>Market share (%)</th>
<th>Price (CZK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volkswagen E-golf</td>
<td>76</td>
<td>41.8</td>
<td>915 900</td>
</tr>
<tr>
<td>BMW i3</td>
<td>70</td>
<td>38.5</td>
<td>900 000</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>32</td>
<td>17.6</td>
<td>730 000</td>
</tr>
<tr>
<td>KIA Soul EV</td>
<td>2</td>
<td>1.1</td>
<td>849 980</td>
</tr>
<tr>
<td>Mercedes-Benz B ED</td>
<td>2</td>
<td>1.1</td>
<td>1 020 000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>182</strong></td>
<td><strong>100</strong></td>
<td><strong>877 518</strong></td>
</tr>
</tbody>
</table>

Note: Only EVs sold and available in the Czech vehicle market in 2014.

Here, the resulting price in the row Total was calculated as weighted average.

\(^{30}\)© Motoreu.com (2016); Kia Motors CZECH s.r.o. (2012)

of all prices:

\[ \sum_{i=1}^{5} p_i \times ms_i, \quad (15) \]

where \( p_i \) is the purchasing price of a vehicle \( i \) and \( ms_i \) its market share.
Appendix B

Figure 28: NetLogo Interface