

**Bachelor Project**



**Czech  
Technical  
University  
in Prague**

**F3**

**Faculty of Electrical Engineering  
Department of Cybernetics**

## **Fleet Electrification Decision Support Tool**

**Vít Šenfeld**

**Supervisor: Ing. Martin Schaefer**

**Field of study: Open Informatics**

**Subfield: Artificial Intelligence and Computer Science**

**May 2021**



## I. Personal and study details

Student's name: **Šenfeld Vít** Personal ID number: **483446**  
Faculty / Institute: **Faculty of Electrical Engineering**  
Department / Institute: **Department of Cybernetics**  
Study program: **Open Informatics**  
Specialisation: **Artificial Intelligence and Computer Science**

## II. Bachelor's thesis details

Bachelor's thesis title in English:

**Fleet Electrification Decision Support Tool**

Bachelor's thesis title in Czech:

**Nástroj pro podporu rozhodování při elektrifikaci vozového parku**

Guidelines:

Electromobility is rising and the adoption of an electric vehicle (EV) is being considered by growing number of people and companies. When we are considering if an EV is suitable for us, we might use our mobility history and consider if our mobility needs are satisfiable by EV. The goal of the thesis is to create a tool that would take a mobility needs and try to find a operation plan for EV to satisfy the needs. The output of the tool is a plan itself to show where and when the EV would need to charge. Moreover, each plan induce the indicators of the suitability of the EV for the respective mobility needs. The indicators are then useful when users decide whether to purchase an EV.

1. Research the related problems to electrification of fleets and planning (consider using existing planner [3,4]) for EVs and briefly introduce the existing solutions similar to the desired tool.
2. Design the concept of the desired tool with a focus on a single vehicle/user. Describe and motivate the usage of the components.
3. Implement the functional prototype of the tool. Describe the fundamental algorithmic components.
4. Demonstrate the usage of the tool on available data or on the artificial examples.

Bibliography / sources:

- [1] GLOBISCH, Joachim, Elisabeth DÜTSCHKE a Martin WIETSCHEL. Adoption of electric vehicles in commercial fleets: Why do car pool managers campaign for BEV procurement? Transportation Research Part D: Transport and Environment. 2018, 2018(64), 122-123. Available at: <https://www.sciencedirect.com/science/article/pii/S136192091630774X>
- [2] GREAVES, Stephen, Henry BACKMAN a Adrian B. ELLISON. An empirical assessment of the feasibility of battery electric vehicles for day-to-day driving. Transportation Research Part A: Policy and Practice. 2014, 2014(66), 226-237. Available at: <https://www.sciencedirect.com/science/article/pii/S0965856414001359>
- [3] Marek Cuchý, Michal Jakob: Electric Vehicle Travel Planning with Lazy Evaluation of Recharging Times. SMC 2019: 3168-3173
- [4] Marek Cuchý, Michal Stolba, Michal Jakob: Whole Day Mobility Planning with Electric Vehicles. ICAART (2) 2018: 154-164

Name and workplace of bachelor's thesis supervisor:

**Ing. Martin Schaefer, Artificial Intelligence Center, FEE**

Name and workplace of second bachelor's thesis supervisor or consultant:

Date of bachelor's thesis assignment: **08.01.2021** Deadline for bachelor thesis submission: **21.05.2021**

Assignment valid until: **30.09.2022**

Ing. Martin Schaefer  
Supervisor's signature

prof. Ing. Tomáš Svoboda, Ph.D.  
Head of department's signature

prof. Mgr. Petr Páta, Ph.D.  
Dean's signature

### III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

\_\_\_\_\_  
Date of assignment receipt

\_\_\_\_\_  
Student's signature

## Acknowledgements

I would like to thank my supervisor Ing. Martin Schaefer, for the helpful consultations, patient guidance, valuable comments, and help with all the problems that occurred. Also, I would like to thank Ing. Marek Cuchý for the permission to use the planner within this thesis and for all the planner modification that he implemented according to my propositions. Also, I want to thank Dimitris Iliou and Jiří Humpl for their work on the visualizer used as the basis of the front-end part of my tool and for their implementation of my propositions. In addition, I would like to thank my family for their great patience and support during my studies.

## Declaration

I declare that I have prepared the presented work independently and that I have listed all the sources of information used within it in accordance with the Methodical Instruction on Adherence to Ethical Principles in the Preparation of University final theses.

Prague, May 20. 2021

## Abstract

With the expansion of electromobility, a growing number of people and companies consider replacing their conventional vehicles with electric ones. These potential users need to find out, whether it is possible to fulfil their actual mobility needs with an electric car or not. This bachelor thesis explores the possible facilitation of the decision-making process by creating a multi-functional tool. The proposed tool processes the mobility needs of a particular user and decides whether it is suitable for him to buy an electric vehicle. First, the thesis explores current studies dealing with factors influencing the decision-making process about electrification. At the same time, it considers current options of obtaining a tool that can plan trips of electric vehicle based on user's requirements on visiting specific locations at a particular time (a planner). With this knowledge, the tool is then proposed and implemented, which shall facilitate the decision making. It does so by collecting user's requirements, and by using the planner, it evaluates whether it is suitable for the user to buy an electric vehicle. For this purpose, it uses both electrification score, which is introduced in this thesis and also mainly visualization that compares electric vehicle plan with the plan for a conventional vehicle. The last part of the thesis demonstrates the functioning of the electrification score. Then there is demonstrated the functionality of the created tool by using two artificial agendas (sets of user's requirements on visited location).

**Keywords:** electric vehicles, electrification evaluation, decision making about electrification, electromobility

**Supervisor:** Ing. Martin Schaefer

## Abstrakt

S rozšiřováním elektromobility narůstající počet lidí a firem zvažuje, že nahradí své současné konvenční automobily elektromobilem. Tito potenciální uživatelé potřebují zjistit, zda lze uspokojit jejich současné jízdní potřeby prostřednictvím elektromobilu. Tato bakalářská práce se zabývá usnadněním tohoto rozhodovacího procesu, čehož má být dosaženo vytvořením multifunkčního nástroje. Navržený nástroj na základě požadavků na využití automobilu konkrétním uživatelem zhodnotí, zda je pro něj vhodné elektromobil zakoupit. Práce se nejprve zabývá průzkumem existujících publikací, které se týkají faktorů ovlivňujících rozhodování o elektrifikaci. Zároveň zhodnocuje současné možnosti získání nástroje schopného plánovat trasy elektromobilu, splňující požadavky uživatele na navštívení daných lokací v daných časech. S těmito znalostmi je pak navržen a implementován samotný nástroj, který usnadní budoucímu uživateli rozhodování tím způsobem, že posbírá uživatelské požadavky a za využití plánovače vyhodnotí, zda je pro daného zájemce výhodné, aby si zakoupil elektromobil. K tomuto účelu slouží jednak elektrifikační skóre, které je v této práci představeno a především vizualizace, která porovnává plány elektromobilu s konvenčním automobilem. V poslední části práce je nejprve znázorněno fungování elektrifikačního skóre, posléze je na dvou různých umělých agendách - seznamech požadavků uživatele na navštívené lokace; představeno fungování vytvořeného nástroje.

**Klíčová slova:** rozhodování o elektrifikaci, vyhodnocování elektrifikace, elektrická vozidla, elektromobilita

**Překlad názvu:** Nástroj pro podporu rozhodování při elektrifikaci vozového parku

# Contents

<b>1 Introduction and Motivation</b>	<b>1</b>		
<b>2 Related Work</b>	<b>3</b>		
2.1 Factors Influencing Willingness to Adapt BEV	3		
2.1.1 Factors Influencing Fleet Managers	3		
2.1.2 Factors Influencing Individual Buyers	4		
2.1.3 Factors Used within the Tool	7		
2.2 BEV Planner	8		
2.2.1 Planner Requirements	8		
2.2.2 Obtaining a Planner	9		
2.2.3 Used BEV Planner Introduction	10		
<b>3 Methodology</b>	<b>13</b>		
3.1 Components of the Tool	13		
3.1.1 Supported Inputs	14		
3.1.2 Accessing the Planner	16		
3.1.3 Processing Planner Output and Creating Visualizer Input	16		
3.1.4 Proposed Modification of Planner	18		
3.1.5 The Visualizer	19		
3.1.6 Tool Back-end	20		
3.2 Electrification Score	21		
3.2.1 Total Time Score	21		
3.2.2 Activity Delay Score	21		
3.2.3 Fuel Price Score	22		
3.2.4 Green Score	23		
3.2.5 Final Electrification Score	23		
<b>4 Implementation</b>	<b>25</b>		
4.1 Planner Modifications	25		
4.1.1 Improving Stability of the Planner	25		
4.1.2 Planning within the Czech Republic Support	26		
4.1.3 Allow Specifying Vehicle Parameters Used for Planning	27		
4.1.4 Charging Stations at Activity Locations Support	27		
4.1.5 Extension of the Planner Responses	28		
4.2 Visualizer Modifications	28		
4.2.1 Visualizer Introduction	28		
4.2.2 Proposed Modification of Visualizer	29		
4.2.3 Modifications and Additions of Views	29		
4.2.4 Views Switching System	30		
4.2.5 Agenda Creating and Upload Support	30		
4.2.6 Preparations for New Back-end Integration	31		
4.3 Google Map Location History Export Processing	31		
4.4 Tool Agenda Export Processing	32		
4.5 Accessing the Planner	32		
4.6 Creating Visualizer Input	33		
4.6.1 Planner Output Converter	33		
4.6.2 Comparison Creation Tool	34		
4.7 Visualizer Back-end	34		
<b>5 Results</b>	<b>37</b>		
5.1 Electrification Score	37		
5.1.1 Simplified Demonstration Agenda	37		
5.1.2 The Experiment Explanation	38		
5.1.3 Results Demonstration and Discussion	39		
5.2 Agenda A - Introductory	41		
5.2.1 Introduction of Agenda and the CV Plan	42		
5.2.2 Scenario One - Short-range Vehicle	42		
5.2.3 Scenario Two - Mid-range Vehicle	44		
5.2.4 Scenario Three - Mid-range Vehicle with additional charging stations	45		
5.2.5 Comparison of Scenarios	46		
5.3 Agenda B - Time Pressuring	47		
5.3.1 Introduction of Agenda and the CV Plan	47		
5.3.2 Scenario One - Mid-range Vehicle	47		
5.3.3 Scenario Two - Long-range Vehicle	49		
5.3.4 Scenario Three - Long-range Vehicle with Additional Charging Stations	50		
5.3.5 Comparison of Scenarios	51		

<b>6 Conclusion</b>	<b>53</b>
<b>Bibliography</b>	<b>55</b>
<b>A User guide</b>	<b>57</b>
A.1 Attachment structure and content .....	57
A.2 Github repository with the tool	59



## Figures

2.1 Projected Total Cost of Ownership (TCO) in Los Angeles for five to ten year ownership periods (Breetz & Salon 2018) . . . . .	7
3.1 Data flow diagram . . . . .	15
3.2 The user's intended passage through the visualizer . . . . .	19
5.1 Time score . . . . .	39
5.2 Green score . . . . .	40
5.3 Price score . . . . .	40
5.4 Price score . . . . .	40
5.5 Total score dependence on arrival delays share on total agenda duration . . . . .	41
5.6 Delay score dependence on arrival delays share on total agenda duration . . . . .	42
5.7 The CV plan view - agenda A . .	43
5.8 The EV plan view - agenda A scenario 1 . . . . .	43
5.9 The comparison view - agenda A scenario 1 . . . . .	44
5.10 The CV plan view - agenda B .	48

## Tables

3.1 Values of subscores in Electrification score . . . . .	24
5.1 Demonstration Agenda . . . . .	38
5.2 Experiments parameters . . . . .	38
5.3 Agenda A . . . . .	42
5.4 Agenda A - Scenario One - comparison . . . . .	44
5.5 Agenda A - Scenario Two - Comparison . . . . .	45
5.6 Agenda A - Scenario Three - Comparison . . . . .	46
5.7 Agenda B . . . . .	47
5.8 Agenda B - Scenario One - Comparison . . . . .	49
5.9 Agenda B - Scenario Two - Comparison . . . . .	50
5.10 Agenda B - Scenario Three - Comparison . . . . .	51



# Chapter 1

## Introduction and Motivation

Today, many people are considering buying an electric vehicle (EV), but they are not sure if it would be suitable for them, because, for example, they do not trust it to cover well their daily routine without creating any delays due to significantly higher refuelling times than conventional vehicles (CV) have. Also, they might be concerned about the relatively low density of charging stations compared to gas stations necessary for CV use. And if they decide to buy an EV, they need to choose the right EV for them. There are two main versions of EV - pure electric vehicle and hybrid EV (HEV). This bachelor thesis will only cover buying purely electric vehicles, as there is nearly no difference between using HEV and CV represented by ICE (Internal combustion engine) vehicles. Compared to pure electric vehicles, HEVs are not limiting driver in any way they - have an equal driving range and as fast refuelling as CV.

The main goal of this paper is to create a tool that will help its users (potential BEV adopters) to decide whether it is suitable to substitute their current CV with a battery electric vehicle (BEV) (the only version of pure electric vehicle in widespread use) or not and thus facilitate their decision making.

The theoretical part of this paper will introduce factors influencing decisions about buying BEV. As the primary goal of this thesis is to facilitate the decision-making process, whether to replace the user's current CV with a BEV or not, there is a need to find out how the daily routine (daily routine is a set of activities user needs or wants to do - it has specified order and each of the activities starts at specified time - eq. arrive to work at 8:00, return home at 16:00, etc.) of the adopter will be potentially changed. Therefore I need to obtain a tool that will allow me to plan BEV trips based on locations that need to be visited - a BEV planner - as I will use these BEV plans for comparison with the CV vehicle plans. There is currently few existing BEV planner thus I should consider whether create my own planner for BEV or use an existing one.

In the practical part, we shall design an application that will calculate if and how will potential BEV users have to change the driving routine he has with CV and display the BEV plan compared to CV plan. Therefore I

shall obtain a visualizer - part of the tool that will display the BEV plan and its comparison with CV plan. Then I shall evaluate some factors mentioned in the theoretical part, which are crucial issues while adapting an EV. As it is appropriate to make it easy to use, it was decided to allow to use of already existing data containing the daily driving routine of the user. After exploring options in this area, I decided to add support for location history exported from Google Maps. Also, it will be allowed to create a new schedule for which a plan will be created directly in the application - user will have the possibility to creates his own artificial daily routine (by setting locations and time information of the activities). And as it is unnecessary to develop our own planner for EV driving, I decided to use already existing that was slightly modified to satisfy the needs of this project. Also, visualising part of the application is based on already existing application but with heavy modification to suit the needs of this project. Although this tool will be fully functioning, it will mainly serve as proof of concept for combining BEV routes planners and visualizators and for scoring suitability for electrification of individual driving routines.

## Chapter 2

### Related Work

This part should introduce most important factors influencing willingness to adapt BEV and their potential usage during this work. Also it will discuss the possibilities of obtaining a planner and introduce the chosen one.

#### 2.1 Factors Influencing Willingness to Adapt BEV

There are many factors influencing willingness to adapt BEV; we need to select only a few suitable for this paper. This part of the paper aims to introduce a few of the factors and then also choose which one will be suitable for use within this thesis. BEV can be adapted by individual people or by companies (by their fleet managers). According to the share of company cars is larger therefore we should start with factors influencing willingness of companies (but many factors should be important also for individual buyers).

##### 2.1.1 Factors Influencing Fleet Managers

From a perspective of fleet manager influencing factors could be for example improving image of company, fulfilling ecological policies (Sierzchula 2014), first mover advantage, government regulations and grants, driving range and time lost during charging (Globisch, Dütschke & Wietschel 2018).

##### Government Regulations and Grants

Regulations (for example taxes for non-BEV, or BEV only parking places) and grants (reducing the cost of BEV acquisition or possible tax rebates) are in fact quite important for decision process of fleet managers (Globisch, Dütschke & Wietschel 2018). Nonetheless, this paper will mostly not take them into account due to differences in various countries. Every possible mention of them therefore will apply only to the Czech Republic.

##### External Image of Company

Many companies want to improve their public image by implementing ecological policies, but this paper will not assess this factor directly, but it overlaps

with other factors more important to us that are also better measurable. For example companies might want to present how many litres of gasoline or milligrams of CO<sub>2</sub> their BEV saves, which is something we will examine.

### ■ Fulfilling Ecological Policies

Many companies want to adapt BEV in order to fulfil ecological policies. Possible motivations might be government regulations and grants, public image or ecological awareness. Therefore, it is important to show how much on average will BEV fleet reduce air pollution, traffic noise, etc. over a fleet consisting of conventional vehicles. In this paper this part is we only consider air pollution because it can be shown more clearly.

### ■ Cost in Comparison to CV

According to (Sierzchula 2014) „organisations are more likely to adopt vehicles that have high purchase costs but offer the potential of lower total ownership costs through reduced operating expenses“ which may have an effect in favour of BEV. In spite of this, currently fleet managers are discouraged by the initial cost of BEV. This contradiction might be caused by the fact, that the payback period is too long (one company calculated payback period of seven years (Sierzchula 2014)). In the future when price of BEV drops (not necessarily to the CV price level) and payback period will be shorter, there is high probability, that first statement will take effect and part of fleet managers will adapt BEV for economic reasons. Currently BEV adoption is driven by other reasons, but price remains as important factors because fleet managers are only willing to pay certain amount of extra money for the fact that they use BEV.

### ■ Delays in Comparison to CV

Delays created by using BEV instead of CV results into extra price for using BEV for example in form of salaries (paying employees only for waiting until their BEV is charged) or by creating delays in transport of goods important for the running of the company and thus resulting losses. Losses created by delays might be acceptable if they are compensated by lower operating cost of BEV, therefore it is important to know how long the delays will be and how much will the company save by using BEV instead of CV.

### ■ 2.1.2 Factors Influencing Individual Buyers

Factors influencing individual buyers are often the same as for fleet managers, but the reasons behind them could be slightly different.

One problem of factors influencing individual buyers is that as yesterday and today most of the potential adopters come from the "early adopters" group, that is quite enthusiastic about BEV (and also mostly about new technologies

in general), tomorrow other factors will become more influential as BEV will be widely adopted by mainstream vehicle users.

### ■ Ecology

Motivation for buying BEV instead of CV could also be ecological awareness. According to (Karpíšková 2020) in the study for the Czech Republic, most of the respondents saw environmental-friendliness as the main advantage of BEV usage. (Smith 2010) claims that CO<sub>2</sub> emissions could be reduced by circa 25 to 40 % from current levels if the current CV is replaced with a BEV, which is not negligible. It is important to understand that the BEV emissions are not zero; although the BEV itself does not commit any, there are significant emissions coming from creating the electricity needed and transferring it to a charging station. These emissions are even higher than the emissions created from oil extraction and processing and its transfer to a gas station. On the other hand, total emissions of the CV compared to BEV are higher (Rolim, Gonçalves, Farias & Óscar Rodrigues 2012). Also, according to (Rolim, Gonçalves, Farias & Óscar Rodrigues 2012) most drivers of EV consider that EV has an impact on their driving style - they were less speeding and driving more economical, which results in lower consumption and thus even lower pollution created.

### ■ Availability of Charging Stations

One of the influencing factors while adapting BEV is also the availability of charging stations (density of charging infrastructure and whether the potential user has a charging station at home/work). Also very important is access to a reasonable charging station at home because it, according to (Axsen, Goldberg & Bailey 2016), improves the value of BEV for the mainstream user. The overall availability of charging stations affects a few others factors, such as delays. As stated in (Axsen, Cairns, Dusyk & Goldberg 2018), only 66 % of potential mainstream users have access to reasonable charging stations in their vicinity. Their study was made for British Columbia and not the Czech Republic. Still, despite differences in the exact numbers, it confirms that the availability of charging stations is an issue. This is confirmed by (Karpíšková 2020) where more than 18 % of respondents stated that a small number of charging stations is the biggest limitation of owning a BEV for them, making it the third most common group after high purchase price and small range.

The density of the charging station network is also important because (Sun, Huang, Liu, Chen, Yao & Kashyap 2017) stated that 84 % of users "claimed they could only bear to spend 10 min driving to find a charging pile". They also claim that the users expect in the future to charge most often "in their own parking lot", the charging in the company parking lot should be more often and expect charging less in public charging stations - this means that we should focus not only on public charging station network but also on their at home/ at work availability - this is supported by the fact that 70 % of BEV

owners charged their vehicle only at home according to (Vassileva & Campillo 2017); this could be caused by the fact that less than 20 % of respondents in their survey in Sweden usually drives more than 100 kilometres per day which means they rarely need to charge anywhere else.

Also, it is important to differentiate between various charging stations, as they could create different delays due to their speed (or location, as charging at work or home usually creates no delay etc.). Also, for example, charging at work could reduce the cost of charging. The same applies for charging at home when, for example, using energy from installed solar panels on the roof of the house (that would also significantly improve environmental friendliness compared to the power that comes from the standard energy mix in the Czech Republic).

### ■ Delays

Delays are not the only problem for companies but also for individual adapters of BEV. The only difference is that individual users are normally not losing money because of delays as companies do. Still, the impossibility to be everywhere on time could be a huge factor in individual buyers decision making about BEV adapting. The delays of BEV are usually created because of the additional refuelling (charging) need comparing to CV (except for the refuelling, the BEVs are as fast as CVs), and too big delay could make the trip impossible to take. Because the additional delay of BEV is created by the refuelling speed and relatively short range of the BEVs compared to CVs.

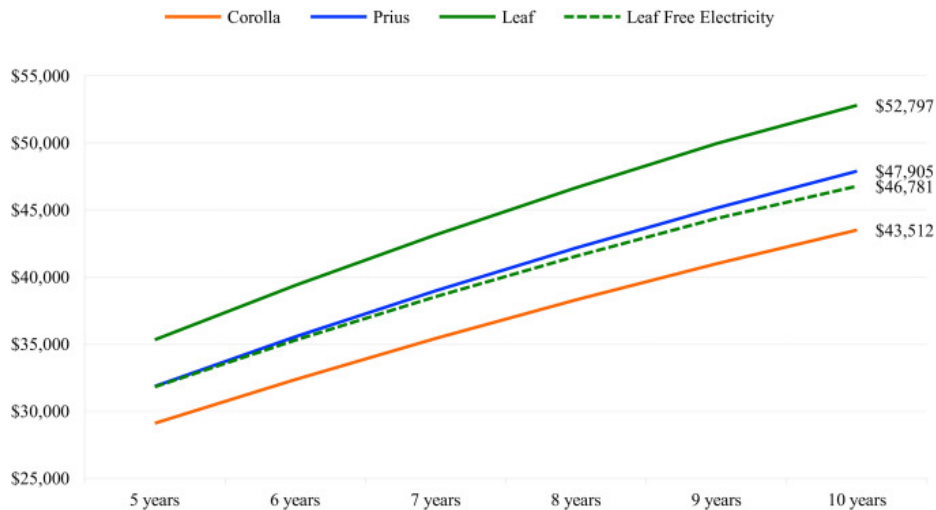
Although (Langbroek, Franklin & Susilo 2018) states that the users are relatively willing to cancel non-mandatory trips when they become impossible to take due to short-range (and thereby created delay - they cannot arrive at the goal destination at such time it will still make sense to take the trip), still (Ryghaug & Toftaker 2016) claims that a 'range anxiety' (fear of running out of electricity) is still an issue for some of the among potential BEV adopters nowadays. This fear is often irrational and (Langbroek, Franklin & Susilo 2018) claims it could be decreasing over time. Nevertheless (Greaves, Backman & Ellison 2014) claims that in their study, based on GPS data they collected over five weeks in Australia, 73 % of BEVs with a range of 60 km and 20 % of BEVs with a range of 255 km needed additional recharging option in addition to the current ones. Therefore it still is useful to evaluate for every potential user whether the range of the BEV is long enough for him or not and thus dispel his fears.

### ■ Cost in Comparison to CV

Cost is nowadays not as important deciding factor as it might seem as according to (Ryghaug & Toftaker 2016), early adopters (who are or at least were the majority among the BEV adopters) are "willing to accept the additional costs associated with EVs" - (Potoglou & Kanaroglou 2007) stated



that in Canada "individuals are willing to pay between \$2000 and \$5000 if their next vehicle would emit only 10% of a present day average car. But (Ryghaug & Toftaker 2016) also says that for potential future (and current) mainstream BEV adopters, the cost will, of course, play a significant role in their decision making and thus cost of BEV adopting will be compared to the cost of CV. (Potoglou & Kanaroglou 2007) says that households would pay (as an additional cost) "\$2200 to \$5300 in order to save \$1000 in annual fuel costs", which supports the importance of BEV cost in comparison to CV. Still, nowadays, according to (Breetz & Salon 2018), the price difference is higher than \$5300 for comparable cars. The higher price of BEV will not repay over ten year period when compared to CV or HEV (as could be seen in figure 2.1) if the government does not heavily subsidise the BEV, but there is an expectation that this will change in the future. In (Karpíšková 2020) more than 23 % of respondents stated that the high purchase price is the most significant obstacle of owning a BEV, making it the most common disadvantage stated.



**Figure 2.1:** Projected Total Cost of Ownership (TCO) in Los Angeles for five to ten year ownership periods (Breetz & Salon 2018)

### 2.1.3 Factors Used within the Tool

This section shall introduce the factors I will later use within the tool. I have decided not to use any factors that are hard to evaluate - such as benefits for the external image of the company, fulfilling ecological policies (as they are fundamentally changing over time). I have decided to take delay as the main factor - both arrival delays to a destination (that could persuade an individual user to cancel the trip) and total delay compared to a CV (that causes financial losses to companies). These are also connected to the "availability of the charging stations" and obviously to the "range anxiety". I have also decided to have cost as a minor factor, but not the adopting cost that is calculated by the companies but rather the cost that comes from everyday usage (i.e.

the price of fuel). That is because the BEV price could be heavily affected by various government grants, discounts etc. which are also changing over time. The last minor factor is the ecology - strictly in the sense of pollution reduction.

As I stated before, the availability of the charging stations affects a few of the factors that will be used later within the tool. Therefore it is important to focus more on this topic, even though I will not directly assess it. For the tool, it is important to work with real-life charging stations set to simulate real-life possibilities as much as possible. It is not crucial to have also actual prices for charging at the station etc. (as that changes quite fast over time and price is not a primary factor for us) but to have the charging station at their location and ideally with an actual charging rate is essential for the plan to be precise. But the charging stations set will contain only public charging stations. As I stated before, the availability of charging station at home and at work is also crucial as for example, according to (Greaves, Backman & Ellison 2014) 47 % of the trips in their study was separated by more than ten hours which is enough time to recharge the BEV fully. We could assume that a pause between trips that long is probably mostly taken at home or work. But we should not limit this only to at home and at work charging stations, the possibility for the user to add a charging station shall be in every location he wants to visit - according to (Greaves, Backman & Ellison 2014), only 20 % of trips in their study was separated by less than one hour, which means that mostly the activities will be long enough to charge the BEV reasonably during them if there is a charging station available.

## ■ 2.2 BEV Planner

BEV planner is one of the crucial parts of this thesis, as we need to create plans for BEV based on a current driving routine of the user to decide whether it is suitable for electrification. The plan is a set of actions - containing activities, drives, refuelling etc., that are time-ordered and together should fulfil the agenda set by the user and provide enough information about the way it is fulfilled. First, I will introduce requirements for the planner that needs at least partially be fulfilled for the planner to be beneficial to this project. Then I will discuss possibilities for obtaining a planner (creating my own, take one fully done or taking one working that will be adjusted to fulfil my needs).

### ■ 2.2.1 Planner Requirements

The basic purpose of every (BEV) planner is to take users agenda that needs to be fulfilled and return a plan that fulfils it if possible. The BEV plan is quite similar to the CV plan; both of them show how the user transfers from activity to activity, they inform us about the arrival times etc., but the BEV plan also needs to contains information tackling BEV - battery capacity, energy spent and most importantly visits of the charging stations. This, of

course, is the most important part of the planner also for this thesis. We need this to work stably with agendas that span over few days and could contain at least lower plates of activities.

Also, it should return some basic information about created plan such as spent kWh, charged kWh and so on.

The used planner should use as the main criterion delay or at least total time because, as it was described before in the criteria part of thesis, that is one of the important decision factors when deciding about adapting BEV. This is the criterion that is most easily simulated by the planner, as we do not need to have, for example, real prices of kWh for each charging station that would be needed when the price would be the main criterion. Also, time criteria affect the other, as was described in the criteria description part of this thesis.

Because of the used visualizer described in later parts of the thesis, we need the planner to return routes when each point of returned geometry of the routes is returned with datetime when the point was reached.

The used planner should also work in the Czech Republic (it should support planning with activities within the Czech Republic) and ideally should allow us to define our own set of charging stations.

Also, it would be good to have the possibility to add a new charging station directly with the input agenda. This would allow us to simulate charging stations at home and at work, which is also important for a few of the criteria.

The used planner should allow us to define our own car. It should solve plans in such a way that it will handle the differences between small BEV with short-range and bigger and more expensive BEVs with longer range.

### ■ 2.2.2 Obtaining a Planner

As stated before, there are three possible ways to obtain a planner - creating one, using a fully completed one or get one that would be later altered to suit the needs of this thesis.

A few existing fully completed planners are available, and using a fully completed planner is a good possibility because it would allow me to focus on different important things for this project. Disadvantages are, for example, that it returns slightly different information than is necessary or it would not allow me to specify my own charging stations set (and thus allow the user to specify whether he has charging station at home/work etc.) - which is for example the case of the A better Routeplanner tool(available at abetter-

routeplanner.com). Also, I probably would not be able to get any reasonable technical support for it. Another important objection to using the completed planner is the fact that we could not deploy it to the CTU server, so it would be needed to send the information to a foreign one. Also, I would probably have to obtain permission to use it. Therefore I decided not to use an already fully completed planner from foreign sources.

Creating my own planner is also an exciting option as it would allow me to have a great insight into how planners work. But creating my own planner would probably take too much time to allow me to fulfil other goals of this thesis. This is the main reason that persuades me to discard this option. Also, it would not have any good reason to create a completely new planner when there are other functioning planners that we could use or at least use as groundwork for other improvements of the planner.

The last option is to find an already created with the possibility to alter it in such a way it will suit the needs of this project. The main disadvantage is that I will not have such an insight into the BEV planner topic as I would have if I created my own one, and also, it will be still more time consuming than using an out-of-the-box solution. On the other side, this approach will allow me to use a planner that fulfils more of my requirements than out-of-the-box one and even more than a planner potentially created by myself (as I probably would not be able to create a planner that fulfils all of the requirements in reasonable time that will not affect other necessities). As there was a suitable BEV planner project in development at CTU FEE, I have decided to go this way, which will allow me to concentrate also on other important components as is, for example, integration of visualizer etc. The chosen planner will be described in the next section of this thesis.

### ■ 2.2.3 Used BEV Planner Introduction

I have decided to use an already functioning planner that will be modified to suit the needs of my thesis. It is the planner described in (Cuchý, Štolba & Jakob 2018) that is currently developed at CTU FEE.

This BEV planner solve a new variant of the trip planning problem - Whole Day Mobility Planning with Electric Vehicles (WDMEV). Its main advantage is that it solves trip planning for the whole day instead of solving every trip independently. This planner could optimise based on one of three available criteria - total time (the original one that was introduced in (Cuchý, Štolba & Jakob 2018)) and also greenness and total price. As stated in (Cuchý, Štolba & Jakob 2018), when optimising total time, "the optimized global solution is always better than the single trip baseline solution, sometimes with the difference in hours" and moreover " although the algorithm explicitly optimizes only for the time metric, it outperforms the baseline solution in the two other metrics for most instances as well" (the other two metrics are cost and consumption that is quite similar to greenness).

In the original version of the planner I had access to, the planner was only functional when planning within one day. Also, the locations of activities were limited in an unpleasant way because it was limited to an area in Bavaria - "As a testing location we use a rectangular area of the real-world road network in Germany bounded by Munich, Regensburg and Passau" (Cuchý, Štolba & Jakob 2018). Also, it did not allow me to specify my own BEV for which it should plan, nor it allowed me to add a new charging station within the input. It does not also fulfil other requirement described in Planner requirements part of this thesis that is to include time-dates to every point in a route geometry. However, it should still be possible to adapt it in such a way it fulfils most of my requirements once I precisely describe every change I need for it.

The planner originally also contained a front-end part that let users create the set of activities they want to be fulfilled, and then it displays the solution to them (as most similar tools do). Although it is quite similar to few parts of the tool I shall design, it does not really fulfil the needs of this thesis as it does not provide enough information to the user (especially the comparison with CV). Still, it could be seen as the (ideological) predecessor of my tool.



## Chapter 3

### Methodology

The methodology chapter shall introduce the general idea of my solution that should facilitate the decision-making process about electrification. The solution is creating a unified tool that will display all the necessary information after it processes the user's daily routine or demanded activity set. (Activity means that the user wants to be at a specific activity location for a particular activity duration of time, and ideally, the activity should start at a specified activity arrival time). First, I will introduce the tool itself and its components, including the visualizer (basically the front-end part of the tool). Also, I will introduce proposed modifications of the used Planner. Then the electrification score, which will be part of the information the tool should pass to the user, shall be introduced.

#### 3.1 Components of the Tool

The main goal of my thesis is to design (and later create) a tool that should help its user decide whether adopt BEV instead of his current CV or not. This means the tool will have to collect inputs from the users, solve them with the usage of the planner and then deliver the information that is helpful in such a decision process. In this section, I will tackle the needed components of the tool and also the modification of the used planner that the tool shall interact with.

The components tackling the collection of the user's input should allow him to create his agenda (demanded activity set) or upload the location history he acquired from other sources. Then the components for communication with the planner will be needed - that means I will have to create converters that transform the input into a form accepted by the planner and components directly responsible for the accessing of the planner. After these parts receive the response from the planner, there should be components that will take these results, extract the needed information and converts them into a form in which they should later be displayed to the user. The last components should display this information - it is called the visualizer. It is basically the front-end part of the tool - this means the before introduced parts expect from inputs collection should be considered parts of the back-end.

Still, the term back-end here is only used for the component that directly handles the communication with the front-end and runs the interconnection between other components. Also, it is important to notice that because the used BEV planner is not created by me and will be run independently from the tool, I did not consider it as a part of the tool back-end. Data flow between individual components described before, visualizer and planner can be seen below in the diagram of data flow (Figure 3.1). In this section, I will explain their usage and also the requirements for each of them. In the diagram, you could see that the tool will take the input - location history file(s) (or its artificial counterpart), maximum arrival and departure delays and also the parameters of the BEV, then the converter will create a request for the planner (i.e. planner input) based on these inputs which will be sent to the planner. After the tool receives a response from the planner, it either creates a new request if the previous one was unsuccessful (with relaxed delay limits), or it starts processing the response. The tool from the response creates information on suitability for electrification, and also it converts the response (BEV route plan), so the visualizer could display it. It also use the same settings (except the BEV parameters - it now has a nearly unlimited range to simulate the CV) to obtain a similar output for the CV vehicle. All these parts are then handed to the visualizer.

#### ■ 3.1.1 Supported Inputs

As I have already stated, I have decided to allow two ways of specifying the agenda users want to fulfil - creating it directly within the tool and uploading their existing location history from other sources (and thus allowing them to use the real-life data). This section should not correctly tackle the way users will hand this to the tool, but rather how I process it once they pass it to the tool. Although I previously mentioned input processing as one component, it needs to be separated into two different components due to a significant difference between inputs based on their source. I will first introduce the location history export processing and then also the processing of the agenda created directly within the tool.

#### ■ Location History Export Processing

One of the main intended features of my tool is that it should be able to process real-life data with location history and try to decide whether it is advisable to adapt BEV for this particular usage. It will also be a huge competitive advantage for my tool when for example, comparing with the original planner "tool" that allowed only the use of artificially created inputs. Therefore I have decided to add support for the usage of Google map location history exports because Google maps are widely used and could allow a great portion of the users to use this feature.

Google map location history can be exported via google map location history website, but only in google own format of data - KML (Keyhole Markup



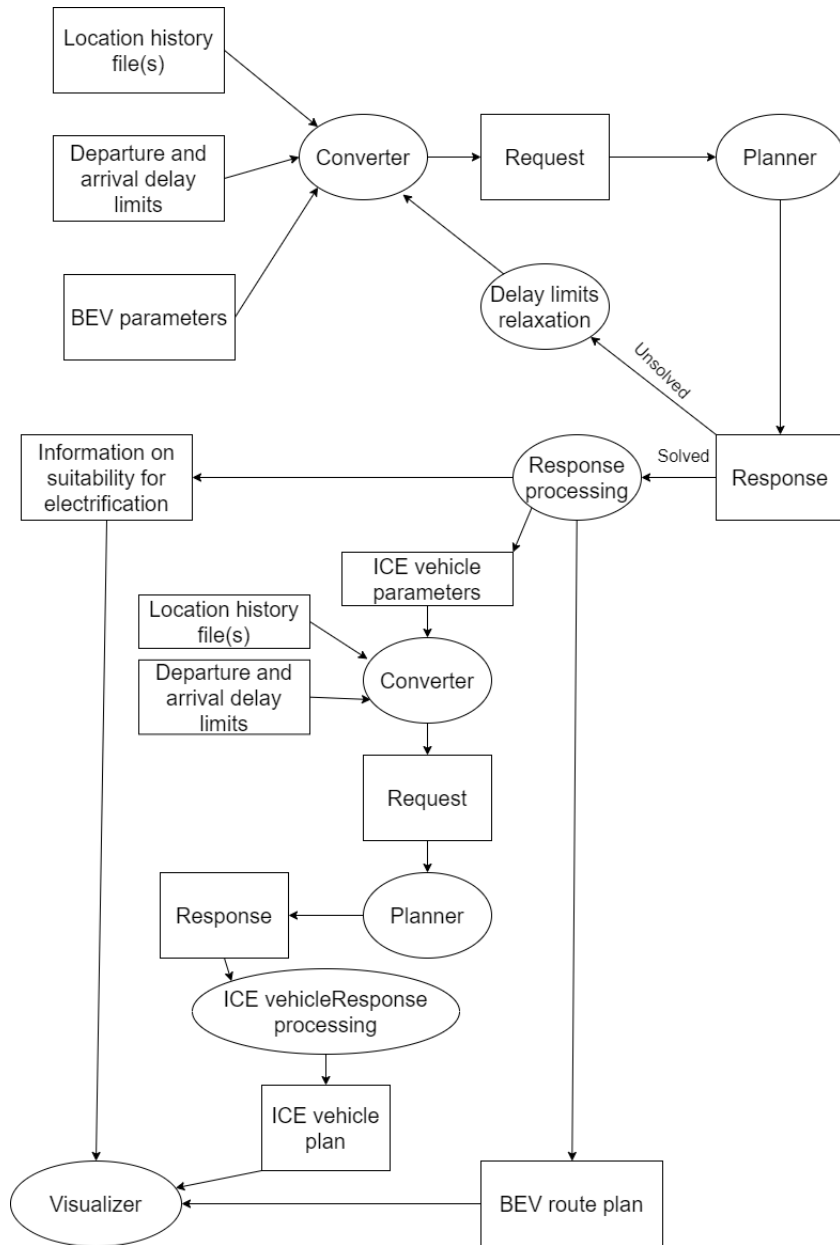


Figure 3.1: Data flow diagram

Language) that is based on XML (Extensible Markup Language) and is used to display geographic data. There is also an export limitation that one file can only contain one day. This file needs to be converted to JSON with data formatted in a way planner is designed to accept them. This will do **kml, google format to JSON, planner format converter**. It is also necessary to **allow changing of departure and arrival delay limits** of activities because sometimes it is impossible to do the activities at the exact same time with EV as with CV. Therefore, we often need some more “manoeuvring space” for the planner to work with to allow the planner to get

results. Because it is only possible to get one-day history at one time, in future, we also need to solve **merging of several history files**.

### ■ Agenda Created Within the Tool Processing

Alongside real-life location history, this tool should also be able to let the user create his own agenda manually (it will be one of the features added to the visualizer that I will describe later) because not everyone uses mobile devices that stores their location history, also some people turn this feature off or they use devices which location history is unsupported by my tool. Also, it is user-friendlier to let the user create his own agenda in the visualizer instead of forcing him to obtain his location history and upload it (the idea is that the user could use the tool in the earlier stages of the decision process with his handmade artificial agenda and also in the later stages, where he needs to acquire more precise information based on real-life data). Therefore I need to create **GEOJSON, visualizer format to JSON, planner format converter**.

### ■ 3.1.2 Accessing the Planner

Access to the planner is handled using REST API. Originally except accessing it through terminal/python script etc., there was also a web site where it is possible to choose points on a map, create a sequence of activities and send it to the planner. It also displayed the results on the map. Unfortunately, because the used map (provided by Mapbox) was deprecated and out of order, it is currently not working. Therefore to handle **access to the planner**, I implement a short function in python that takes an input data, access the planner and saves the result for future use.

Finally, I shall create a function that takes the previously mentioned functions and implement Algorithm 1 based on Figure 3.1. It takes input from the user (agenda), max delay and combines them to create an input for the planner, which is then handed to the planner. Once it receives a result, it returns an error or unsolved message if the planner response does not contain a BEV plan. If the response contains a BEV plan, it converts the response to a format accepted by the visualizer. In this case, it also uses the max delays and agenda to create a similar planner input this time for a CV. Once it also obtains a CV plan, it converts it again for the visualizer and then uses both CV and BEV plan to create a comparison between them. Then it returns the BEV plan, the CV plan and the comparison.

### ■ 3.1.3 Processing Planner Output and Creating Visualizer Input

It is needed to process the results of the planner to get parts of the output information we want to know—this information I will then have to convert so it could be accepted by the visualizer. Basically, I will have to create

**Algorithm 1:** Accessing of the planner

---

```

data ← user_input;
planner_input_BEV ← converter(data, max delays);
response ← accessPlanner(planner_input_BEV);
if response is error then
  | return 'Error';
else if response is unsolved then
  | return 'Unsolved';
else
  | planner_input_ICEV ← converterICEV(data) ;
  | response_ICEV ← accessPlanner(planner_input_ICEV) ;
  | comparison ← createComparison(response, response_ICEV) ;
  | return response, response_ICEV, comparison ;

```

---

three separated parts of the input for the planner - BEV plan, CV plan and comparison. Hence I will have to create at least two tools **planner response format to visualizer format converter** and also **creator of comparison from planner response**.

### ■ Creating Visualizer Input - BEV Plan

Creating a visualizer input containing BEV plan from planner output will be done by **planner response format to visualizer format converter**. This will be done by simple recreating a planner output in such format it will be accepted by the planner. The planner I use returns every information needed for creating visualizer input (activity arrival/departure times, activity location, duration of activity/charging/moving, kWh spent, kWh charged, the geometry of every "moving" action, etc.) except date-times for every point in "moving" actions geometries, this is needed for animating trips in the visualizer. The planner returns date-time only for essential points in the trajectory as is start and end, or arrival to the crossroads etc. I will also have to solve this issue so that I will have a date-time for every point in the trajectory. (Since the structure of the returned date-times is as I described it, it is not the best option to interpolate points with a curve as it could produce meaningless values. Also, I do not require to be the date-times as precise as possible because It would not have any real benefit.

### ■ Creating Visualizer Input - CV Plan

As I have stated before, I will simulate CV (ICE vehicle) planning by using the planner I will use for the BEV planning, and I will simply set vehicle parameters so that the range is nearly unlimited. (This could be done because BEV charging creates more significant delays than CV refuelling.) Therefore I could use the same **planner response format to visualizer format converter** tool that I will create for converting the BEV plan.

## ■ Creating Visualizer Input - Comparison

The comparison file should contain not only the comparison between CV and BEV but also information that are not directly part of the planner input, as are, for example, distances between actions points (lengths of trips). Another part of the comparison file is the Electrification score that I will describe later and its explanation (basically short pre-created written evaluation of every "subscore"). The creation of all components described in this paragraph will be part of **comparison creation** tool.

### ■ 3.1.4 Proposed Modification of Planner

The planner should use criteria based on criteria specified in this paper in the theoretical part (for example, a sum of squared delays of activities) or at least similar ones during planning. Currently, it takes into account the total time duration of the plan, the total energy used and total cost of used energy which means that it does partially fulfil this criterion by total time criterion. I will discuss the possibility of a new criterion (sum of squared delays of activities) that will fulfil my requirements for used criterion even better than total time and propose few changes to the planner so it will also meet other requirements introduced in Planner requirements section. I shall too introduce a few additional new features and fixes that will improve the overall quality of the planner output for my tool. Also, the used planner could not be used with activities located within the Czech Republic. It will be needed to change the planner in such a way it will allow it.

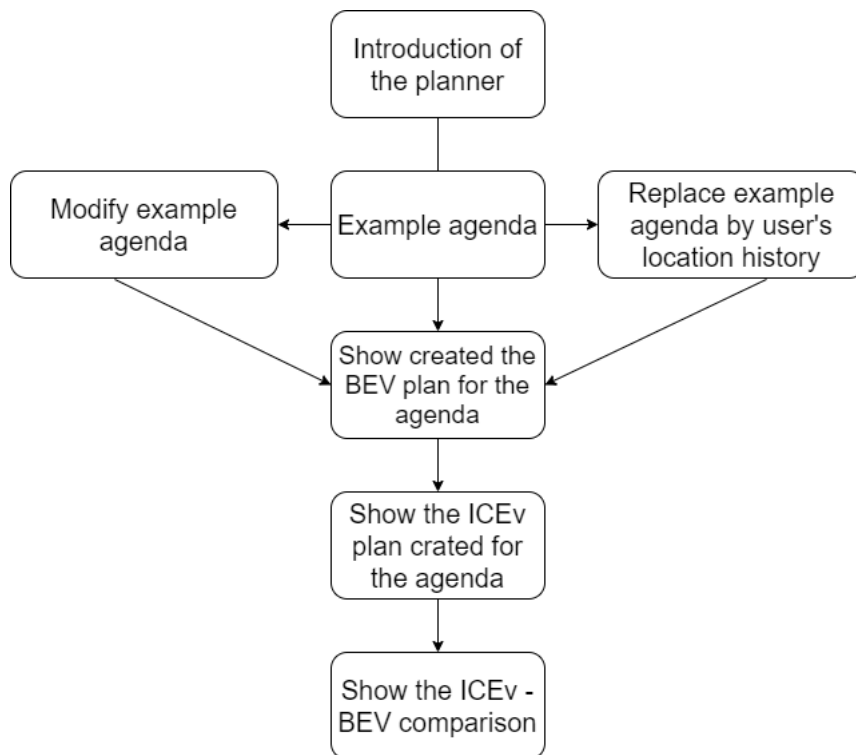
Proposed modifications:

- Make the planner more stable (currently can only solve 2-4 activities including start and end within few hours, for more complex input, it usually returns out of bounds error). Therefore:
  - Allow planning for more activities
  - Allow planning over multiple days
  - Check whether instabilities in certain situations are created by reasons stated above or by something else
- Allow planning within the Czech Republic
- Allow specifying car parameters used for planning (battery capacity, consumption, range, etc.)
- Allow adding new charging stations (i.e. at home, at work)
- Add charged kWh info of every charging to output (currently only contains price)
- Allow specifying price of charging or remove info about price (if price cannot be explicitly set for every plan, it will be better to count it outside planner)

- Add date-time to every point of the trip's geometry
- Add delay info (I will have to compute it on my own for comparison creation because of reasons I will explain later, but this will still make at least creating BEV/CV input to visualizer much easier to create)

### 3.1.5 The Visualizer

I need either obtain or create a visualizer that could display all the specified information to the user and also that it will follow the intended passage of the user through the information (Figure 3.2). This will be handled by creating specific 'views' used for introduction specific parts of the information to the user. There should be one for showing the plan (solution of the user's input returned by planner) with CV, one that should do the same with the BEV and a final comparison which should show them both and also display the evaluation of electrification suitability. Also, it is needed to allow creating user's own agenda besides the example one, uploading location history files etc.



**Figure 3.2:** The user's intended passage through the visualizer

The requirements for the visualizer are:

- to support the different views - BEV, CV and comparison and display all the necessary information within them

- to have a reasonable system for switching between individual views that will force the users into intended go through but it will also allow him to go back and recheck any information he want
- to allow the creation of own agenda including setting if there is a charger at the activity location
- to allow to specify vehicle the planner should plan with
- to add support for history location files upload

### ■ 3.1.6 Tool Back-end

I will also have to create a new back-end for the visualizer. Its primary purpose will be to connect the visualizer with the planner while handling all the differences in input/output files formats. Also, it should create a comparison and send it with a BEV plan and CV plan to the front-end and, most importantly, handle unsolved planner inputs by relaxing delay limits. This means I need to use all the components described before and connect them together to form a back-end that implements Figure 3.1 (end especially it should obtain the results from the BEV planner by implementing the Algorithm 2 although parts of it will be implemented in other components than directly in the one I specified as 'back-end'). Algorithm 2 takes the agenda from the user, sets opening delay limits (based on the preset of the tool) and uses them to try to obtain a solution using Algorithm 1. It does so by relaxing the delay limits. If the delay limits exceed a certain preset limit, the algorithm returns an error.

---

#### Algorithm 2: Back-end algorithm to obtain the results

---

```

data ← user input;
max_delays ← maximally allowed delay limits;
diff = int;
run = 1;
while run do
  BEV plan, ICEV plan, comparison = algorithm1(data,
    max_delays) if BEV plan == 'Error' then
    | return error;
  else if BEV plan == 'Unsolved' then
    | max_delays += diff ;
    | diff *= 2 ;
    | if max_delays > limit then
    | | return error;
  else
    | return BEV plan, ICEV plan, comparison;
end

```

---

## 3.2 Electrification Score

Based on factors influencing willingness to adapt BEV introduced in the theoretical part, I have created an electrification score that shall inform users of our application whether his ICE vehicle usage is suitable for electrification. I have decided to use a score with 100 points scale that is calculated by using 4 components based on several factors from the theoretical part: total time score, activity delay score, fuel price score and green score.

### 3.2.1 Total Time Score

$$\text{Total time score} = \text{tsv} \cdot \left(1 - \frac{(\text{ev\_time} - \text{cv\_time})}{\text{cv\_time}}\right) \quad (3.1)$$

**ev\_time** ... total duration of plan when using BEV

**cv\_time** ... total duration of plan when using ICE vehicle

**tsv** ... time score value (out of total 100 points)

Total time score simply classifies how much BEV relatively slower than its ICE vehicle counterpart is. Compared times also contains activities duration as we need to know how important the total delay is compared to total time. Both times we get directly from the planner because even though it is possible to get duration from google location history files or from agenda input, we need to also take into account that the planner does not always select as fast route as a driver can thanks to his real-life experiences and to balance this factor, we also use ICE vehicle time we get from planner. (Where ICE vehicle is simply a BEV with nearly unlimited battery)

### 3.2.2 Activity Delay Score

$$\text{A. d. s.} = \text{dsv} \cdot \left(1 - \left(\sum_{\text{activity} \in \text{activities}} \frac{\text{delay}_{\text{activity}}^2}{(4 \cdot \text{rtt}_{\text{activity}})}\right) \cdot \frac{1}{|\text{activities}|}\right) \quad (3.2)$$

$$\text{dsv} \geq \text{Activity delay score} \geq -2/3\text{dsv} \quad (3.3)$$

$$\text{delay}_{\text{activity}} = \min(\text{BEV\_at} - \text{ICEv\_at}, \text{BEV\_at} - \text{Agenda\_at}) \quad (3.4)$$

**activities** ... set of all activities in the plan

**BEV\_at** ... BEV arrival time to activity

**ICEv\_at** ... ICE vehicle arrival time to activity

(taken from planner response)

**Agenda\_at** ... when was car originally supposed to arrive to the activity

**rtt** ... route time to activity is time difference between leaving previous activity and arriving to the current one

**dsv** ... delay score value (out of total 100 points)

The reason why we need another time score in addition to the total time score is that the total time score is not quite precise as it compares only total times. This one classify well only plans where every delay is lower than square root of route duration (and few of them needs to be significantly lower)

For example, when we have a BEV plan with duration of 1000 minutes and the delay against ICE vehicle plan is 50 minutes, than it achieves a relatively high total time score. But when all 50 minutes of this delay is obtained during one drive from activity to activity that in total takes 55 minutes then this plan should not be classified so high as it is with total time score, which is something that activity delay scores handles well.

I have decided to compare BEV arrival time with ICE vehicle arrival time or original agenda (input from the planner or from google location history file) depending on which difference is lower. This is because I do not want to penalise the BEV plan that arrives earlier than (or shortly after) supposed arrival time in situations when ICE vehicle is significantly earlier at the activity point (as this is evaluated by Total time score), but also I do not want to penalise late arrival to the destination when it could not be reached earlier even with an ICE vehicle.

But in spite of the fact that this score handles well this "activity delays" we also need the previous type so because this score tends to underestimate plans thanks to the square of delay in the computation. However, this is little bit compensated by the  $(4 \cdot rtt_{activity})$  part of the equation.

Also, for this reason, has activity delay score lower limit on classification set on minus two-thirds of its total value.

### 3.2.3 Fuel Price Score

$$\text{Price score} = \text{psv} \cdot \left(1 - \frac{\text{ev\_price}}{\text{cv\_price}}\right) \quad (3.5)$$

$$\text{cv\_price} = \frac{\text{conventional\_km}}{100} \cdot \text{avg\_per100km\_fuel} \cdot \text{liter\_fuel\_cost} \quad (3.6)$$

$$\text{ev\_price} = \text{spent\_kwh} \cdot \text{kwh\_price} \quad (3.7)$$

**conventional\_km** ... sum of length of ICE vehicle plan routes in km

**avg\_per100km\_fuel** ... average fuel consumption of ICE vehicle per 100 km in liters

**liter\_fuel\_cost** ... cost of liter of fuel (gas, diesel)

**spent\_kwh** ... kWh spent by BEV when completing its plan

**kwh\_price** ... average price of charged kWh in Czech Republic as we do not currently have the price of charging set correctly in planner

The fuel price score is currently relatively straightforward. It is included in the electrification score because, as was stated in the theoretical part, saving coming from using BEV instead of ICE vehicle are also an important decision



factor for some potential BEV users.

The problem with this score is that it really does not hit its top value (except for cases with heavy recuperation use), This score could be improved significantly when the planner will work with real-life prices of charging set, where for example charging at work (if there is a charger) will be free as an employee benefit. Then it would be more precise and therefore get higher weight in the final electrification score. Also, it would regularly hit its top value, which currently occurs not very often.

### ■ 3.2.4 Green Score

$$\text{Green score} = \text{gsv} \cdot \left(1 - \frac{\text{ev\_pollution}}{\text{cv\_pollution}}\right) \quad (3.8)$$

$$\text{ev\_pollution} = \text{spent\_kwh} \cdot \text{pollution\_ev\_const} \quad (3.9)$$

$$\text{cv\_pollution} = \frac{\text{conventional\_km}}{100} \cdot \text{pollution\_cv\_const} \quad (3.10)$$

**conventional\_km** ... sum of length of ICE vehicle plan routes in km

**spent\_kwh** ... sum of kWh spent by BEV across all routes in plan

**pollution\_ev\_const** ... on average CO2 per 1 kWh

- (780 g/kWh (Kolbe 2019))

**pollution\_cv\_const** ... on average CO2 per 1 liter of petrol

- (2310 g/kWh (Kolbe 2019))

Ecology is also one of the decisions making factors when making a decision about adapting BEV instead of an ICE vehicle. Therefore electrification score also includes subscore touching this topic. All information about emissions per kWh is from real-life use from China (this means that they are probably quite pessimistic for Czech Republic use as the Czech Republic have a different composition of electrical sources).

This score is quite similar to the price score (in its current version); it might seem logical to merge them together, but I want to have them separated for better clarity and also because there is a possibility that the price score will be updated when the planner will work with real-life charging prices. The main reason of this score is to evaluate the environmental friendliness of using BEV instead of ICE vehicle when taking into account CO2 emissions per one standard fuel unit and thus comparing the consumption of them. Finally, this compares saving created by using electric energy instead of gasoline with pollution created by necessary detours for charging (As gas station network is denser than charging stations network, especially in the Czech Republic.).

### ■ 3.2.5 Final Electrification Score

Total electrification score is the sum of all subscores (total time score, activity delay score, fuel price score and green score). Total time score and activity

delay score have a higher value than the other two, as they are quite crucial (when compared, for example, with green score) and are the only ones coming that always use only exact values from planner response. Therefore I decided to set the value of the total time score to 45 out of 100 and the activity delay score to 30 out of 100. The price score value is set to 15 as it comes from more exact values than the green score. The green score has a value 10 out of 100.

<b>Subscore</b>	<b>value in Electrification score</b>
Total time score	45 (out of 100)
Activity delay score	30 (out of 100)
Price Score	15 (out of 100)
Green score	10 (out of 100)

**Table 3.1:** Values of subscores in Electrification score

## Chapter 4

### Implementation

In this part, I will introduce began with introducing its components. First, I will introduce the BEV planner and visualizer and their state before working with them. Then I will introduce components that are solely created by me and changes I propose to make on the planner and visualizer. Next, I will focus on a description of how every component was created and describe changes on the visualizer and planner, which was done personally by me or at least participated in them. The last part will focus on evaluating how I managed to process the proposed components and changes. This section will focus on describing and evaluating how new components were created and proposed modifications were applied. Although most of the new parts were created by me, parts of the modifications were made by other people due to the fact that they were out of my field, or they wanted to modify their project themselves. Therefore I will state for each modification whether I made it or it was made by someone else. I will start this section by describing the modifications. Then I will describe new components, with the backend being the last thing I shall describe.

#### 4.1 Planner Modifications

All of the proposed planner modifications were not implemented by me. Nevertheless, it is still important to mention the modifications here, as they have a great direct impact on the functionality of my tool. Mostly I have only created specification on how it should work and a few example files that should be processed without problem after the modification. There is one notable exception to it that I will describe later.

In this section, I shall go through every proposed modification of planner and evaluate whether they were (at least partially) implemented, and then eventually explain the functionality of the modification, or they were not implemented, and the explain why it was decided not to implement it.

##### 4.1.1 Improving Stability of the Planner

The modification concerning the stability of the planner fulfilled every expectation I have mentioned in the paragraph tackling it in the introduction



complex and even originally for the Bavarian set, there was a need to cluster the charging stations to make it computationally lighter, I have decided to use the second option. The number of charging slots will be preserved for each charging stations, but they have only one general charging rate. I have decided to use for each charging stations the charging rate of its slowest charging slot. Therefore won't become optimistic and will be somewhat slightly pessimistic when compared to real life. Due to the lower density of charging stations in most parts of the Czech Republic compared to Bavaria, I did not have to cluster the charging stations anymore. When I have generated the new version of the charging stations set, I have to attach it to the planner files and modify the configuration file again.

### ■ 4.1.3 Allow Specifying Vehicle Parameters Used for Planning

The planner now allows specifying own BEV; actually, it now requires having basic vehicle parameters (battery capacity and vehicle range) within the input. This was very important to me, as it also allows me to simulate planning for the CV with this BEV planner. There were two possible options how to implement this modification either allow detailed vehicle parameters specification or use the basic setting that was already introduced. The main advantage of using the advanced version is that it will let the planning to be more precise. The main disadvantage is that it would be allowed only to choose from two or three predefined vehicles instead of allowing him to specify his own to exactly suit the BEV he would potentially purchase. I have decided to use the basic parameters version to allow the planner to work more generally. Also, even though the variant with more complex parameters setting will be more precise today, it might happen that in the future, the predefined vehicles will be replaced with much better newer versions, and they will become obsolete, and the tool then will have no use. In contrast, with the basic parameters version, the user could, instead of the outdated predefined vehicle, easily specify his own directly within the planner only with simple parameters these future BEVs while allowing the planner to be still usable.

### ■ 4.1.4 Charging Stations at Activity Locations Support

The actual version of the planner allows specifying if there is a charging station at the activity location. Suppose there is a charging station at the location. In that case, the input needs to contain a specification of this charging station as part of the user location dictionary, which is part of the property of every activity point. Similarly is also handled possible charging station at the end or start location. If there is no charging station, the input could stay the same as before the modification. Since I want to keep my tool user friendly as much as possible, I only demand information whether there is a charging station at the activity location or not. This means I do not have any additional information about the charger, such as charging rate, price, etc. Therefore whenever there is a charging station, I use the same

standardised charging station specification that I add to the input (I take that specification from the charging stations set I have mentioned above, it is one of the slower chargers, and it also shares the same price as every charging station in the set.).

### ■ 4.1.5 Extension of the Planner Responses

Proposed modifications mostly were implemented. There is now info about charged kWh of every charging, also spent kWh of every moving activity. The information about the price was preserved, although I do not use it, but they could be helpful in the future when the planner uses charging stations set with recent real-life prices. The delay info was also added. The most problematic part is the date-time that should be added to every point of the trip's geometry. The actual version of the planner returns these date-times only for significant points (start or end of the trip, arrival to a junction, etc.); for other points, it contains a null value. As this information is needed for the visualizer, I have handled it elsewhere, and I will describe it later.

## ■ 4.2 Visualizer Modifications

This section will go through every proposed visualizer (front-end) change; I will evaluate whether they were implemented, then discuss how they were implemented or why they were not implemented. Also, I will state for every modification how I participated in it.

### ■ 4.2.1 Visualizer Introduction

Although I originally intended to create my own visualizing app that would work only locally, I have later concluded that a web application will be more suitable. Thus I have to create or obtain a front-end part of it (from now on, I will refer to it mostly as the visualizer).

I have decided to use a visualizer that was currently in development on CTU FEE. This visualizer was intended only to show trips, charging and charging stations, all of this loaded from a file. It also could animate the trajectories in time. Other than this, it has nearly no other functionality. MapBox powers the map of this visualizer. Besides the visual part, which consists of mentioned map and buttons to switch between view-modes (charging, trips, charging stations), it consists only of JavaScript scripts used for preprocessing and animation. It was run by ApacheHTTPserver (which was non-ideal for my usage). The most important thing for me is that the visualizer has a basic graphic part of it already finished and could allow me to propose and sometimes even implement significant changes to suit the needs of this thesis.

### ■ 4.2.2 Proposed Modification of Visualizer

Since I have already introduced the visualizer I will use, I could now specify the proposed modifications of it so it will fulfil my requirements for the visualizer.

I need to modify the planner in such a way it could display all the specified information to the user and also that it will follow the intended passage of the user through the information (Figure 3.2). Also, it is needed to allow creating user's own agenda besides the example one, uploading location history files etc. The advantage is that I consider the current (at the beginning of my work on my thesis) graphical design of the visualizer as very fitting for my intentions, so it won't have to be altered. I will need to introduce new parts (that will display additional information to the current ones) that will follow this design, change the overlay of existing parts a little bit and introduce new views (for example, BEV - CV comparison view in addition to current one, where it only shows the BEV/CV plan). However, I do not have to create a new overall graphic design for the visualizer.

Proposed modification of the visualizer are:

- Add new comparison view (and processing of the comparison data)
- Update current BEV plan view, so it displays all the information contained by a BEV plan
- Create CV plan view - basically copy of BEV plan with disabled information concerning only BEV
- Create a reasonable system for switching between individual views
- Prepare user guide
- Allow creating own agenda including setting if there is a charger at the activity location
- Allow to specify vehicle the planner should plan with
- Add support for history location files upload
- Connect the visualizer frontend with its newly created backend part

### ■ 4.2.3 Modifications and Additions of Views

The new comparison view is one of the most critical parts of the visualizer modifications as it could also work as a standalone mode. In contrast, the others do not provide a sufficient amount of information. Based on my specification, a new comparison view was added. It displays all the information from the comparison input. Also, it displays on the map both the BEV and CV plan.





form within the index.html. This form is specified to accept any file as an input. This event calls a `uploadAgenda()` function, where the parameter is the selected file. The rest of the process is handled via this `uploadAgenda` functions (`upload_agenda.js`). This function first selects information about the first file of its input. Then it uses `FileReader` to read the file and save it to a variable. After short processing, it sends the data within a JSON file to the back-end. The rest of the input processing process (interacting with the back-end and visualizing the results) was already described.

#### ■ 4.2.6 Preparations for New Back-end Integration

The necessary modifications for making the planner back-end work correctly will be explained in this section. For using the current visualizer front-end with the new back-end, there are few necessary modifications of imports, the visualizer folder structure, etc., that needs to be implemented. In contrast to the previously explained visualizer modifications, this one was implemented entirely only by me..

First, I have to create a new visualizer folder structure - the main Flask script is in the top folder. It also contains three sub-folders - one that contains Python scripts necessary for the back-end to work (various converters I will describe, etc.). The other two sub-folders contain things for the visualizer front-end; one of them (`templates`) contains the `index.html` file (that is rendered by the new back-end as will be explained later), the other (`static`) includes all the things that are loaded by the index (JavaScript scripts, various images, other HTML files, etc.). The structure of the static sub-folder, to some extent, copies the original structure of the visualizer folder.

Also, it was necessary to convert all the imports in all the HTML and JavaScript files. While the changes within the HTML files were only tackling formatting differences so that Flask will accept them, the changes in the JavaScript files had to tackle the new folder structure.

### ■ 4.3 Google Map Location History Export Processing

I have created a script for converting google map location history export to a format accepted by the planner (**kml, google format to JSON, planner format converter**) that fulfils all the requirements I have introduced before. It **allows changing of departure and arrival delay limits** - the original arrival and departure time is set as the arrival and departure times from the location history, and there is a possibility to move these times (standard setting of this converter alone is preserving original times, but the unified tool that is handling this by default relaxes the delay times) when preserving the duration, thus creating the possibility of a delay. At the same time, there is a need to specify own vehicle (necessary information for creating planner

input). Also, it supports **the merging of several history files**, even though the unified tool does not support multiple files processing, regardless I have preserved this feature, and it is available when using this converter independently. I have used Python to create this converter.

It is approached by utilising function `kmlToJSON()` where the input parameters are in the order loaded kml data, the vehicle specification and optionally max delays. The output is a list of activity names, a list of activities to be used when creating comparison and a dictionary containing the planner input. It could also be approached by using the function `kmlToJSONfile()` with parameters in order: list of input files names, output file name and vehicle specification and optionally delays. It returns a list containing activities names and a list of activities for comparison creator, and the data for a planner are saved to the file).

## 4.4 Tool Agenda Export Processing

The **GEOJSON, visualizer format to JSON, planner format converter** was created successfully. It has all the features that the location history converter has except handling multiple files at once. This feature was not necessary as the planner creates agendas spanning over multiple days without any problem, while the location history exports always contain only one day. Again I have used Python to create the converter.

Also, access to this converter is possible in two ways. Either by function `geojsonFileToJSON` or by function `geojsonToJSON`. Both of these functions have up to three input parameters, one compulsory and two optional. The first one and the only compulsory is with a name of a file containing visualizer output for the first one or a dictionary containing the output directly for the second one. The optional parameters are delays specification (if not set, both arrival and departure times stays the same) and vehicle (parameters of one of the predefined vehicles are used) specification. As well as for the location history converter also for this converter was the most crucial issue to handle the differences in various formats (datetimes, locations, etc.) and allowing to fill in the missing information.

## 4.5 Accessing the Planner

All goals I have described in the introduction paragraph about accessing the planner were fulfilled. I have created a script in Python that handles it all. Originally I have prepared two functions - `accessLocalPlannerWithFile(input file name, output file name)` and `accessLocalPlanner(input data)`. Then I have prepared function `accessPlanner(input data)` to access a planner deployed on a server. The last pair of functions return a planner output; the first one saves it to a file. All three functions were then meant to be used

when we access the planner separately, without connection to other part. All three of them requires input data already formatted for the planner—these functions fully fulfil the goals mentioned above.

Nevertheless I have decided to create functions with more abilities than just accessing the planner. Most of its features are from other components of this project and they use even the above described functions to access the planner, but together they form an unit with great possibilities. I have implemented functions `tryToFindSolutionVisualizerOutput(data, delays)` and `tryToFindSolutionKML(data, delays)`, where dictionary data for the first function contains the visualizer output and for the second one it a history location export. The functionality of both functions is the same. They convert the data to a format accepted a planner, then they try to get solution from the planner by using above mentioned functions for its accessing. If it returns error code, they returns strings with the error message, if it returns no solution it returns null. If it succeeds and gets a solution from a planner, they then converts the plan to a data format so they are accepted by the visualizer, also they try to get a solution for ICE vehicle (vehicle with nearly unlimited range) - it is almost guaranteed this succeeds as it returns reasonable solution for problem with grater complexity. Then they creates a BEV - CV (ICe vehicle) comparison (I will describe comparison and plan converting later). They both returns BEV plan, CV plan and a comparison.

## 4.6 Creating Visualizer Input

Processing the planner's response is one of the most crucial parts of the tool. An incorrect representation of the results will significantly devalue the abilities of the unified tool to fulfil its goals. I have created two separated components - planner response format to visualizer format converter (planner output converter) and comparison creation tool, that should handle the creation of the visualizer input.

### 4.6.1 Planner Output Converter

The planner response format to visualizer format converter is a simple Python script, which takes information taken from the planner output and converts them so they could be displayed in the visualizer. It does not provide any information other than that in the planner response. There is a function `actionsToFeatureCollection()` which takes as the input parameters list of the actions from the planner response (created by function `getActionsFromDict(planner output)`), start action from the agenda, end action from the agenda, total delay created by (`getEndDelay(planner output)`) and activity names (as the planner does not preserve them). Both start and end actions are obtained by a function that extracts them from the original input files. This is necessary as the planner did not return start and end activities as normal activity. Except for the need to obtain additional information for

converting to the visualizer format, there is also a need to have the datetime for every location in the trip geometry, which the planner does not fulfil. As I have previously written, the best option would be not to use interpolation, rather consider the speed being constant (for example, once we arrive at a highway, the vehicle would have a constant speed, this could be to some extent applied even to traffic jams etc.) between every datetime information we have. Therefore I have decided to replenish the datetimes evenly between every known pair. The function mentioned earlier meets every expectation I have introduced for it, although the input needed for it is quite complex.

This function is used for converting both CV plan and BEV plan, as there is no difference between them in the planner output.

### ■ 4.6.2 Comparison Creation Tool

Main goal of the comparison creation tool is to generate comparison file containing the electrification score introduced above and provide additional information that are not directly part of the planner output, but could be obtained using this output, and could be used for the BEV - CV comparison. The comparison file is generated by `createComparison()` function. It takes actions extracted from both BEV and CV plans returned by the output, also actions extracted from the original input (either visualizer agenda export or history location file), optionally values of subscores in the unified electrification score and also optionally dictionary parameter, where could information such as fuel price etc. be specified.

## ■ 4.7 Visualizer Back-end

I have decided to use Flask as it does not require any special external tool to run it. It means that Flask is a relatively simple framework, but sufficient to make working everything need in this project. Another advantage is that it is developed in Python and based on Python, which allows us reusing of an already existing code.

One of the crucial requirement for the back-end is to allow me to preserve all the functionality of the visualizer created using JavaScript scripts without needing even partially to use my backend for it. Of course, that requirement is obvious and should almost always be fulfilled, but it is important to check that it really is so.

I have managed to create a new back-end for the visualizer that reached every goal set. As I had stated before, I used Flask for it. The main purpose of the back-end is to provide a smooth connection between the visualizer front-end, planner and every component introduced in this thesis.

Since there was a need to retain all the JavaScript functions that

were already created, I decided that the back-end will only handle the initial startup of the visualizer. Then, the switching between individual parts of it, animations, etc., will be handled through the already ready functions.

Since I have already described individual components and their use, I will only describe the general idea of how they are interconnected inside the back-end, and I will not go into too much detail. The visualizer back-end now contains three functions: `index()`, `newPlanProcessing()`, `kmlProcessing()`. The main and sole purpose of the `index()` is to render `index.html` (and thus allow viewing the web application).

The functions `newPlanProcessing()` and `kmlProcessing()` are there to get and return results from the planner to the inputs provided by a user through the visualizer front-end. This means they both need to handle GET and POST HTTP(Hypertext Transfer Protocol) methods. Both of them obtain the user's inputs from the front-end part, using a request object that is part of the Flask package and its function `JSON` for receiving a request in a JSON format. Then they are trying to get results by using the `tryToFindSolution` functions that were already introduced in the Access the Planner section. They are trying to obtain the solution by gradual relaxing of the delay limits (by doubling them) until the solution is received, or the delay limit is unreasonable (if it is necessary to allow delays longer than one week, then there is no reason in trying to obtain solution anymore as it is clear that the electrification makes no sense in this case). Also, when the `tryToFindSolution` functions return an error (which means that the input caused a planner problem), these backend functions also return an error code.

The communication between the front-end and back-end is provided using AJAX calls from JavaScript parts of the visualizer. It sends the user's input to the back-end and accepts the back-end's response(both in JSON formats). The response either contains valid CV and BEV plans and the comparison saved into a jsonified dictionary when successful. It contains a similar dictionary with the same keys and null values when there is no solution. The first case is returned with code 200 (success); in the second, it is returned with code 400.



## Chapter 5

### Results

In this chapter, I aim to demonstrate the functionality of my tool that should facilitate the decision to adopt the BEV. First, I will shortly introduce how does the scoring system work. Then I will go through six scenarios based on two different agendas (three scenarios for each) to demonstrate the functionality of the tool. For all of them, I will first introduce the agenda we want to electrify, then I will describe how the planner handled it, and at the end, I will evaluate its suitability for electrification. All the scenarios were processed through the tool introduced before (we named it "If I had EV" Tool), which is currently available at [its.fel.cvut.cz/ifihadev](https://its.fel.cvut.cz/ifihadev) where any user of it could use it to evaluate his own created or upload agenda.

#### 5.1 Electrification Score

In this section, I will demonstrate the functioning of the electrification score system. First, I will introduce a simplified agenda that will be used, then explain the experiment I have made with it, and as the last point, I shall discuss the results.

##### 5.1.1 Simplified Demonstration Agenda

As was already described when introducing the electrification score, I will need information about the original agenda, resulting BEV plan, and CV plan. All this is in this experiment represented by the same demonstration agenda. The demonstration agenda could be seen in the following table:

Action	duration [min]	delay [min]	length [km]	consumption [kWh]
Drive 1	100	-	100	13
Activity A	50	0	-	-
Drive 2	100	-	100	13
Activity B	50	0	-	-
Drive 3	100	-	100	13
Activity C	50	0	-	-

**Table 5.1:** Demonstration Agenda

It contains information about action type (drive or activity), duration of the action, delays of the activities, length of drives and consumption created by drives. This is the base BEV plan that will be modified for the purposes of this experiment. The base CV plan is the same, except there is no information about consumption. Note that delay in this table means delay against the original agenda (if it will be negative, it means that for this plan, the vehicle arrived earlier than in the original agenda., this means that the BEV delay in the electrification score is counted as a minimum(BEV\_delay, BEV\_delay - ICEv\_delay).

The demonstration agenda is a simple one with three drives and three activities; all three drives have the same length (100 km), duration and consumption. Also, all three activities have the same duration and base delay. The connection between drive parameters is based on the assumption that every km cost one minute and 13/100 kWh. This assumption will be used later. Other important preset parameters are in the following table (Table 5.2) and they are used for every experiment mentioned in chapter Results.

Parameter	BEV	CV
Fuel price [Kč]	3 per kWh	30 per liter
CO2 pollution [g]	780 per kWh	2310 per liter
consumption per 100 km [l]	-	9

**Table 5.2:** Experiments parameters

### ■ 5.1.2 The Experiment Explanation

I aim to demonstrate the functioning of electrification score based on input parameters based on simplified real-life events (in this case, the need for charging). I will preserve the setting of the ICE plan all the time. I will be modifying the BEV plan. I will be adding length to the Drive 1 action (because there is a need to charge the car, and I will have to drive additional kilometres to reach the charging station and return to the original route, for simplification reasons, the charging time is not taken into account). Every extra kilometre also affects other (see the assumption in the previous section) parameters. Every minute of additional duration will also affect the delays of all the following activities. I will test three different scenarios - one where the



only delay of the following activity (Activity A) is affected, one where two subsequent activities are affected (Activity B will share the same delay with Activity A) and one where all three activities are affected (Both Activity B and C will have the same delay as Activity A). I will start with no change, and by adding one kilometre per change, I will get up to two hundred additional kilometres (which is two times the original length of the drive).

### 5.1.3 Results Demonstration and Discussion

First, I will explain the results of the first scenario. Then I will introduce the results of the rest and compare them.

The results of the first scenario could be seen in (Figure 5.5). In the first phase, the score is declining by copying the inverse quadratic function. Then it becomes linearly decreasing. This is caused by the delay subscore (based on quadratic function) hitting its minimum. The rest of the subscores are linearly descending, as could be seen in (Figure 5.1, Figure 5.2, Figure 5.3), also they will stay the same regardless of the scenario. Whereas the delay scores change, as could be seen (Figure 5.4). The reason why the scores in (Figure 5.1, 5.2 and 5.3) do not drop to zero is that I want to compare the graphs with the same ranges of additional kilometres (and for example, for time score, it would be needed to add 450 additional kilometres before it reaches zero instead of the intended two hundred).

It is visible (Figure 5.5) that we achieve a relatively good score for the first scenario when the additional length is shorter than 50 km (half of the first drive length), which I consider reasonable. As I have already stated,

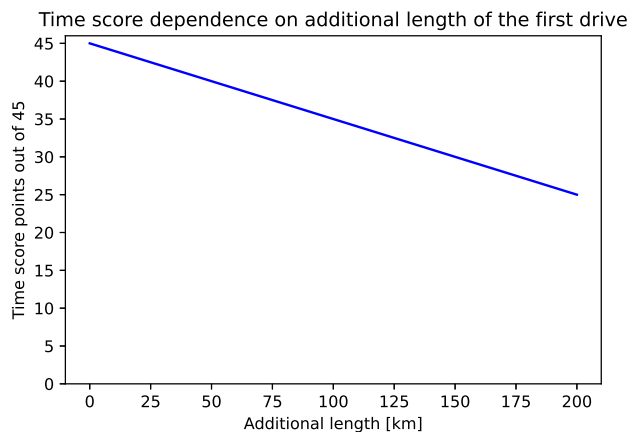


Figure 5.1: Time score

the only subscore that changes between scenarios is the delay score. The delay score causes deterioration of results when the delay is also transferred to other activities than the first one, as could be seen (Figure 5.6) and could be expected due to (Figure 5.4). It also shows that while there is enough

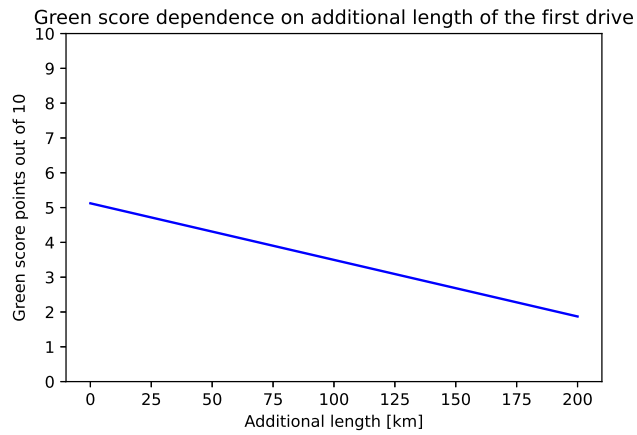


Figure 5.2: Green score

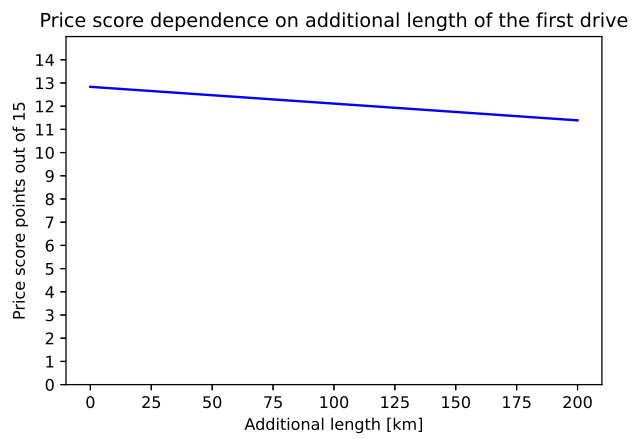


Figure 5.3: Price score

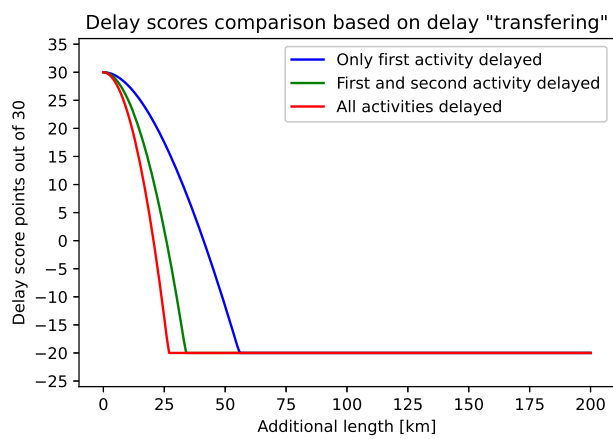
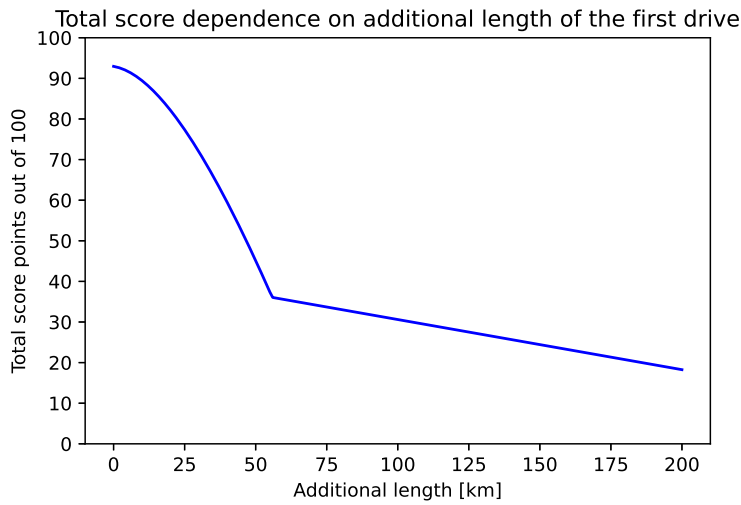


Figure 5.4: Price score



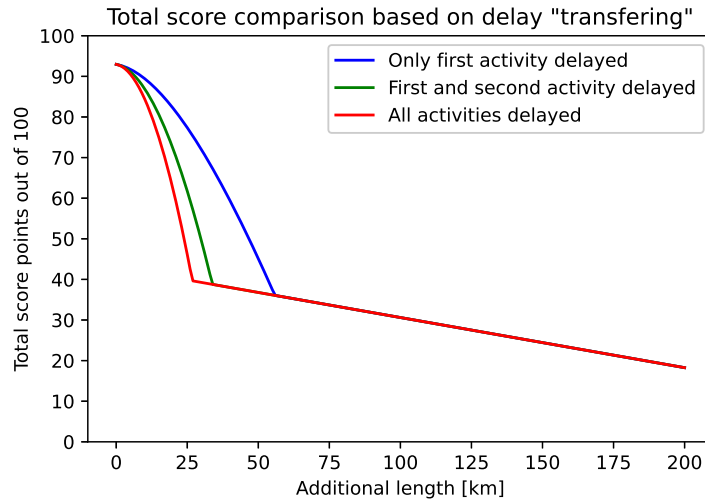
**Figure 5.5:** Total score dependence on arrival delays share on total agenda duration

time to reduce delay caused by charging between activities, it could be allowed to make a detour for charging with length up to 50 kilometres (half of the first drive). When the delay is not reduced between activities (which means that the original agenda was set so that we are always everywhere on time and there is no reserve time), then the detour should be shorter than 25 km (a quarter of the first drive).

These results confirm that the electrification score is usable in real-life usage. It takes into account the time stringency of the plan. It also considers the additional length of tour caused by using BEV instead of a CV, etc.

## 5.2 Agenda A - Introductory

Agenda A is shorter introduction agenda on which I shall demonstrate the possibilities of the tool. I will test it with three scenarios. They will differ in used BEV and also in the availability of chargers at activity points. For each scenario, I will first describe the modifications against the base agenda and BEV specifications. Then I will introduce the BEV plan that was returned for it. Finally, I will compare it to the CV plan (There is only one CV plan for all the scenarios as the different chargers availability and battery specifications do not affect the CV plan). After the sections tackling individual scenarios, I will compare all the BEV plans together, and then I shall evaluate this comparison.



**Figure 5.6:** Delay score dependence on arrival delays share on total agenda duration

### 5.2.1 Introduction of Agenda and the CV Plan

Agenda A is a simple one consisting of six locations (start, end and four activities) - five unique locations as the start city is the same as the end city) to visit. Its expected duration is 9 hours (half of it is the sum of activities duration, and the rest is for transfers between individual locations).

Location	Cheb	Pilsen	Prague	Most	Carlsbad	Cheb
Activity	Start	Quick break	Exam	Meeting	Shopping	End
Expected start	8:00	9:00	10:10	14:10	15:40	17:00
Duration [min]	0	15	180	30	45	0

**Table 5.3:** Agenda A

The CV plan created for the agenda has a total duration of 8 hours and 50 minutes, which means that it is slightly faster than expected. Throughout the plan, it has accumulated almost 20 minutes of activity arrival delay. The length of the CV plan is 404.4 kilometres. The CV plan view in the tool could be seen in (Figure 5.7).

### 5.2.2 Scenario One - Short-range Vehicle

For the first scenario, there are no charging stations available at the activity locations. I have decided to use BEV with quite a short-range (155 km provided by 18 kWh battery). I have expected the BEV plan for these parameters will contain significant delay compared to the CV plan.

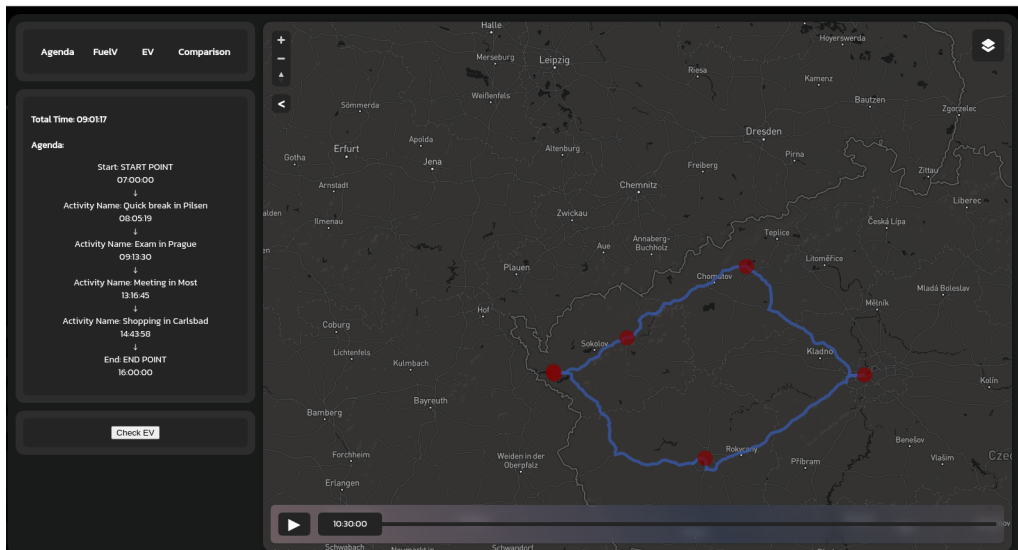


Figure 5.7: The CV plan view - agenda A

## BEV plan

The planner returned a solution with a duration of 9 hours and 8 minutes. The total length of the plan is 405.6 kilometres. An important fact is that due to the short range of the BEV, there is a need to charge the BEV 4 times during the plan (for half an hour and 30 kWh), which created a total sum of arrival delays of 70 minutes). The BEV plan view in the tool could be seen in (Figure 5.8). Note that only two charging breaks are visible in (Figure 5.8) on the map due to the proximity of the other two to activity points which cover them up. But all four could be seen in the agenda part of Figure 5.8.

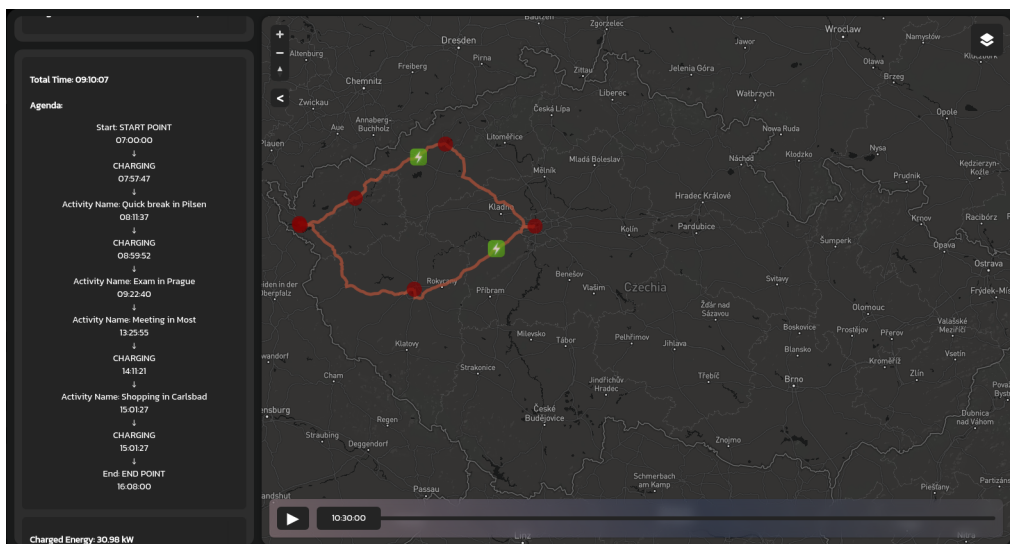


Figure 5.8: The EV plan view - agenda A scenario 1

### Comparison with CV plan

The comparison view could be seen in (Figure 5.9). The essential information is in the following table. As I have already stated, the delays caused by charging caused BEV to delay much higher than the CV delay. Also, the 18 minutes difference between BEV and CV total times must be considered when considering that total BEV driving time is only 4 hours 38 minutes. The time difference and delay difference caused the electrification score to be 75 out of 100. Which is still relatively high. It means that the electrification will be recommendable if there is no need to be precise in activity arrival times (because as is stated in the score explanation, "Activity arrival delays of BEV are too high compared to ICE vehicle".).

Vehicle	CV	BEV
<b>Total time</b>	8h 50 min	9h 8min
<b>Sum of arrival delays</b>	20 min	70 min
<b>Length [km]</b>	404.4	405.6
<b>Cost [Kč]</b>	1091	145
<b>Saved CO2 [g]</b>	-	46145
<b>Charged [kWh]</b>	-	30.98
<b>Spent [kWh]</b>	-	48.64
<b>Charging time</b>	-	30 min
<b>Electrification score out of 100</b>	-	74.86

Table 5.4: Agenda A - Scenario One - comparison

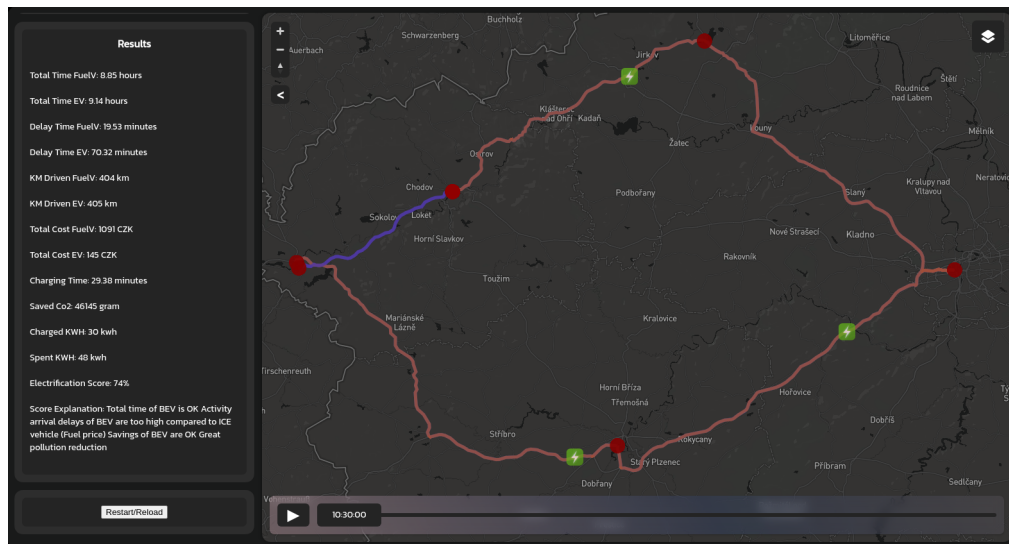


Figure 5.9: The comparison view - agenda A scenario 1

### 5.2.3 Scenario Two - Mid-range Vehicle

The second scenario differs from the first one only by using slightly better BEV. It has a range of 265 kilometres provided by a battery with a capacity

of 36 kWh (this vehicle is one of the presets that could be selected in my tool, whereas I manually created the vehicle used within scenario one for purposes of the scenario). All the other settings stay the same.

### ■ BEV Plan

In this BEV plan, there is a need for two charging breaks. One is between Pilsen and Prague, the other during Carlsbad activity, even though there was added no charging stations at activity locations (it might be because there is a charging station located in the base charging stations set).

### ■ Comparison with CV Plan

There are only slight differences between the CV plan and the BEV plan. The difference in total time is only 4 minutes in favour of the CV plan, and the CV plan is also better in the sum of arrival delays parameter (by 8 minutes). For this scenario, the advantages of BEV, such as ecological friendliness, lower usage price etc., combined with relatively similar time parameters as the CV, has resulted in a very good score of 91.53 out of 100. This means that this agenda is recommended for electrification with the specified vehicle.

Vehicle	CV	BEV
<b>Total time</b>	8h 50 min	8h 54min
<b>Sum of arrival delays</b>	20 min	28 min
<b>Length [km]</b>	404.4	404.5
<b>Cost [Kč]</b>	1092	170
<b>Saved CO2 [g]</b>	-	39831
<b>Charged [kWh]</b>	-	25.62
<b>Spent [kWh]</b>	-	56.73
<b>Charging time</b>	-	28 min
<b>Electrification score out of 100</b>	-	91.53

**Table 5.5:** Agenda A - Scenario Two - Comparison

### ■ 5.2.4 Scenario Three - Mid-range Vehicle with additional charging stations

Although a very good electrification score was achieved in the second scenario, I will still introduce the third scenario, but my aim is not to make the score better; instead, it demonstrates the possibilities of my tool. The last scenario preserves the vehicle used in the second scenario. The difference between them is the availability of charging stations at the activity points - specifically in Prague and Carlsbad.

## ■ BEV Plan

There is only one charging action during the whole plan. This charging is at the activity location (Prague), and its duration is 153 minutes. The considerable duration caused by the fact that the preset charging stations which are used at activity location have quite a low charging rate. On the other hand, it removed the need to charge elsewhere (which could make the total duration of the plan longer). It arrived with 5 minutes delay to Pilsen, with 3 minutes delay to Prague, with 6 minutes delay to Most and 4 minutes to Carlsbad.

## ■ Comparison with CV Plan

As could be seen, thanks to charging at the activity location instead of at some charger along the way, the time parameters are nearly the same for the CV and BEV plan, and the delays are the same for the BEV plan and the CV plan. This means that the time and delay score is even higher than in the second scenario. The other parameters except for charging time (that has no direct importance for the electrification score) remained nearly the same. It has resulted in another excellent electrification score of 92.4 out of 100 points. It is only slightly better than in the second scenario; as for this agenda, the advantage of charging at the activity locations cannot be fully demonstrated. Nevertheless, it fulfilled my goal to demonstrate the tool's ability to add charging stations to the activity locations.

Vehicle	CV	BEV
<b>Total time</b>	8h 50 min	8h 51min
<b>Sum of arrival delays</b>	20 min	20 min
<b>Length [km]</b>	404.28	404.28
<b>Cost [Kč]</b>	1091	170
<b>Saved CO2 [g]</b>	-	39820
<b>Charged [kWh]</b>	-	28.32
<b>Spent [kWh]</b>	-	56.70
<b>Charging time</b>	-	153 min
<b>Electrification score out of 100</b>	-	92.40

**Table 5.6:** Agenda A - Scenario Three - Comparison

### ■ 5.2.5 Comparison of Scenarios

All the scenarios achieved quite a high electrification score, but the second and third were still significantly better. The differences in used BEVs cause this difference. On the other hand, the difference between the second and third scenarios is relatively small. Even though it was slightly higher for the third scenario (thanks to additional charging stations at activity locations), the already great score of the second one could not be improved even more. These scenarios demonstrated the need for allowing BEV specification for every user's input because it was shown that used BEV could make a significant



difference in scoring and the recommend ability of electrification. Also, it is vital to notice that although the CV plans share the same inputs (as the differences in the scenarios did not affect them), still there are minor differences between them. Still, they did not affect the results (comparison with BEV) negatively.

## 5.3 Agenda B - Time Pressuring

For agenda B, I will continue the same way I did for agenda A. While agenda A was based on the potential needs of the individual user (it was based on one of my own trips, with slight modifications to allow better demonstration of the tool possibilities), the agenda B is meant to demonstrate more of a company use (for example of the delivery company). Also, I would like to display the importance of the possibility to add charging stations at activity locations more than I did with agenda A.

### 5.3.1 Introduction of Agenda and the CV Plan

Agenda B is quite a long one; it consists of eight locations to visit ( seven unique) - start end and six activity locations. It spans exactly over 13 hours, 4 hours and 30 minutes belongs to activities duration, and rest for transfers. This agenda is quite a time pressuring one, as will be shown later. It is also nearly twice as long as agenda A (840 kilometres compared to 404 kilometres). It means it is a more significant challenge for the BEV planner and the processing of the results. This allows me to demonstrate the possibilities of my tool more than the agenda A.

<b>Location</b>	Cheb	Carlsbad	Prague	Brno	České Budějovice
<b>Activity</b>	Start	Delivery	Delivery	Delivery	Meeting
<b>Expected start</b>	8:00	8:25	10:00	12:30	16:00
<b>Duration [min]</b>	0	15	45	90	75
<b>Location</b>	Plzeň	Tachov	Cheb	-	-
<b>Activity</b>	Delivery	Delivery	End	-	-
<b>Expected start</b>	19:00	20:0	21:00	-	-
<b>Duration [min]</b>	25	20	0	-	-

**Table 5.7:** Agenda B

The CV plan could be seen in (Figure 5.10). The CV plan could not reach all the activities at the specified time, which means this agenda is quite challenging to meet. (It has a duration longer by 11 minutes than intended and created 49 minutes of the sum of arrival delays).

### 5.3.2 Scenario One - Mid-range Vehicle

For the first scenario of agenda B, I will again use the BEV with 265 kilometres long-range provided by a battery with a capacity of 36 kWh. There are no charging stations at activity locations available.

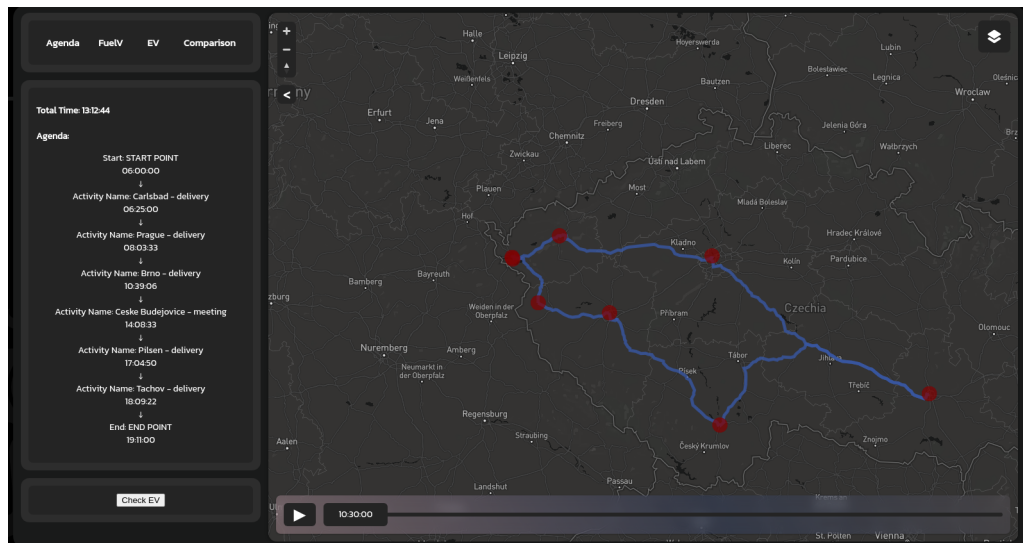


Figure 5.10: The CV plan view - agenda B

## BEV plan

Due to a relatively short range of the BEV compared to the total length of the agenda, there was a need for three visits of charging stations (on trips from Prague to Brno, from Brno to České Budějovice and from České Budějovice to Pilsen).

## Comparison with CV Plan

As could be seen from the table, the BEV plan is much worse than the CV one. It has a longer duration by 40 minutes, a considerably bigger sum of arrival delays (147 minutes). Because the length of the plan (longer by 15 kilometres) also did not reach an as good reduction of cost and pollution as it could in different scenarios. These all factors together created a bad electrification score of only 40.03 points. This means that electrification of this agenda in this scenario is not recommendable but is possible (at least for the early adapter type of user that was introduced in the theoretical part) for the common user. In the introduction of agenda B, I have stated that it is meant to be for a delivery company, and in this case, I will highly not recommend the electrification.

Vehicle	CV	BEV
<b>Total time</b>	13h 10 min	13h 50min
<b>Sum of arrival delays</b>	47 min	194 min
<b>Length [km]</b>	840.39	855.97
<b>Cost [Kč]</b>	2269	360
<b>Saved CO2 [g]</b>	-	81010
<b>Charged [kWh]</b>	-	85.46
<b>Spent [kWh]</b>	-	120.14
<b>Charging time</b>	-	28 min
<b>Electrification score out of 100</b>	-	40.03

**Table 5.8:** Agenda B - Scenario One - Comparison

### ■ 5.3.3 Scenario Two - Long-range Vehicle

In the second scenario, I shall use different vehicle than in the first one as scenario one demonstrated the previous vehicle is unsuitable for such a lengthy agenda. It will be again one of the preset vehicles of my tools, this time with a range of 500 kilometres provided by a battery with a capacity of 55 kWh. This means that it has a more extended range but also better effectiveness - it could drive over 9 kilometres per kWh, whereas the previous one could only drive 7.4 kilometres. Again, there will be no charging stations available at the activity locations.

#### ■ BEV Plan

Usage of BEV with more extended range than in scenario one resulted in a reduction of chargings during the plan (from three to two - between Prague and Brno and between Brno and České Budějovice). This resulted in reduced total time (from 13 hours and 50 minutes to 13 hours and 24 minutes) and delays (from 194 to 104 minutes). Also, there was a significant reduction in length, as both of the visited charging stations were located near the ideal route. As I have stated before, the better efficiency of the BEV created a great reduction of cost of the agenda fulfilment and better ecological friendliness (reduced indirect CO2 pollution).

#### ■ Comparison with CV Plan

In the second scenario, the difference in length and duration between the CV and BEV plan was lower than in the first one. Also, thanks to the better efficiency of the used BEV, it was more Eco-friendly and cost-effective when compared to CV than in the first scenario. This resulted in an electrification score of 80.44 points, which is a good result but could be still improved.

Vehicle	CV	BEV
<b>Total time</b>	13h 10 min	13h 24 min
<b>Sum of arrival delays</b>	47 min	104 min
<b>Length [km]</b>	840.39	840.58
<b>Cost [Kč]</b>	2269	287
<b>Saved CO2 [g]</b>	-	100168
<b>Charged [kWh]</b>	-	44.71
<b>Spent [kWh]</b>	-	95.58
<b>Charging time</b>	-	13 min
<b>Electrification score out of 100</b>	-	80.44

**Table 5.9:** Agenda B - Scenario Two - Comparison

### ■ 5.3.4 Scenario Three - Long-range Vehicle with Additional Charging Stations

For the last scenario of agenda B, I will use the same as before (500 kilometres range provided by 55 kWh battery). The difference between these scenarios is in the availability of charging stations. This time, there is charging stations at every activity location (I originally intended to allow only two to three activity charging stations, but it turned out that the planner did not use them correctly and ignored them - this is partially solved by allowing all the chargers, although it still chargers also outside the activity locations even though it could seem unnecessary). The main goal of this scenario is to find out whether it is possible to improve the already good score from scenario two to get an even better one (achieve 90 points or more).

#### ■ BEV Plan

The resulting BEV plan contains three chargings (between Prague and Brno, then during a Brno activity and during the activity in České Budějovice). Overall even though there were more charging breaks than in the previous scenario, and the total charging duration was also significantly higher, this plan has a lower total time and the sum of arrival delay. The other parameters remained circa the same. Interestingly, it does not charge during Prague activity but rather during the transfer from Prague to Brno. This is caused by one of the planner features, which tries to simulate real-life charging behaviour of users by "use of reactive charging behaviour" because "A typical user does not plan the charging until the battery has dropped below some threshold" (Cuchý, Štolba & Jakob 2018) - the user does not want to charge in Prague due to high battery charge level. Still, the BEV does not have a range long enough to reach Brno without charging; this means it has to at least shortly charge at one of the chargers along the way to Brno from Prague (ideally one with a high charging rate).

### ■ Comparison with CV Plan

As could be seen in the following table, the BEV plan is nearly the same as the CV plan - a difference of 3 minutes in total time and 17 minutes in accumulated arrival delays. This, combined with a great reduction of cost and pollution by BEV when compared to CV (that is caused by the length of the BEV plan, which is the same as for CV), caused the electrification score to be 92.78 out of 100 points. That is a great score, and electrification would be highly recommendable in this case.

Vehicle	CV	BEV
<b>Total time</b>	13h 11 min	13h 14 min
<b>Sum of arrival delays</b>	49 min	65 min
<b>Length [km]</b>	840.67	840.86
<b>Cost [Kč]</b>	2270	287
<b>Saved CO2 [g]</b>	-	100102
<b>Charged [kWh]</b>	-	45.56
<b>Spent [kWh]</b>	-	95.61
<b>Charging time</b>	-	161 min
<b>Electrification score out of 100</b>	-	92.78

**Table 5.10:** Agenda B - Scenario Three - Comparison

### ■ 5.3.5 Comparison of Scenarios

Agenda B offered more significant differences between individual scenarios than agenda A did. The first one displayed a situation where electrification will be inappropriate. The second situation was one where electrification is considerable (maybe even recommendable), and this difference was achieved by using a different BEV. This is a possibility already introduced in agenda A - it allowed us to charge at charging stations that caused fewer additional kilometres and were "faster" and thus it lower delay. The third scenario offered a situation where agenda A could be electrified very well and is the only one where I will recommend the electrification even if it was meant for a delivery company, as was stated in the agenda B introduction. It was achieved by adding charging stations to activity locations and thus was displayed the importance of it. This was my main goal for agenda B. Agenda B also displayed few exciting facts about the planner. It also revealed the functionality of a planner with an agenda challenging to fulfil even with the CV and confirmed that the electrification score still works reasonably well even for this kind of situation. And again, it demonstrated the differences between individual scenarios for the same agenda caused by other factors such as BEV parameters.





## Chapter 6

### Conclusion

This thesis explores creating a tool that should facilitate user's decision-making about adopting battery electric vehicles instead of the currently used conventional vehicle (internal combustion engine vehicle). We have researched problems regarding the decision making factors of potential BEV adopters. Also, I have introduced the need for obtaining a BEV planner for creating the tool and proposed my requirements for the planner. I have discussed possibilities for obtaining the planner.

With the usage of previously stated information, I have proposed the tool, introduced every necessary component of such a tool and discussed the possibility of use of real-life user's current vehicle usage within the tool to improve the decision-making process. To facilitate the decision-making process, I have also proposed the electrification score, which should inform the user how suitable his driving routine is for electrification. This score uses a hundred point scale, with zero being the worst result and one hundred being the best result. This score consists of four "subscores" - time score, delay score, price score and green score, that are all based on the decision making factors and was in detail introduced in sections related to the electrification score. I have also discussed obtaining the front-end part of my tool, proposed modifications to it. Then I have in detail explained the creation of the tool, evaluating how I have met the previously stated expectations for every part.

Results showed us the functioning of the tool on two different agendas and a total of six scenarios. It displayed the functionality and importance of few selected components of the tool. Also, I have evaluated and discussed the advisability of electrification in such a case for every scenario.

This thesis could be used as a tool for individual user's decision making about adopting a battery electric vehicle instead of their current vehicle. It could even be used by companies in their decision making about individual cars. It not only scores the suitability of electrification but also displays information about important factors in the decision-making and route plans for both CV and BEV to compare.

In future work, we can propose and add new criteria for the BEV planner and allow the user to specify his priorities and provide more precise and targeted information for every individual user. It was already mentioned in this thesis as one of the possible modifications, but it was not implemented in favour of other more important parts. Also, we could ensure the usage of a set of charging stations with actual information about prices in such a way it will always stay up to date; this modification will greatly improve the price information, especially when it will be connected with allowing the user to set specifications for the charging stations, he decided to add to the set (such as at home, at work, etc.). This modification will also greatly improve the price "subscore". Extension of the possibilities of user's to upload or create their own agenda the tool should help to make a decision about as is support for new history location files formats etc. is also possible modification.

I have fulfilled goal 1 (Research the related problem to the electrification of fleets and planning (consider using existing planner), briefly introduce existing solution similar to the desired tool.) - in the Related Work chapter. The second goal (Design the concept of the desired tool. Describe and motivate the usage of the components.) was fulfilled mainly within the Methodology chapter. Goal 3 (Implement the functional prototype of the tool. Describe the fundamental algorithmic components.) was fulfilled within the Methodology chapter (describing the algorithmic components) and chapter Implementation. The last goal (Demonstrate the usage of the tool) was fulfilled within chapter Results specifically in sections 5.2 Agenda A - Introductory and 5.3 Agenda B - Time Pressuring. The "If I had EV" tool is currently available at [its.fel.cvut.cz/ifihadev](https://its.fel.cvut.cz/ifihadev).

In conclusion, this thesis has proposed and implemented a tool that should facilitate the decision-making process about adopting battery electric vehicle instead of conventional ones. It is based on using a BEV planner combined with data about the user's real-life vehicle usage. Results showed that the tool that I have proposed and implemented is fully functioning and fulfils its purpose.





## Bibliography

- Axsen, J., Cairns, J., Dusyk, N. & Goldberg, S. (2018), ‘What drives the pioneers? applying lifestyle theory to early electric vehicle buyers in canada’, *Energy Research & Social Science* **44**, 17–30.  
**URL:** <https://www.sciencedirect.com/science/article/pii/S2214629618303670>
- Axsen, J., Goldberg, S. & Bailey, J. (2016), ‘How might potential future plug-in electric vehicle buyers differ from current “pioneer” owners?’, *Transportation Research Part D: Transport and Environment* **47**, 357–370.  
**URL:** <https://www.sciencedirect.com/science/article/pii/S1361920915302704>
- Breetz, H. L. & Salon, D. (2018), ‘Do electric vehicles need subsidies? ownership costs for conventional, hybrid, and electric vehicles in 14 u.s. cities’, *Energy Policy* **120**, 238–249.  
**URL:** <https://www.sciencedirect.com/science/article/pii/S0301421518303422>
- Cuchý, M., Štolba, M. & Jakob, M. (2018), ‘Whole day mobility planning with electric vehicles’.  
**URL:** [https://electrific.eu/wp-content/uploads/2018/04/ICAART\\_paper.pdf](https://electrific.eu/wp-content/uploads/2018/04/ICAART_paper.pdf)
- Globisch, J., Dütschke, E. & Wietschel, M. (2018), ‘Adoption of electric vehicles in commercial fleets: Why do car pool managers campaign for bev procurement?’, *Transportation Research Part D: Transport and Environment* **64**, 122–133. The contribution of electric vehicles to environmental challenges in transport. WCTRS conference in summer.  
**URL:** <https://www.sciencedirect.com/science/article/pii/S136192091630774X>
- Greaves, S., Backman, H. & Ellison, A. B. (2014), ‘An empirical assessment of the feasibility of battery electric vehicles for day-to-day driving’, *Transportation Research Part A: Policy and Practice* **66**, 226–237.  
**URL:** <https://www.sciencedirect.com/science/article/pii/S0965856414001359>
- Karpíšková, M. (2020), Vývoj elektromobility v České republice, Bakalářská práce, ZČU, Západočeská univerzita v Plzni.  
**URL:** <https://dspace5.zcu.cz/handle/11025/40132>
- Kolbe, K. (2019), ‘Mitigating urban heat island effect and carbon dioxide emissions through different mobility concepts: Comparison of conventional



# Appendix A

## User guide

This part contains the basic information needed about attachment of this thesis and other important facts about the project.

### A.1 Attachment structure and content

The folder structure of the thesis attachment is as follows:

```
Senfeld_thesis_attachment
├── requirements.txt
├── Score_demonstration
│   ├── Score_demonstration.py
│   ├── score_demonstration.ipynb
│   └── graphs
├── ev_visualizer
│   ├── main.py
│   ├── planner_accessing
│   │   ├── comparison_creation.py
│   │   ├── kml_processing.py
│   │   ├── planner_accessing.py
│   │   ├── response_processing.py
│   │   ├── visualizer_preprocessing.py
│   │   └── visualizer_output_processing.py
│   ├── static
│   │   └── extensions
│   │       └── upload_agenda.js
├── demonstration_scenarios
│   ├── agenda_A
│   └── agenda_B
├── images
└── specifications
```

Note that only files mentioned in this overview were created by me! The rest of the files needed to run the tool was created mostly by other people - first for a different project and later

**specifically for purposes of this tool - although I also contributed to few of them with minor fixes and updates.**

Now I will describe content and use of every important part of the attachment:

**requirements.txt** should be used for creating the (Conda) environment you use for running the tool locally. It contains every package necessary for running the tool successfully.

**Score\_demonstration** folder contains a notebook (**Score\_demonstration.ipynb**) you could use to experiment with the score (in the first part of it). The second part of the notebook is used for generating the graphs. All the graphs created by me that are used within this thesis are saved in the graphs folder. The **Score\_demonstration.py** contains all the functions necessary for running the notebook.

**ev\_visualizer** contains the tool that was described in this thesis. How to run it locally is described in the readme file that is attached to it. It also contains an example location history file that could be used for testing the tool.

**main.py** is the part that was described in the thesis as the back-end (chapter 4.7).

**comparison\_creation.py** contains the part of the tool that was described in section 4.6.2.

**kml\_processing.py** is the "kml, gogole format to JSON, planner format converter" described in chapter 4.3.

**planner\_accessing.py** is the part responsible for the connection to the planner - it was described in chapter 4.5. Note that only the parts focused on accessing are functioning if you do not have a local version of the planner!

**response\_processing.py** contains function for basic processing of the planner response. They are then used within visualizer preprocessing and comparison creation scripts.

**visualizer\_preprocessing.py** is responsible for converting the planner output to a format accepted by the visualizer - as described in section 4.6.1.

**visualizer\_output\_processing.py** contains the "GEOJSON, visualizer format to JSON, planner format converter" described in chapter 4.4.

**upload\_agenda.js** contains the part of the visualizer responsible for location history files upload processing (section 4.2.5).

**demonstration\_scenarios** contains two subfolders with agendas (A and B), and each of them includes three subfolders with scenarios (one to three) - they contain the input files a results from the Results (Agenda A, Agenda B) part of the thesis. They contain the "inputs" generated from the visualizer output (visualizer\_agenda files) and the processed responses (example\_BEV with BEV plan, example\_ICEv with CV plan and comparison within file example\_comparison). It is possible to revisualize the results in the planner (in place of the demonstration agenda) if it runs locally. It is just needed to replace the files (example\_BEV.geojson, example\_ICEv.geojson and example\_comparison.json) within ev\_visualizer/static/data\_source with a particular trio of files and restart the tool.

**images** contains the images created by me used within the tool. (The figures with diagrams and the screenshots used within the Results section.)

**specifications** contains .md files with specification of BEV/CV plan (Plan.md), comparison file (Comparison.md) and planner input (Planner-input.md)

## ■ A.2 Github repository with the tool

The "If I had EV" Tool could also be found in the ev\_visualizuer (github.com/aicenter/ev\_visualiser) repository at GitHub. It is currently not freely accessible, but there is an intention to change it in the future. Specifically it is developed within branches ifihadev (github.com/aicenter/ev\_visualiser/tree/ifihadev) and ifihadev\_BPversion (github.com/aicenter/ev\_visualiser/tree/ifihadev\_BPversion). The first branch is in active development; it will be supported in terms of bug fixes, and also potentially, it will contain new features. The second branch (ifihadev\_BPversion) contains a version of the tool that is attached to this thesis; it is not intended to change it in any way in the future.