Towards the Electrification of Taxi Fleets

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Abstract

Electric Vehicles are one important piece in the battle towards reducing oil dependency, carbon and tail pipe emissions, as well as city noise. Evidently, electric mobility with all of its advantages has gained momentum during the last decade with increasing utilization by many sectors of the society. Undoubtedly, professional fleets' operators (e.g. taxis) would be prime candidates to switch to this paradigm, and would certainly increase Electric Vehicle's visibility. However, taxi drivers are still conservative in switching to this new mobility paradigm in many parts of the world. In this thesis, with the help of empirical data, we evaluate whether Electric Vehicles together with conventional charging stations could replace current Internal Combustion Engine vehicles for taxi mobility and study the implications for the taxi business. To perform this study, we resort to a detailed mobility dataset of a taxi fleet collected in a mid-sized European city. The results provide a first indication that such transition towards electric mobility is feasible for the vast majority of the vehicles of the fleet and that simple AC chargers at taxi stands could suffice to provide the necessary range autonomy. Furthermore, we created a Virtual Dashboard, where we applied the Energy Consumption Model to help taxi drivers perceive the reality of owning an Electric Vehicle.

Keywords: Electric vehicles, Taxi mobility, Energy consumption, Empirical data, Charging Infrastructure.

Resumo

Os Veículos Elétricos desempenham um papel fulcral na mitigação da dependência petrolífera, redução das emissões de carbono e gases poluentes, bem como poluição sonora. Evidentemente, a mobilidade elétrica com todas as suas vantagens tem ganho força na última década com a crescente utilização por parte de vários setores da sociedade. Sem dúvida que os motoristas de frotas profissionais (e.g. taxistas) seriam excelentes candidatos para a mudança para este novo paradigma, o que aumentaria a visibilidade dos veículos elétricos. Contudo, taxistas ainda estão reticentes em mudar para esta nova solução de mobilidade em muitas partes do mundo. Nesta dissertação, com a ajuda de dados empíricos, avaliamos a possibilidade de veículos elétricos, juntamente com estações de carregamento convencionais, conseguirem substituir os atuais veículos de combustão interna que compõem a frota de taxis na cidade do Porto, Portugal, estudando para tal as implicações no negócio dos taxistas. Os resultados indicam que tal transição para a mobilidade elétrica é viável para a vasta maioria dos veículos da frota, e que carregadores AC instalados nas praças de táxi seriam suficientes para fornecer a energia necessária para assegurar a autonomia da frota. Adicionalmente, criamos um Painel Virtual, onde foi aplicado o Modelo de Consumo de Energia, permitindo aos taxistas a perceção da realidade de possuir um veículo elétrico.

Palavras Chave: Veículos Elétricos, Mobilidade de Taxis, Consumo de Energia, Dados empíricos, Infraestrutura de Carregamento.

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Gostava de agradecer a todos os que de alguma forma impactaram o meu percurso na FCUP, em especial:

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À Mariana.

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Ao Paulo, onde quer que estejas, sei que estás sempre a olhar por mim.

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E por fim, a todos os meus amigos.

Dedico a todos os que me apoiaram desde o primeiro momento nesta grande caminhada.

Contents

List of Tables

List of Figures

Listings

Acronyms

AC Alternating Current

DC Direct Current

DWC Dynamic Wireless Charging

EV Electric Vehicle

FIFO First-In, First-Out

GPS Global Positioning System

ICE Internal Combustion Engine

JRC Joint Research Center

JVM Java Virtual Machine

NEDC New European Driving Cycle

PHEV Plug-In Hybrid Electric Vehicle

QDWC Quasi-Dynamic Wireless Charging

RoI Return of Investment

SoC State-of-Charge

SWC Static Wireless Charging

WLTC World-wide Harmonized Light-duty Test Cycle

WMTC Worldwide Motorcycle Emission Test cycle

WPT Wireless Power Transfer

Chapter 1

Introduction

The electrification of car-based transportation has been increasing rapidly over the last few years as the development of technology has allowed a substantial decline on the cost of batteries. This development has been motivated by the highest potential, of Electric Vehicles (EVs), to achieve clean transportation, due to the fact that there are no tailpipe emissions. For the purpose of this thesis, an EV is defined as an electric battery powered vehicle, that can be recharged by plugging in to household electricity, home chargers or public chargers.

In Europe, Internal Combustion Engine (ICE) cars are set to disappear soon: all new registered vehicles are to be zero-emission starting from 2035 [1] and many manufacturers have already adjusted their strategies to meet this target. In turn, EVs offer important advantages: i) in terms of air pollution mitigation, providing about 40%-50% greenhouse gas emissions decrease compared to ICE vehicles [2]; ii) lower running costs, which leads to a lower total cost of ownership [3, 4]. These advantages have already influenced many countries to define fiscal policies that further motivate the migration from ICE vehicles to EVs. These measures include the implementation of financial incentives to the purchase of EVs, adoption of additional taxes on petroleum-based products and increased funding for research and innovation of EVs.

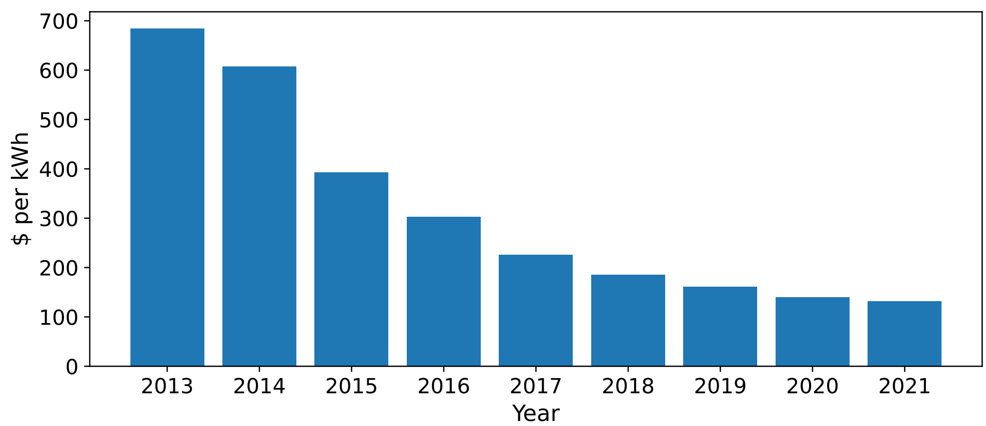


Figure 1.1: Evolution of the price of batteries for EVs from 2013 to 2021 [5]

The price of batteries is the main factor in the total price of an EV, and according to BloombergNEF's annual battery price survey [5], the aforementioned price has been declining throughout the years. Currently, they are in an all time low, with a value of 132 $/kWh in the end of 2021 (Figure 1.1).

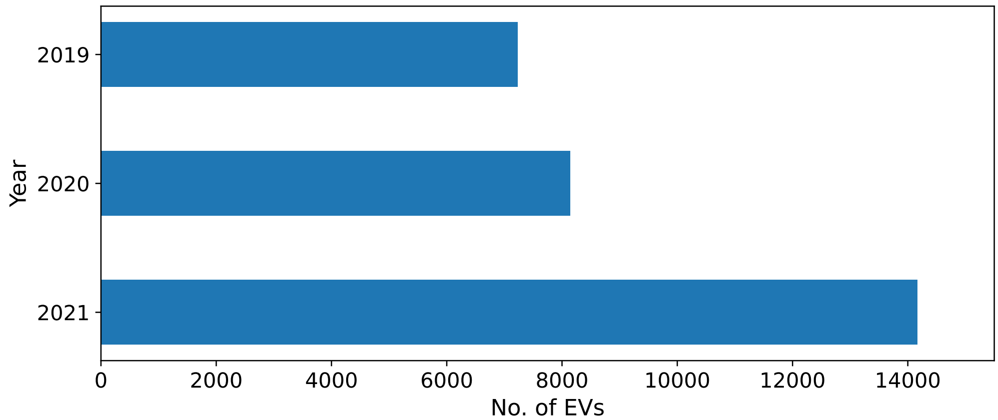


Figure 1.2: Number of EVs sold in Portugal from 2019 to 2021 [6].

In Portugal, the number of EVs has been growing, as wee can see in Figure 1.2, with the number of vehicles sold in 2021 almost doubling that of 2019. At the end of 2021, EVs had a share of 10% of the market, whilst EVs together with Plug-In Hybrid Electric Vehicles (PHEVs) had 20% [6], as depicted in Figure 1.3. In other words, one in five cars sold in Portugal during 2021 has electric propulsion motors.

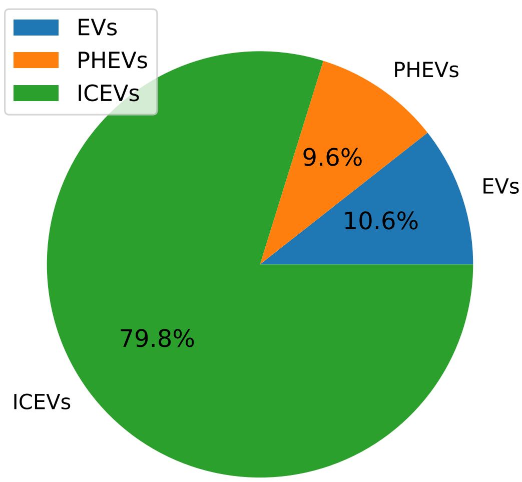


Figure 1.3: Pie chart of the EVs sold in Portugal in 2021 [6].

Despite the noticeable success of this migration, professional fleets (namely taxi drivers) are still very conservative in adhering to this type of mobility. The main concerns are related to the limited range and the long battery charging times, that are seen as important disadvantages in terms of the economic efficiency of a real-time transportation business. A limited (dedicated) infrastructure of electric charging stations [7] (for instance, in taxi stands), the high costs of using fast chargers (similar to diesel or petrol costs), and the perception that EVs cost more than ICE vehicles [3] further contribute to a minimal share of EVs in taxi fleets. In fact, in September 2021, from the +3,000 taxis operated in Portugal using the *Taxi-link*'s taxi dispatch system, only 19 of these were EVs (0.53%).

1.1 Thesis Purpose, Contributions and Objectives

The recent increase in the cost of diesel and petrol is substantially reducing the profit margin of professional fleets that travel several thousands of kilometers per month. For the over 3000 taxis that are powered by Taxi-link, supporting the study on this thesis, this fuel cost normally represents between 20 to 30% of the total taxi revenue. Theoretically, EVs could reduce this cost to less than 10% of the generated revenue, making it difficult to understand the current residual share of EVs in taxi fleets. Furthermore, the mobility pattern of taxis, with average speeds of 30 km/h in urban areas and significant idle times at taxi stands [8], seem suitable for the paradigm of electric propulsion, contrary to what happens for instance in fleets that essentially travel on highways at the maximum allowed speed. To that end, taxi drivers are considered as primary candidates or the electrification of the fleet: even though EVs have much lower driving ranges compared to ICE vehicles, taxi drivers will not be affected since the distance of most of the trips are below 20 km.

The parking time at taxi stands also seems very suitable for charging EVs, not with fast Direct Current (DC) chargers, but with much more common and less expensive Alternating Current (AC) chargers, identical to those installed domestically. This alternative would have the advantage of battery lifetime maximization and could prove sufficient to the charging needs of taxi fleets.

This thesis intends to study - based on a detailed dataset of a taxi fleet collected throughout a month - whether the 24h mobility of a taxi, together with the paradigm of AC chargers at taxi stands is completely suitable for the current autonomy and charging characteristics of EVs. This study will serve as a proof-of-concept to a tool which will be installed in the taxi-link driver's APP. This tool will simulate the consumption of an EV, and provide the drivers the means to compare the reality of owning an EV versus the driver's ICE vehicle.

1.2 Publications

The work from this Thesis resulted in the following publications:

- **J. Neves**, A. Loureiro, P. M. d'Orey, V. Miguéis, Á. Costa and M. Ferreira, *"Empirical Evaluation of the Performance of Electric Vehicles for Taxi Operation"* 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), 2022, pp. 1-6, doi: 10.1109/VTC2022-Spring54318.2022.9860830. [9]
- A. Loureiro, B. B. Oliveira, V. L. Miguéis, A. Costa, **J. Neves**, M. Ferreira, *"A study on optimal charging infrastructure size and location to support electric taxi fleets using real trajectory data"*, Journal of Research in Transportation Business and Management, submitted.

1.3 Organization

The remainder of this thesis is organized as follows. Chapter 2 provides an extensive literature background. Chapter 3 presents the large-scale taxi mobility dataset collected in the city of Porto, Portugal. The methodology to determine the energy consumption of electric taxi fleets is given in Chapter 4, together with the Virtual Dashboard. The analysis of the implications to transition towards electric mobility is detailed in Chapter 5. Concluding remarks and future work directions are given in Chapter 6.

Chapter 2

State of the Art

2.1 Electric Vehicles

In the past decade, there has been an increase in the development of Electric Vehicles (EVs). The past years have been a formative period for the industry, which is also reflected in the literature through various studies: Weldon et al. (2018) [3] focused on total cost of ownership of EVs versus Internal Combustion Engines (ICEs) vehicles, showing that: "EVs are already cost-competitive with ICE vehicles when considering the 10-year analysis period"; Sanguesa et al. (2021) [10] reviews the advancement of the technology of EVs with regards to battery technology trends, charging methods, new research challenges and opportunities, as well as an analysis of the worldwide market situation and a study of the near future within this field; Kucukvar et al. (2022) [11] studied environmental efficiency, considering the life cycle impacts of electricity generation, with the results revealing that 16 out of 27 European countries are being efficient, while Wolfram and Lutsey (2016) [2] studied environmental impact together with the technology cost; in Sun et al. (2020) [12] we can find a comprehensive review of the technical development of current and emerging EVs technologies, as well as a study for their future application. The article focuses on numerous topics, e.g battery, charging, the electric motor and charging infrastructure; Furthermore, there are also some works on the future of the industry and its prospects [13, 14].

Following the main goal of this thesis, previously described in Section 1.1, the following Sections will focus on the electric mobility of taxi fleets, is advantages, disadvantages and recent developments.

2.2 Electric Taxis

The transition towards electric mobility has generated a lot of interest in the scientific community. However, there is a lack of focus on the evaluation of the technical and/or economical feasibility of the full electrification of taxi fleets. In this section, we will take a closer look at some relevant works in the literature.

The early phases of adaptation of taxi fleets from the city of Shanghai, China, revealed they the EVs had no market competitiveness without the financial support of the government, in a study by Wang et al. (2015) [15]. However, there were already some hints that within a 5 year time frame (until 2020), EVs would rise to have the same profitability of a classical ICE taxi. On the other hand, Kim et al. (2017) [16] studied the use of electric taxis in the city of Seoul, South Korea, by analyzing driving and charging data from ten electric taxis. This study manifests the feasibility of the transition of EVs for taxi operations, from both a financial and environmental perspective. However, it is underlined in this study the need of support to the structure, by means of operating behaviors, charging infrastructure, policies and regulations, as well as the advancement of the battery technology.

The analysis of the performance of EVs is not only made through real-life experimentation, but also through simulation of the fleets. Bischoff and Maciejewski (2014) [17] performed a simulation of an EVs taxi fleet in a small city scenario, resorting to the agent-based transport simulation *MATSim*. The results showed that the level of service provided by the taxis in everyday operations had no negative impact. However, the authors proposed a model where the taxis would be dispatched by highest State-of-Charge (SoC), instead of the conventional First-In, First-Out (FIFO) system. Alternatively, Deyang et al. (2016) [18] used the Advisor [19, 20] system to simulate the behavior of a set of EV taxis, in the city of Shanghai, China to find the optimal battery size. The results showed that an electric taxi, equipped with a battery of 60 kWh could satisfy the power requirements, achieving optimal profits, as well as minimal carbon dioxide emissions.

Tian et al. (2014) [21] studied the patterns of operational and charging behaviors of EVs in the city of Shenzhen, China. They resorted to real taxi Global Positioning System (GPS) data of 600 EV taxis, and found that commercial operations of EVs can be profitable - given specific supportive policies for EV taxis - in the metropolitan area. Furthermore, the study shows that the travel and occupied times/distances are comparable for ICE and EV taxis.

Hagman and Langbroek (2018) [22] studied the conditions for the EV transition of taxis, based on data and experiences of one of the largest taxi companies in the Grater Stockholm region, Sweden. In their study, they made an assessment of the financial and operation implications of using EVs in a taxi fleet. Due to the lower driving range of EVs, and the long charging times, most taxi drivers need to sacrifice revenue, service time and plan the charging of their vehicle. This is especially true in cases that the EV is used in more that one shift per day (these planned charging sessions tend to occur at quieter times, such as lunch breaks, or some night periods). Consequently the authors underline the importance of incentives, such as companies booking preferably zero emission taxis, and a zero emission priority queuing system at Stockholm's main international airport, as well as some costumers' preferences for EVs to compensate for the additional charging time. Finally, the authors showed that an EV can have a lower Total Cost of Ownership and a higher profitability than an ICE taxi (the revenue per shift is slightly lower, due to the average working shift duration being shorter, but the revenue per hour is higher).

In the same line of thought, Hu et al. (2018) [23] examined the feasibility of transitioning the famous ICE yellow cabs to EVs in the city of New York, United States of America. With the trip data collected from the yellow taxis during the whole year of 2013, the authors were able to examine the implications of the driving patterns on EVs, and determine its feasibility. This work also states the need for more public chargers. By doing so, it would have allowed the transition of more than half of the taxi fleet to EVs.

Yang et al. (2016) [24] investigated the market potential and environmental benefits for the EV transition for the taxi fleet in Nanjing, China. Once again resorting to GPS data, the authors studied the travel patterns of taxi drivers, and found that 19% to 56% of the ICE vehicles in the taxi fleet could be replaced with EVs without driving pattern changes. Moreover, this study claims that a taxi fleet composed of only 54% EVs could reduce tailpipe emissions by 48% in comparison with a fleet composed of 100% ICE vehicles.

Optimization models and simulation [25, 26] are two approaches usually applied to infer about the charging infrastructure required to enforce such switch. Funke and Burgert (2020) [26] studied the electrification potential of the taxi fleet in the city of Karlsruhe, Germany. To do so, the authors analyzed 161 taxis, and found that a 25% to 45% share of electric taxis would have a lower cost than an ICE taxi. However, they stated the need of a more appropriate charging infrastructure. In a more recent study, Rajagopal et al. (2022) [25] stated that in contrast to the current focus on EV policies for private use, targeting professional fleets vehicles, such as taxis, would: "deliver superior environmental, economic and social returns on public investments". Further, the authors showed that 23000 EVs with a range of only 200 km and a network of 3000 chargers could satisfy 100% of the of the app-taxi daily demand in the city of New Delhi, India.

Fraile-Ardanuy et al. (2018) [27] used real mobility information of 460 taxis as a decision support to promote the transition of ICE taxi cabs to EVs in the city of San Francisco, United States of America. The results show that 75% of the current taxi fleet could be replaced by EVs with a standard - at the time - battery capacity of 24-30 kWh. Furthermore, the results show that the percentage of taxis capable of transitioning to EVs could potentially increase to 100%, given the evolution of the price and capacity of batteries. Finally, the authors performed economic analysis of the introduction of EVs in the fleet, and despite the increase of 10% of the purchase cost of the vehicle, the service, maintenance and repair costs, as well as fuel costs can be reduced by 77-84%. This results in a potential reduction of the total cost of 21%.

The determination of the optimal location for the placement of a charging network also plays a critical role in the conversion towards EVs. Asamer et al. (2016) [8] used the operational taxi data from 800 vehicles from the city of Vienna, Austria, to maximize the coverage of taxi journeys. Cilio and Babacan (2021) [28] propose a data-driven framework to study the smallest charging infra-structure to support fully electric taxi fleets. In their work, they characterised typical taxi drivers using large datasets of GPS data collected of ICE vehicles in the city of Istanbul, Turkey. However, the conclusions are supported by the usage of fast chargers. Finally, Yang et al. (2018) [29] presented a data-driven optimization-based approach to allocate chargers in the city of Changsha, China. The proposed model was applied using large scale GPS data collected from the city taxi fleet, and stated that maintaining subsidies for vehicle purchase is as important as the support for public chargers.

2.3 Wireless Charging

Charging an EV is currently one of the main challenges the industry is facing. The hassle of the cables, and the inconvenience of having to plug and unplug the device to charge the vehicle leads to the growing research in the field of Wireless Power Transfer (WPT). This is especially important for taxis parked in taxi stands, where the vehicles are in constant need of taking the next available place in the stand, as the taxis depart for services. In terms of ecological and sustainable points of view, WPT is considered to be safer for the environment, as well as more reliable [30, 31]. For that reason, in this Section, we further analyse the technology, and a real world case for the taxi industry.

There are three different WPT modes:

- **Static Wireless Charging (SWC)** [31, 32] allows cars to be wireless charged while parked. This method benefits from the elimination of shock hazard, and the ability to be installed in convenient locations, such as home garages, parking lots and especially taxi stands;
- **Dynamic Wireless Charging (DWC)** [31–34] enables the vehicle to be continuously charging whilst driving. This process is made possible through coils embedded under the surface of the road;
- **Quasi-Dynamic Wireless Charging (QDWC)** [31, 34] system takes advantage of the time vehicles are stopped for short periods of time, e.g. at traffic lights, to wirelessly charge the vehicle.

Every model described would be a great benefit for taxi drivers, as it would help reduce range anxiety, but for the purpose of this study, only the SWC model will be considered.

2.3.1 Real Use Case in a Taxi Stand

From the city of Oslo, Norway, comes a pioneer project, which uses a SWC system to wirelessly charge electric taxis parked in a taxi stand [35]. The technology uses 25 Jaguar I-Pace SUVs, equipped with inductive charging pads developed by a former NASA consultant and CEO of Momentum Dynamics. This is an action powered by the Norwegian government in a plan to combat climate change called *ElectriCity*, which requires taxis to produce zero tail-pipe emissions as soon as 2024.

In this project, multiple charging plates were placed below the pavement in a taxi stand near Oslo's Central Train Station. With this technology, the 25 altered Jaguar SUVs are able to align with the charging pads with the help of painted lines on the road and a guidance system available on the vehicle. Each pad is able to add about 80km to the range of the vehicle for every 15 min the car is aligned with the charging pad. Essentially, this technology can deliver up to 50 kW of charge in small bursts of 6 to 8 minutes, giving the opportunity to charge the vehicle whenever possible, especially between drop off and pick up of passengers. As a result, with enough charging pads distributed through the city, the battery of the electric taxis could permanently be at 75 to 85 percent of the total capacity. This allows taxi drivers to avoid deep cycling the battery, which in turn extends the lifetime of the battery, or allows a driver to purchase a smaller battery vehicle. Lastly, if drivers charge the battery whenever they "have" to be parked in taxi stands, this will avoid any additional charging time and consequently avoid losses in the total revenue.

2.4 Energy Consumption Model

Understanding the advantages (or lack of) in moving towards the usage of EVs calls for a good parametrization of the energy consumption. This can be done with the support of simulations [25] (which contain several simplifying assumptions), or empirical data [23], resulting in simplified energy consumption models.

Despite part of studies exploring real trajectory data, many of them neglect the adoption of an energy model in determining the energy consumption of EVs, opting instead for assuming an average consumption value [23, 25, 26, 28].

In the last decades, several models to estimate the energy consumption of pure EVs have been developed. Those models can be divided into two categories [19, 20, 36–38], namely:

- **Forward** models are fed by driver inputs (e.g., brake or accelerator pedal position) to estimate the torque required to match the desired speed of the driving cycle. Although accurate, the forward models require long execution times.
- **Backward** models use as input the drive cycle $[v = f(t)]$ and the characteristics of the vehicle (e.g., mass) to calculate the energy at the wheels. Working “backward” the energy produced by the power unit is subsequently calculated. Backward models present trustworthy estimates and faster execution times when compared to forward models.

Backward models also consider *steady-state* (constant environment through time) or *quasi-steady* (environment changing slowly enough to be considered constant), which can be a limitation given the dynamics of the application. However, these models represent an appealing trade-off between computational time and accuracy [39].

In conclusion, this work will focus on the combination of real-world taxi operation data with a precise EV consumption model. This will give us the opportunity to study more precisely the suitability of EVs and normal Alternating Current (AC) charging for everyday taxi operations.

Chapter 3

Porto's Taxi Mobility Data

After an extensive review of the State of the Art, in this section we will review our Taxi Mobility Data, collected in the city of Porto. This chapter will focus on how the data was acquired, an explication of how the data is structured for better understanding, and finally the use case and dataset characterization.

3.1 Data Acquisition

Taxi mobility data of is permanently being collected by a fleet of 407 taxis in the city of Porto, Portugal, for the operation of the taxi-link dispatch system. Note that in October 2021, only 7 vehicles of this fleet were Electric Vehicles (EVs), corresponding to 1.5% (6 Nissan Leafs, and 1 Kia e-Niro), as shown in Figure 3.1.

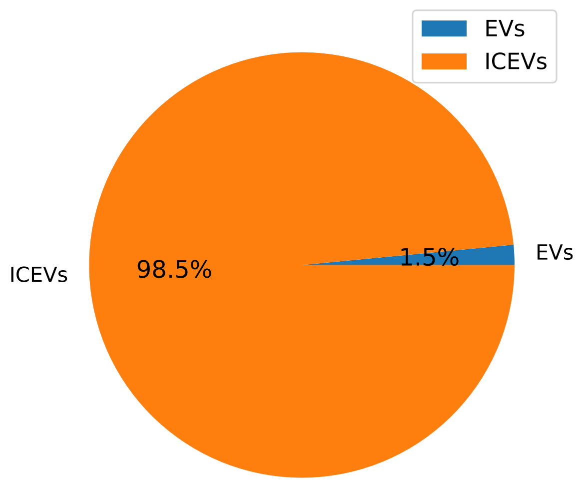


Figure 3.1: Pie chart of the EVs share of the Porto's taxi fleet, October 2021.

All the vehicles of the fleet are equipped with on-board devices (e.g. smartphones, tablets) that permanently collect taxi state information (e.g. *Busy*), positioning and timing data. The data is collected with a frequency of 1 Hz resorting to the Global Positioning System (GPS), which is then periodically transferred to a central server for further processing and storage. Specifically, each trip record has the following attributes:

- taxi identifier;
- taxi state;
- trip start timestamp;
- trip end timestamp;
- taxi stand identifier (only for *Stand* state);
- position that consists of a polyline that contains (latitude, longitude) points of the vehicle trajectory.

Contrary to the work done by Hu et al. [23], where the data set used only provided data of occupied trips (e.g. *busy* state), our data set records trips from all the states. This taxi state is collected from the taximeter or is an input from the driver. The taxi can be in five main states:

- *Busy* (i.e. performing a service);
- *Free* (i.e. roaming for new service);
- *Pause* (i.e. driver is off-duty);
- *Pickup* (e.g. moving towards the assigned customer);
- *Stand* (i.e. vehicle stopped at taxi stand).

For this study, we resort to data collected by the fleet of the largest taxi company in the city (18 vehicles) with only combustion engine vehicles. This company was chosen because all vehicles operate 24h per day (with 2 to 3 different taxi drivers) and all are explored intensively, with service arising mainly at taxi stands or from requests of private clients or assigned by the main taxi central in the city. The collected taxi trajectory data is then used to estimate the energy consumption of vehicles (Section 4.2).

To better understand the taxi business of the fleet used for this study, the next sections provides a set of descriptive statistics.

3.2 Use Case Characterization

In this study, we resort to data collected during the full month of October 2021, in a medium size European city in northern Portugal. Porto has approximately 232 000 inhabitants within a territory of 41.4 km^2 lying in the center of a metropolitan area with 1.737 million inhabitants. Currently, there are 97 public charging stations in the city, totaling 199 plugs for EV charging [40]. However, there is not a single charging station in any of the taxi stands around the city.

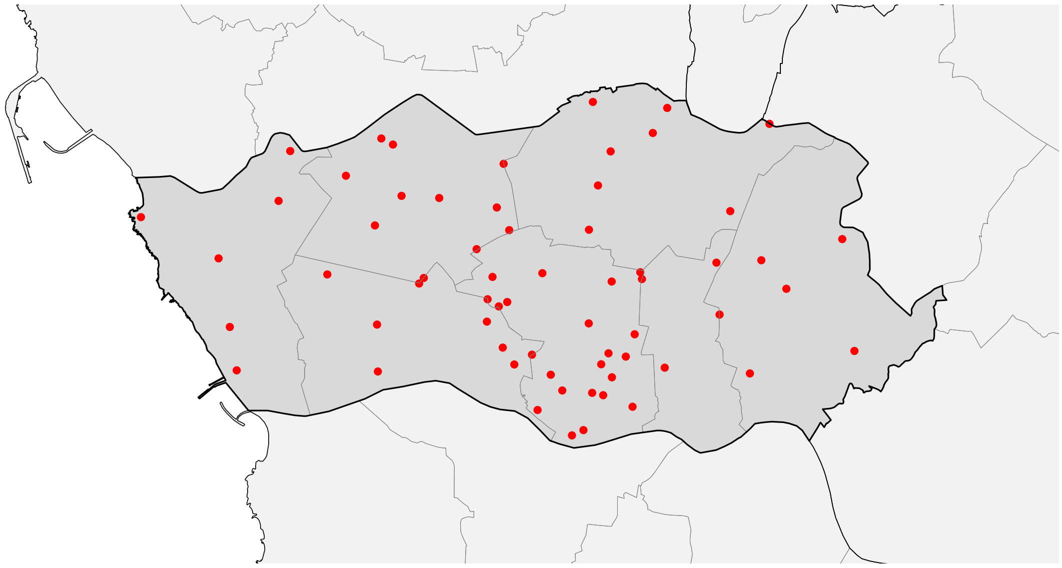


Figure 3.2: Map of the 63 Taxi Stands of the city of Porto.

There are a total of 63 taxi stands spread throughout the city, as depicted by Figure 3.2, but these are mainly concentrated in the city center, commercial, and business districts. The capacity of taxi stands varies widely with the smallest and the largest holding 2 and 31 vehicles, respectively, with an average value of 8.5 vehicles per stand.

Three main operational strategies are followed to pick-up passengers:

- Waiting for passengers in a taxi stand;
- Responding to requests dispatched by a dispatch central or private customers;
- Hailing by a passenger while roaming.

Due to legal requirements, and as the demand for taxi services is generally lower than the supply, drivers mostly park (for significant amounts of time during some periods of the day) in the available taxi stands.

3.3 Dataset Characterization

In the following section, we characterize the taxi service in the city of Porto for better understanding the business operation in the period under analysis, specially considering the operation of EVs.

The dataset consists of a total of 44838 trip records for different taxi states, corresponding to 81430 km travelled. From these records, there were 5222 services for the 18 taxis, which in turn represents 32727 km travelled on the *busy* state. These values show an average of 290 services per taxi during the month of October, 2021.

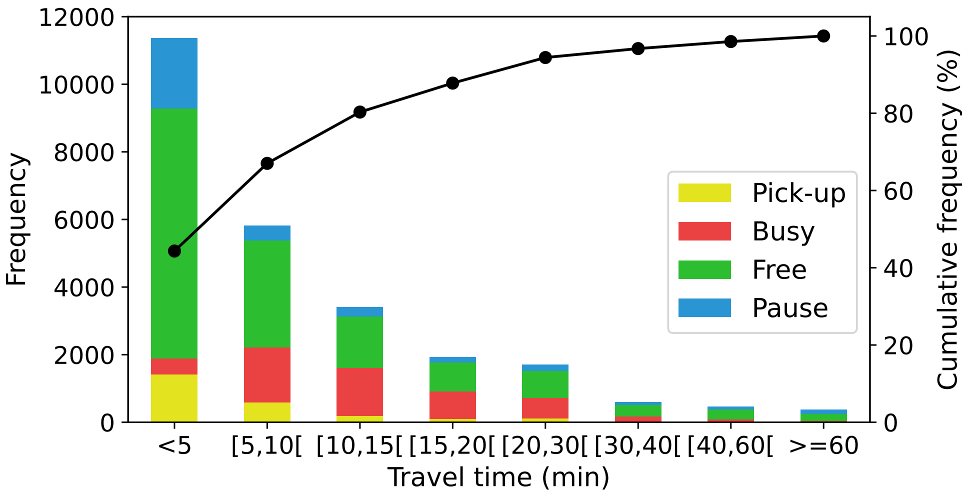


Figure 3.3: Frequency distribution of travel time metric.

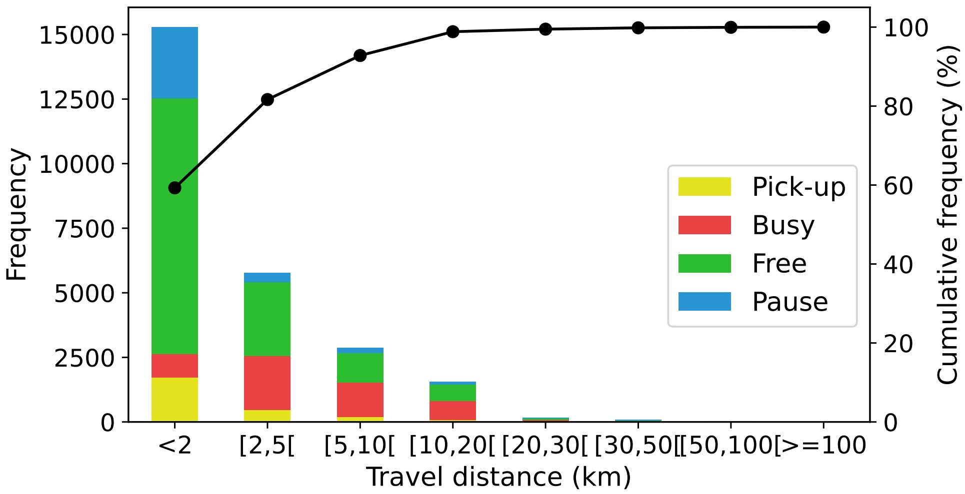


Figure 3.4: Frequency distribution of travel distance metric.

In an attempt to mitigate range anxiety affecting EVs drivers, two of the most important parameters to analyze for electric mobility are *travel time* (i.e. time spent in *Busy*, *Pickup*, *Pause* or *Free* state) and the *travel distance*, which are presented in Figure 3.3 and Figure 3.4, respectively.

The average travel time in the *Busy*, *Pickup*, and *Free* states are approximately 14 min, 7 min and 10 min, respectively. The travel time with onboard passengers is smaller than 15 min for 67.4% of the trips. The small travel times can be explained as vehicles mostly respond to requests arising within the city boundaries.

During this month, each taxi travelled on average a total of 4516 km of which 52.57% were travelled without passengers. The average travel distance in the *Busy*, *Pickup*, and *Free* states are approximately 1818 km, 324 km and 1993 km, respectively.The results show that the travel distance with *Busy*, *Pickup*, and *Free* did not exceed 10 km for 83.6%, 96.3% and 94.8% of the trips, respectively.

Vehicles are parked at taxi stands an average of 3.5 hours per day and the average waiting time at taxi stands was almost 20 min, which shows that the taxi drivers of this company are idle for large periods of time allowing vehicle charging during these periods.

To summarize, we observe that i) travel time and distance are relatively short, ii) the likelihood of performing long services is very small and iii) taxis are parked for long periods at taxi stands. These factors combined can potentially make the operation of EVs in this medium-sized European city very appealing.

Chapter 4

Methodology

In the last Chapter, we focused on the collected data, how it was structured, and performed a brief analysis. Therefore, in this Chapter, we will focus on the Methodology of the project. We will explain in detail the model used to compute energy consumed by a vehicle, how we can apply the data collected in Chapter 3 to the model, and the validation of the model.

4.1 Goals and Setting

This work assesses the feasibility of resorting to electric mobility for operating taxi fleets. Specifically, we aim at assessing the impact that switching from Internal Combustion Engine (ICE) vehicles to Electric Vehicles (EVs) might have on the daily operation of taxis and their profitability. Furthermore, this work also has as objective to evaluate the suitability of using Alternating Current (AC) equipment with low or normal charging speeds (up to 22 kWh) for charging taxis while they are parked in a stand. Note that no charging losses due to the battery or charger inefficiencies are considered in this study. High-speed/rapid Direct Current (DC) chargers are not considered, as previous studies [8, 28, 41] have shown that high currents and temperatures have detrimental effects on the longevity of batteries. Further, the required investments for installing and maintaining fast DC charging are considerably higher, with unfavorable Return of Investment (RoI) given that taxi stands cannot be accessed by other vehicles.

For avoiding or minimizing any inconvenience and revenue loss on the daily taxi operation and business' results, we assume that time periods between services (during which the driver is waiting for the next passenger at the stand) can be harnessed for vehicle charging. Currently, most common charging solutions for EVs require the driver to plug the vehicle to a charger port by means of an electric cable that is unplugged at the end of the process. For simplicity, in this research study, the time for (un)plugging the vehicle is not accounted for, being considered that the battery of the taxi is charged during the entire period the taxi is parked in the stand, i.e., between vehicle arrival and departure. This assumption is in line with the future trend of Wireless Power Transfer (WPT) of EVs (Section 2.3) that is expected to become commercially available in the next decades. Another relevant adopted assumption is the consideration that multiple taxis can be charging simultaneously at the same stand. Our approach also considers a full availability of charging stations in all stands of the network, i.e. every electric taxi present in the stand be charging if needed.

To accomplish the aforementioned goals, we resort to the vehicle trajectory information, which has been analysed in Chapter 3, and collected by the taxi-link dispatching system. With the trajectory data, it is possible to obtain each trip of each vehicle's velocity profiles and, consequently every information needed; After some tests, and taking into account sensor inaccuracies (e.g. Global Positioning System (GPS) positioning errors) we applied a Savitzky-Golay filter [42] (low-pass) to remove instantaneous signal fluctuations contained in the velocity time series $v(t)$ prior to determining the acceleration profile $a(t)$. Acceleration and velocity profiles are then used to estimate the instantaneous energy consumption of EVs using a backward energy consumption model, which is detailed in the next section.

4.2 Electric Vehicle Consumption Model

After an extensive study of Energy Consumption Models (Section 2.4), the quasi-steady backward approach by Fiori et al. [37] was adopted for this work.

The selected model is able to efficiently predict the energy consumed by an EV using only data retrieved by a smartphone. The model inputs are the instantaneous acceleration and speed profiles, and the EV characteristics (e.g. frontal area mass) as given in detail by Table 4.1. The output of the model are:

- Energy consumption *(kWh/km)*;
- Instantaneous power *(kW)*;
- State-of-Charge (SoC) of the battery *(%)*.

The power at the wheels can be calculated using Eq. 4.1.

$$P_{Wheels}(t) = \Big(ma(t) + mg * cos(\theta) * \frac{C_r}{1000}(c_1 v(t) + c_2) + \frac{1}{2}\rho_{Air} A_f C_D v^2(t) + mg * sin(\theta)\Big) * v(t) \tag{4.1}$$

The consumed power is then calculated using P_{Wheels}:

$$P_{Consumed}(t) = \frac{P_{Wheels}(t)}{\eta_d * \eta_{em} * \eta_b} \tag{4.2}$$

where η_d, η_{em} and η_b represent the drive line efficiency, the electric motor efficiency and also the battery efficiency, respectively. These parameters have been set based on two previous studies [43, 44].

The SoC is determined resorting to Eq. 4.3. To represent the worst-case scenario, and given the different efficiencies of regenerative braking systems, this component is ignored in the model.

$$SoC_{Final}(t) = SoC_0 - \sum_{i=1}^{N} \Delta SoC_{(i)}(t) \tag{4.3}$$

$$\Delta SoC_{(i)}(t) = SoC_{(i-1)}(t) - \frac{P_{Consumed\,(i)}(t)}{3600 * C_{bat}} \tag{4.4}$$

4.2.1 Model Parameters

The settings of the main model parameters are given in Table 4.1. The EV considered in this study was the Kia e-Niro equipped with a 64 kWh battery, whose advertised average consumption is 0.153 kWh/km. We consider this vehicle and this battery size adequate for taxi operation given its cost, but also considering the future prospects for the evolution of battery technology. Moreover, this vehicle type is already used by several taxi operators, including one vehicle in Porto's fleet.

Table 4.1: EV Model parameters used in the Consumption Model

Variable	**Value**	Unit	**Description**
$v(t)$		m/s	Instantaneous speed
$a(t)$		m/s^2	Acceleration
m	1521	kg	Mass of the vehicle
g	9.8066	m/s^2	Gravitational acceleration
θ	0	$^\circ$	Road grade
C_r	1.75		Rolling coefficient
c_1	0.0328		Rolling resistance coefficient
c_2	4.575		Rolling resistance coefficient
ρ_{Air}	1.2256	kg/m^3	Air mass density
A_f	2.3316	m^2	Frontal area of the vehicle
C_D	0.428		Aerodynamic drag coefficient
η_d	92	%	Drive line efficiency [43]
η_{em}	91	%	Electric motor efficiency [44]
η_b	90	%	Battery efficiency [44]

4.2.2 Illustrative Example

Figure 4.1 presents an illustrative example of a 400 second trip where the energy consumption model is applied. The top figure shows the speed profile obtained using GPS data (in blue), that is clearly noisy, and the signal resulting from the smoothing (in red), after filtering. As expected, the middle plot shows that the power is clearly correlated with the speed profile. The lower plot shows the reduction of the SoC due to energy consumption.

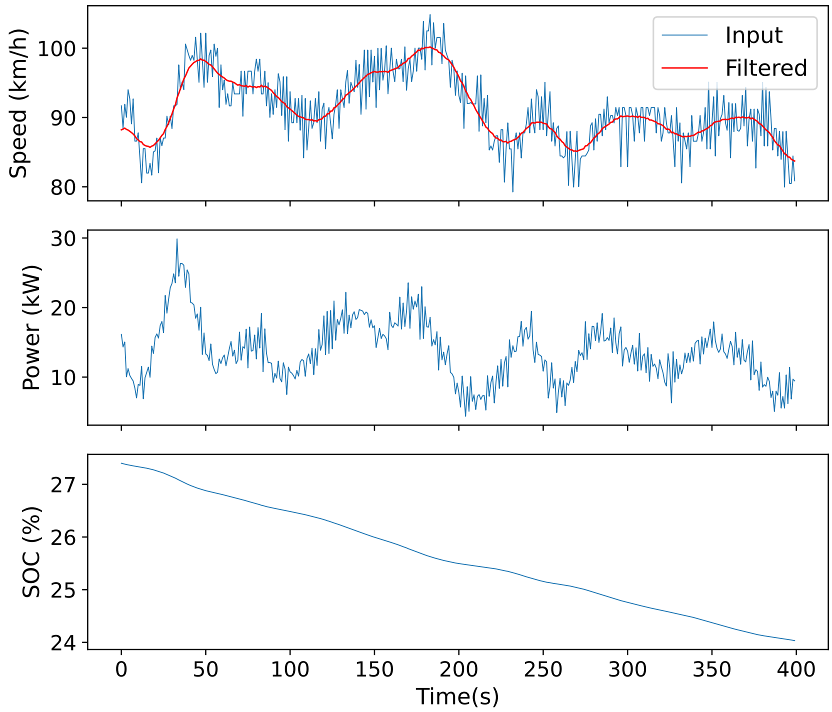
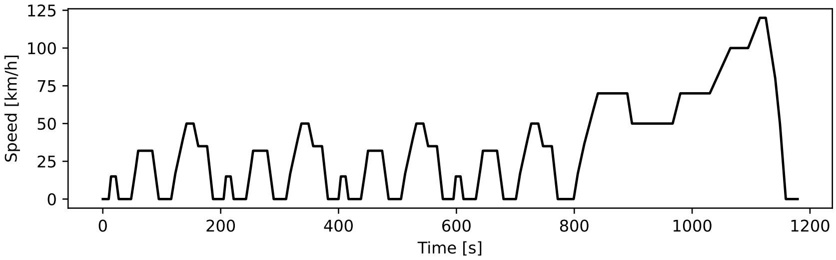


Figure 4.1: Illustrative example of the energy consumption model. The noisy vehicle speed obtained from GPS data is first filtered to remove fast signal fluctuations. This smoothened speed curve is used to calculate the consumed power (middle plot) for subsequently updating the vehicle SoC.

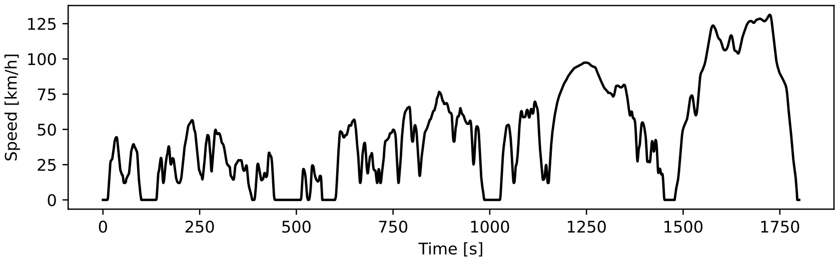
4.3 Model Validation

4.3.1 Theoretical Analysis

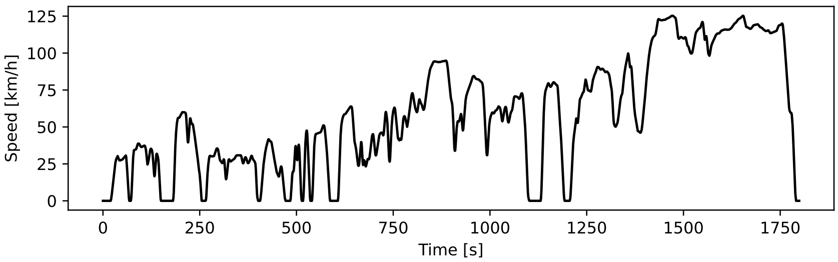
In order to get an accurate validation, we employ three standard driving cycles, the New European Driving Cycle (NEDC), the World-wide Harmonized Light-duty Test Cycle (WLTC) and the Worldwide Motorcycle Emission Test cycle (WMTC), applying each one to the model used in this thesis. Each profile can be found in Figure 4.2. Our results were compared against reference values from the Joint Research Center (JRC) of the European Commission [45]. The results, as presented in Table 4.2, indicate that the implemented model accurately estimates the energy consumption with deviations varying between 1.7 and 8.4%, which are considered acceptable. Increasing the model complexity (e.g. considering additional factors and interactions) should help decrease the prediction error.



(a) NEDC



(b) WLTC



(c) WMTC

Figure 4.2: Normalized driving cycles to assess electric energy consumption

Table 4.2: Model validation using standardized driving cycles

Driving Cycle	**JRC [Wh/km]**	**Model [Wh/km]**	**Error (%)**
NEDC	156.9	154.2	1.7
WLTC	178.4	182.2	2.1
WMTC	182.9	198.3	8.4

4.3.2 Empirical Validation

The implementation of the model proposed in [37] was also tested with data collected from a series of test drives with an electric Citroen E-C4. The tests consisted in 2 round trips Porto - Fafe, which represents approximately 68 km per trip, including urban drive and highway drive. After measuring the distance of each trip and the initial and final SoC measured directly in the vehicles dashboard, we compared the results with the output of the model used in this study. The results can be found in Table 4.3:

Table 4.3: Summary of the empirical validation of the model.

Trip	**Distance** [km]	Measured SoC (%)	Simulated SoC (%)	**Error** (%)
1	68.6	30%	24%	20.0%
2	68.3	23%	24%	4.3%
3	67.0	25%	20%	20.0%
4	68.2	21%	24%	14.3%

The results indicate that the implemented model estimates the energy consumption with an average error of 14.65%. To note that trips 1 and 3 were performed with the *air conditioner* turned on, while in trips 2 and 4 the *air conditioner* was turned off. This behaviour can explain the larger deviation on these two trips.

4.4 Virtual Dashboard

One of the main objectives of this thesis is to create a tool to be installed in the taxi-link driver's APP, capable of simulating the consumption of an EV (Section 1.1). Apart from all the Ecological problems associated with this work (Chapter 1), the motivation also emerges from the fact that taxis will have a 10 year age limit in Portugal, starting from 2024 [46]. This law is a game changer, and will impact hundreds of taxis, taxi drivers and taxi fleets.

In Figure 4.3 we have depicted the number of cars, in the taxi-link's fleet, per year of its first licence plate, together with the years that the Nissan Leaf - the first EV to be mass produced for commercialization - was launched, the first electric taxi in Portugal [47], and the first electric taxi in taxi-link's fleet. If we take a closer analysis of this Figure, together with the aforementioned law, we reach the conclusion that almost 29% of the taxi-link's fleet (approximately 900 vehicles) will need replacement by the end of 2023. As a result, now it's the perfect time to convince taxi drivers of the benefits of using an EV, and the Virtual Dashboard described in this section will help drivers to reach that conclusion.

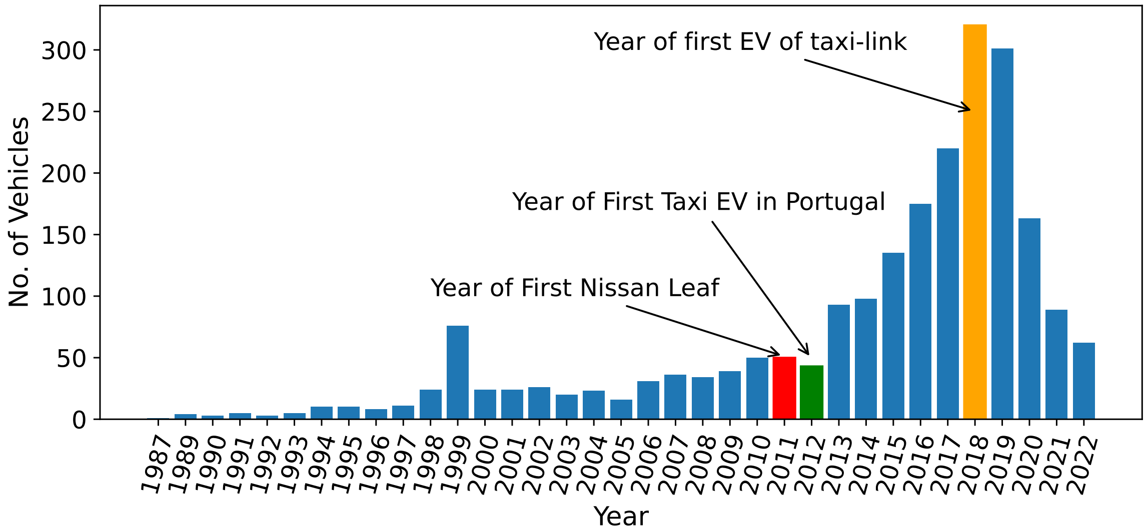


Figure 4.3: Frequency distribution of vehicles by year of first license plate.

4.4.1 Why Kotlin

"A modern programming language that makes developers happier" [48].

Kotlin is a programming language that was created by JetBrains[1] in 2011, with the promise to solve several known limitations of the Java language. Some of the key features of Kotlin are *Conciseness* and *Readability*, with special focus on object and multiple attributes class declarations. Since the beginning, its purpose was to create a language that could be an alternative to Java, while being fully inter-operable - it's possible to call Java code from Kotlin code, and vice-versa - with it, given that both languages run on the same Java Virtual Machine (JVM). With the easiness of adapting Java projects to Kotlin, in May of 2017 *Google* announced the official support for Kotlin on the Android platform, becoming one of the officially supported languages for Android Apps development. This announcement has led to major growth of the language, and thus the research increased around it.

Ardito and Coppola (2020) [49] performed a study to empirically assess some typical promises of Kotlin, and found that it does not affect the maintainability of the applications in Java, in addition to Kotlin leading to more compact code. As a result, the study concludes that the language makes common Java annoyances less frequent, which in turns leads to safer development. On the same note, Oliveira et al. (2020) [50] investigated the recent adoption of Kotlin in the Android Platform from the developers perspective, analysing kotlin related questions on Stack Overflow. The study concluded that developers found the language easy to understand and to adopt on new and existent projects, and that such adoption can bring multiple advantages. This is in line with the work developed by Mateus and Martinez (2019) [51], which studied the adoption of Kotlin in the development of Android applications. The results show that in 2.167 open-source applications, between the years of 2017 and 2018, 11.26% had used kotlin code in

[1] https://www.jetbrains.com

their projects, since Java and Kotlin are interoperable. Of those applications, 63.9% increases the amount of kotlin code with the evolution of the application, and at the same time, the amount of Java code remains the same, or even decreases.

4.4.2 Kotlin versus Java

Kotlin promised to address several known issues and annoyances of Java, but it is not a perfect language, and still is missing some aspects that java covers. In this section, we make a brief comparison between both languages [52]:

- **What Java has that Kotlin does not**:
  - Checked exceptions;
  - Primitive types that are not classes;
  - Static members are replaced with companion objects, top-level functions, extension functions, or @JvmStatic;
  - Ternary-operator;
  - etc...
- **Issues in Java that Kotlin addresses**:
  - Null references;
  - No raw types;
  - Invariant arrays in kotlin;
  - etc...
- **What Kotlin has that Java does not**:
  - Lambda expressions;
  - Extension functions;
  - Null safety;
  - Smart casts;
  - String templates;
  - Singletons;
  - Operator overloading;
  - Data classes;
  - etc...

In Listings 4.1-4.3, we can see some differences between the two languages.

```
//KOTLIN
var bob : Person? = null;
//...
return bob?.department?.name; // safe call

//JAVA
Person bob = null;
//...
if(bob!=null)
    if(bob.department!=null)
        return bob.department.name;
return null;
```

Listing 4.1: Nullability Examples: kotlin vs Java [49]

```
//KOTLIN
val p: Person? = x as? Person

//JAVA
Person p = x instanceof Person?(Person)x:null;
```

Listing 4.2: Mandatory Casts Examples: kotlin vs Java [49]

```
//KOTLIN
data class User(val name: String, val age: Int)

//JAVA
class User{
    private String name;
    private int age;

    public User(String name, int age){
        this.name=name;
        this.age=age;
    }

    public String getName(){
        return name;
    }
    public String getAge(){
        return age;
    }
    public String toString(){
        return "User(name="+name+",age="+age+")");
    }
    public boolean equals(Person){...}
    public int hashCode(){...}
}
```

Listing 4.3: Data Class Examples: kotlin vs Java [49]

4.4.3 *taxi-link* App

After reviewing the language used to create the Virtual Dashboard, we will now take a closer look at the *taxi-link* driver's application. Every taxi driver using *taxi-link*'s services must have this application installed to be able to get services, to print invoices for the trips, set breaks during service, among others.

In Figure 4.4, we can see the initial screen a taxi driver is prompted with after logging in. In this screen the drive gets information of the actual zone, in order to get services from the Passenger's App, as well as a stand queue, enrolls drivers atomatically through GPS. A taxi driver can also get information on other stands (Figure 4.5), namely the number of taxis stationed at the specific stand.

Figure 4.4: *taxi-link* App - Initial Screen

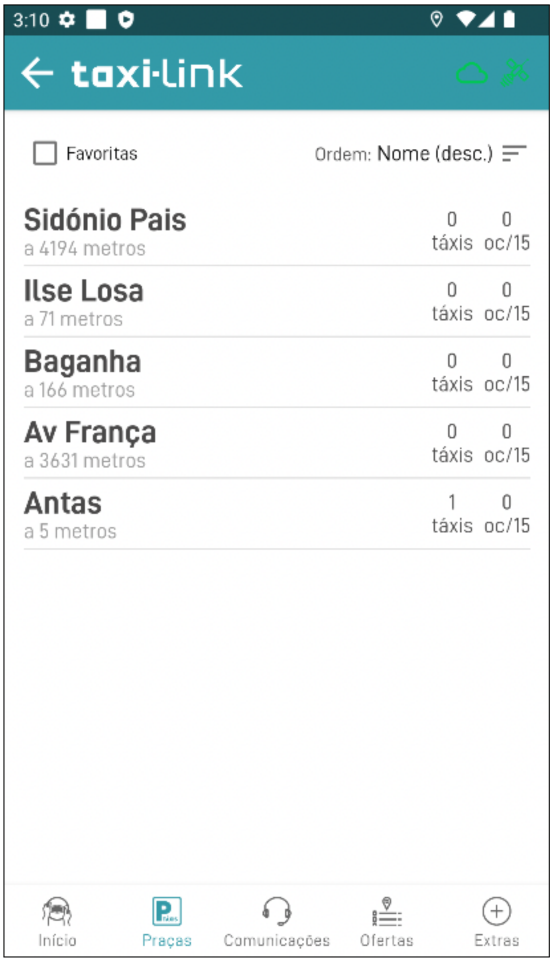


Figure 4.5: *taxi-link* App - Stands List

When a driver gets a service, through the app or picking up a passenger, the system changes to the state *busy* (Figure 4.6). Independently from the state of the taxi (e.g. *busy*, *pause*, *free*), when the GPS detects movement, the Virtual Dashboard is activated (Figure 4.7). Note that it works in the background as well, so the taxi driver can use the app freely, and just check the status of the Dashboard periodically. As a normal dashboard, the driver can see the instantaneous

Figure 4.6: *taxi-link* App - Busy Screen

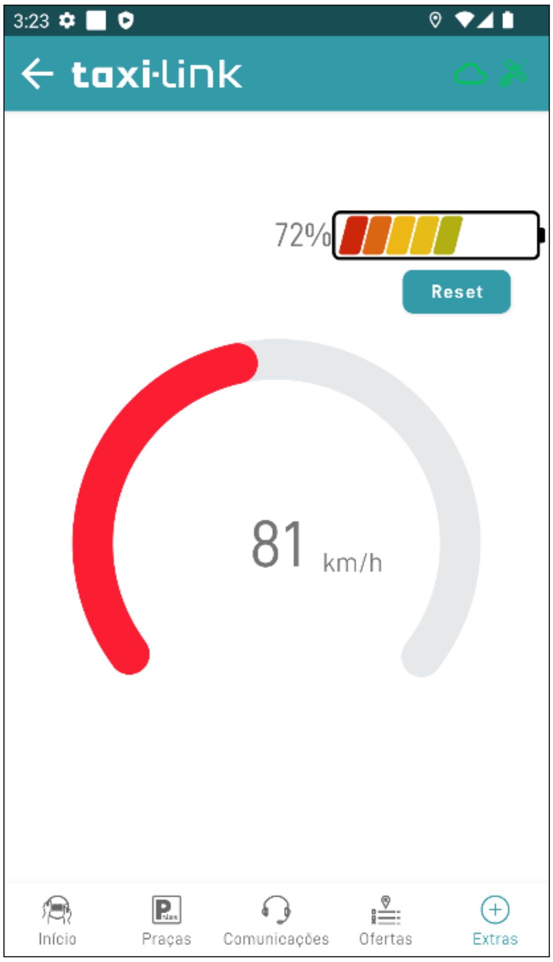


Figure 4.7: *taxi-link* App - Virtual Dashboard

velocity, and especially the percentage of battery. When the driver is at a taxi stand, the battery starts charging, at a rate of 11 kWh/h, up to a maximum of 95%. The percentage of the battery allows the drivers to see the behaviour of the capacity of the battery during each day of service, with different volume of business, and different time spent in taxi stands (charging).

Chapter 5

Results

In this Section, we analyze and discuss the feasibility of transitioning towards electric taxi fleets resorting to large-scale empirical taxi operation data.

5.1 Autonomy Analysis

The energy consumption model described in Section 4.2 was applied to the operational data of the 18 taxis, returning an estimate of the State-of-Charge (SoC) level over time. As an example, Figure 5.1 shows the SoC level variation of a selected taxi over a given day. The blue line represents the SoC assuming that the vehicle is charging while parking at a stand (in green), while the red line indicates the SoC level variation if the vehicle is never charged during operation. This example highlights that periodic charging is required to satisfy the requirements of a working day, otherwise, the autonomy would be depleted after only 15 h.

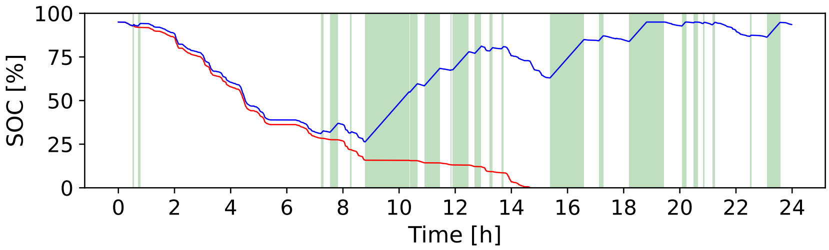


Figure 5.1: State of Charge (SoC) for a given taxi and day. At the start of the day the SoC is 95%. The blue line represents the SoC for a vehicle charged during stops at taxi stands (green areas). The red line depicts the battery depletion curve if the vehicle is never charged during operation.

Figure 5.2 graphically represents the SoC level of each taxi at the end of a given day. In the simulation, a SoC level of 95% was considered for all taxis at the beginning of the first day (Oct. 1st). For the majority of the vehicles, the SoC level at the end of the day remains close

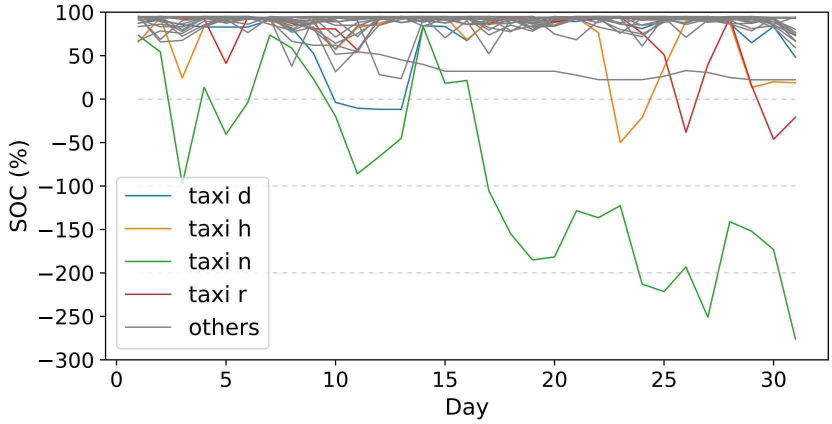


Figure 5.2: Virtual SoC for each individual taxi at the end of the day.

to the maximum level of 95%. The SoC level decreased to negative values only for 4 taxis (*d, h, n, r*), representing cases where the minimum conditions required for continuous operation are not met considering the current demand. Figures 5.3 and 5.4 analyzes the travel distance of each service and the total number of trips executed by each taxi. We observe that the tails of the inverse Cumulative Distribution Function (iCDF) of the travel distance (Figure 5.3) are considerably longer for taxis h, n and r. Furthermore, Figure 5.4 shows that these taxis perform a combination of services with larger travel distances [as measured by the 99^{th} quantile of the individual trip travel distance] (taxis h and r) and/or high number of performed services (taxi n), which increases the autonomy requirements.

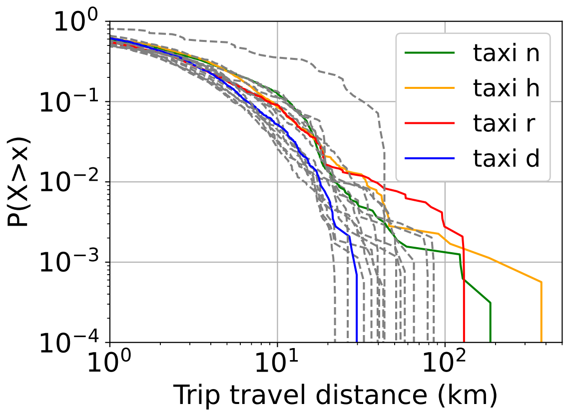


Figure 5.3: Inverse Cumulative Distribution Function

Taxi n is clearly the one whose daily operation is least conductive to switching to electric mobility, attaining negative SoC values most of the days. The total travel distance of taxi n is 12912 km, which is almost three times higher than the average travel distance (4516 km). On the other hand, its average waiting time at taxi stands was just slight above 15 min, below the average value of all taxis (19 min 29 s). These two indicators help to understand the SoC values registered and lead us to believe that, in order to satisfy the current operating routines of this taxi, it would be necessary to adopt an Electric Vehicle (EV) with a greater autonomy, to use

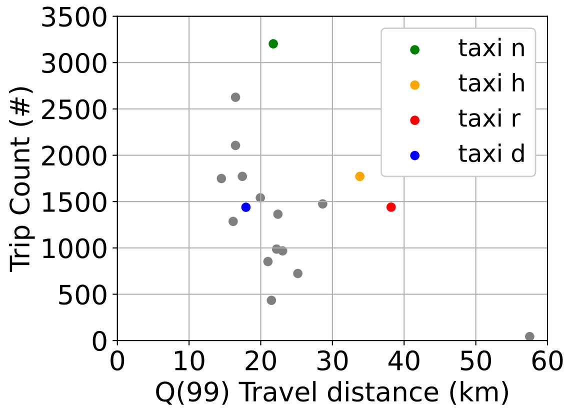


Figure 5.4: Distance vs trip count

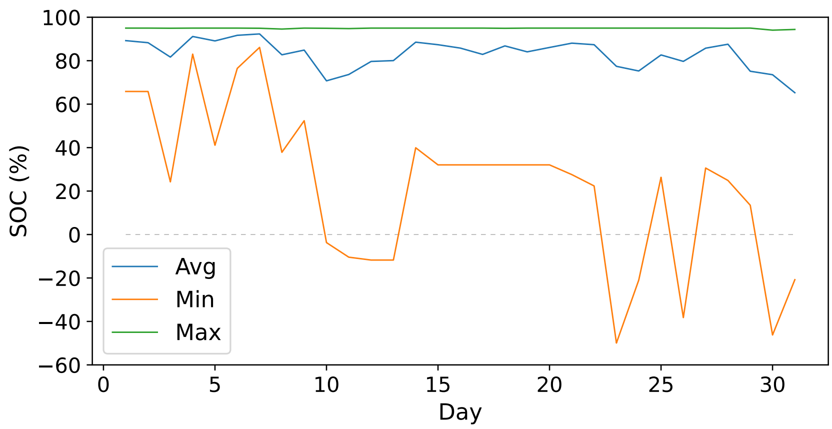


Figure 5.5: Minimum, average and the maximum of SoC for all taxis (excluding taxi n)

faster charging solutions, use hybrid operation models combining EVs and Internal Combustion Engine (ICE) vehicles, among others.

Due to the disparity of values recorded by taxi n when compared to the others, the information from that taxi was disregarded from a more general analysis of the SoC of the vehicles. Fig. 5.5 depicts the minimum, average and the maximum values of the SoC of all the remaining taxis at the end of each day. The results indicate that charging while parked (which is idle time) allows most of the taxis to guarantee enough autonomy to complete their operation. Therefore, electric mobility of taxis is a valid alternative, allowing a considerable reduction in operating costs without loss of profitability.

5.2 Cost Analysis

From the 407 vehicles that compose the taxi fleet operating in Porto, only 8 were pure EVs (corresponding to 1.97%) at the end of October 2021. At the end of 2020, this value was even lower at 1.50% of the EVs. This very low proportion of electric taxis in Porto is clearly far from

Table 5.1: Cost estimate for the average travel distance (4516 km) for the month of Oct. 2021 and two energy sources

Energy Source	**Unit Price**	**Consumption**	**Total Cost (€)**
Diesel	1.604 €/L	7 L/100 km	507
Electricity	0.145 €/kWh	15.3kWh/100 km	100
Public Charger	0.400 €/kWh		276

the values recorded at the national level, where a more significant tendency towards the adoption of EV can be found. Indeed, in 2020, EVs represented a share of 5% of the light passenger vehicles sold in Portugal, while between January and October 2021 the EVs market share increased up to 8% [1]. The EV rate adoption gap (taxi fleet vs national market) can be traced to several different reasons. The high acquisition cost of EVs and the nonexistence of charging stations for exclusive use of taxis are, undoubtedly, two key factors delaying the electrification of the taxi fleet. Electric taxis currently operating are charged at the drivers' home or using a charger from the public network, whose availability varies considerable from day to day and location to location. When charging at home, drivers only pay for electricity but this period corresponds to off-duty periods that are non-existing to taxis that are explored fully, 24h a day, such as the taxis used on this study. Using chargers from the public network (mostly rapid charging stations) leads to higher charging costs, since in addition to the cost of electricity, additional service fees and taxes are charged by the operator.

Table 5.1 presents the average energy rates (diesel and electricity) in Oct. 2021, as well as a reference value for the usage of a public charging station. We also provide an estimate of the total cost for completing the average travel distance of 4516 km. This cost estimate was obtained considering an average consumption of 7 L/100 km in the case of combustion engine vehicle and of 15.3 kWh/100 km in case of EV. For public chargers usage, an average value of 0.40 €/kWh was assumed. These results show that, when using a home charger or low-cost charging points dedicated for taxis, the option for an EV is the most economically advantageous when compared to a combustion engine vehicle or even to the same EV being charged at public charging stations.

[1] https://www.uve.pt/pt

Chapter 6

Conclusions

Electric Vehicles (EVs) are here to stay, not only due to all the environmental benefits, but also to the Total Cost of Ownership of having an EV opposed to having an Internal Combustion Engine (ICE) vehicle. This reasons lead to the necessity of even more research of the field, and consequently more advancement in the industry of EVs. Therefore, the industry of professional fleets (namely taxi drivers) will surely take benefit of this advancements.

In this work we studied the feasibility of using electric propulsion in combination with Alternating Current (AC) charging for taxi operation in a mid-sized European city. A data-driven evaluation has shown that conventional AC chargers installed at taxi stands would provide sufficient autonomy even for taxis operating uninterruptedly, while cutting the costs related to powering the vehicle by more than five times, compared to the cost of fossil fuel. These significant savings would support financing the replacement of ICE vehicles by new EVs just based on the operational saving related to energy costs. The assessment indicates that electric mobility is suitable for the vast majority of taxis, which clearly exhibit moderate requirements in terms of energy consumption given the current service demand.

Clearly, conveying the type of results reported in this paper to taxi drivers is a fundamental step towards the acceleration of the shift from ICE vehicles to EVs. For that reason, we created the Virtual Dashboard, to be displayed in every taxi-driver's application. We are convinced that graphically conveying through a virtual automotive dashboard the behaviour in terms of autonomy, charging times and energy cost savings of a typical EV will clearly show to taxi drivers the results herein reported.

6.1 Future Work

We intend to continue studying the transition of taxi fleets towards electric mobility. The current work relies on a number of simplifying assumptions that will be relaxed in future works. The approach followed in this study contemplates the installation of charging stations in all stands. However, in practice, this approach may not be optimal due to the unnecessary excess capacity of the charging network and the corresponding higher operational costs, despite the availability of public subsidies to fund the installation of such network. We intend to study the optimal number and the location of the charging stations to be installed at the taxi stands. Furthermore, we intend to keep evolving the Virtual Dashboard, to include more metrics to help taxi drivers better perceive the reality of owning an electric taxi.

Bibliography

[1] European Commission. Delivering the european green deal. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/delivering-european-green-deal. Accessed: 2021-12-13.

[2] Paul Wolfram and Nic Lutsey. Electric vehicles: Literature review of technology costs and carbon emissions. *The International Council on Clean Transportation: Washington, DC, USA*, pages 1–23, 2016. doi:10.13140/RG.2.1.2045.3364.

[3] Peter Weldon, Patrick Morrissey, and Margaret O'Mahony. Long-term cost of ownership comparative analysis between electric vehicles and internal combustion engine vehicles. *Sustainable Cities and Society*, 39:578–591, 2018. ISSN: 2210-6707. doi:https://doi.org/10.1016/j.scs.2018.02.024.

[4] Jens Hagman, Sofia Ritzén, Jenny Janhager Stier, and Yusak Susilo. Total cost of ownership and its potential implications for battery electric vehicle diffusion. *Research in Transportation Business Management*, 18:11–17, 2016. ISSN: 2210-5395. Innovations in Technologies for Sustainable Transport. doi:https://doi.org/10.1016/j.rtbm.2016.01.003.

[5] BloombergNEF. Bloombergnef's annual battery price survey. https://about.bnef.com/blog/battery-pack-prices-fall-to-an-average-of-132-kwh-but-rising-commodity-prices-start-to-bite/. Accessed: 2022-07-08.

[6] Associação de Utilizadores de Veículos Elétricos . Vandas veículos elétricos dezembro 2021 portugal. https://www.uve.pt/page/vendas-ve-12-2021/. Accessed: 2022-07-08.

[7] M.O. Metais, O. Jouini, Y. Perez, J. Berrada, and E. Suomalainen. Too much or not enough? planning electric vehicle charging infrastructure: A review of modeling options. *Renewable and Sustainable Energy Reviews*, 153:111719, 2022. ISSN: 1364-0321. doi:https://doi.org/10.1016/j.rser.2021.111719.

[8] Johannes Asamer, Martin Reinthaler, Mario Ruthmair, Markus Straub, and Jakob Puchinger. Optimizing charging station locations for urban taxi providers. *Transportation Research Part A: Policy and Practice*, 85:233–246, 2016. ISSN: 0965-8564. doi:https://doi.org/10.1016/j.tra.2016.01.014.

[9] João Neves, Ana Loureiro, Pedro M. d'Orey, Vera Miguéis, Álvaro Costa, and Michel Ferreira. Empirical evaluation of the performance of electric vehicles for taxi operation. In *2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring)*, pages 1–6, 2022. doi:10.1109/VTC2022-Spring54318.2022.9860830.

[10] Julio A. Sanguesa, Vicente Torres-Sanz, Piedad Garrido, Francisco J. Martinez, and Johann M. Marquez-Barja. A review on electric vehicles: Technologies and challenges. *Smart Cities*, 4(1):372–404, 2021. ISSN: 2624-6511. doi:10.3390/smartcities4010022.

[11] Murat Kucukvar, Nuri C. Onat, Adeeb A. Kutty, Galal M. Abdella, Muhammet Enis Bulak, Fajr Ansari, and Gurkan Kumbaroglu. Environmental efficiency of electric vehicles in europe under various electricity production mix scenarios. *Journal of Cleaner Production*, 335: 130291, 2022. ISSN: 0959-6526. doi:https://doi.org/10.1016/j.jclepro.2021.130291.

[12] Xiaoli Sun, Zhengguo Li, Xiaolin Wang, and Chengjiang Li. Technology development of electric vehicles: A review. *Energies*, 13(1), 2020. ISSN: 1996-1073.

[13] Jack N. Barkenbus. Prospects for electric vehicles. *Sustainability*, 12(14), 2020. ISSN: 2071-1050. doi:10.3390/su12145813.

[14] Amela Ajanovic. The future of electric vehicles: Prospects and impediments. *Wiley Interdisciplinary Reviews: Energy and Environment*, 4, 11 2015. doi:10.1002/wene.160.

[15] Ning Wang, Yafei Liu, Gangzhan Fu, and Yun Li. Cost-benefit assessment and implications for service pricing of electric taxies in china. *Energy for Sustainable Development*, 27:137–146, 08 2015. doi:10.1016/j.esd.2015.05.008.

[16] Seungjae Lee Jooyoung Kim and Kwang Sik Kim. A study on the activation plan of electric taxi in seoul. *Journal of Cleaner Production*, 146:83–93, 2017. ISSN: 0959-6526. Bridging the Gaps for Accelerating Low Carbon Actions in Asia. doi:https://doi.org/10.1016/j.jclepro.2016.06.056.

[17] Joschka Bischoff and Michal Maciejewski. Agent-based simulation of electric taxicab fleets. *Transportation Research Procedia*, 4:191–198, 2014. ISSN: 2352-1465. Sustainable Mobility in Metropolitan Regions. mobil.TUM 2014. International Scientific Conference on Mobility and Transport. Conference Proceedings. doi:https://doi.org/10.1016/j.trpro.2014.11.015.

[18] Kong Deyang, Ma Dan, and Wang Minmin. A simulation study of upgrading urban gasoline taxis to electric taxis. *Energy Procedia*, 104:390–395, 2016. ISSN: 1876-6102. Clean Energy for Clean City: CUE 2016–Applied Energy Symposium and Forum: Low-Carbon Cities and Urban Energy Systems. doi:https://doi.org/10.1016/j.egypro.2016.12.066.

[19] T Markel, A Brooker, T Hendricks, V Johnson, K Kelly, B Kramer, M O'Keefe, S Sprik, and K Wipke. Advisor: a systems analysis tool for advanced vehicle modeling. *Journal of Power Sources*, 110(2):255–266, 2002. ISSN: 0378-7753. doi:https://doi.org/10.1016/S0378-7753(02)00189-1.

[20] K.B. Wipke, M.R. Cuddy, and S.D. Burch. Advisor 2.1: a user-friendly advanced powertrain simulation using a combined backward/forward approach. *IEEE Transactions on Vehicular Technology*, 48(6):1751–1761, 1999. doi:10.1109/25.806767.

[21] Zhiyong Tian, Yi Wang, Chen Tian, Fan Zhang, Lai Tu, and Chengzhong Xu. Understanding operational and charging patterns of electric vehicle taxis using gps records. In *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, pages 2472–2479, 2014. doi:10.1109/ITSC.2014.6958086.

[22] Jens Hagman and Joram Langbroek. Conditions for electric vehicle taxi: A case study in the greater stockhol region. *International Journal of Sustainable Transportation*, 13:1–10, 07 2018. doi:10.1080/15568318.2018.1481547.

[23] Liang Hu, Jing Dong, Zhenhong Lin, and Jie Yang. Analyzing battery electric vehicle feasibility from taxi travel patterns: The case study of new york city, usa. *Transportation Research Part C: Emerging Technologies*, 87:91–104, 2018. ISSN: 0968-090X. doi:https://doi.org/10.1016/j.trc.2017.12.017.

[24] Jie Yang, Jing Dong, Zhenhong Lin, and Liang Hu. Predicting market potential and environmental benefits of deploying electric taxis in nanjing, china. *Transportation Research Part D: Transport and Environment*, 49:68–81, 2016. ISSN: 1361-9209. doi:https://doi.org/10.1016/j.trd.2016.08.037.

[25] Deepak Rajagopal, Viraj Sawant, Gordon S. Bauer, and Amol A. Phadke. Benefits of electrifying app-taxi fleet – a simulation on trip data from new delhi. *Transportation Research Part D*, 102:103113, 2022. ISSN: 1361-9209. doi:https://doi.org/10.1016/j.trd.2021.103113.

[26] Simon Arpad Funke and Tobias Burgert. Can charging infrastructure used only by electric taxis be profitable? a case study from karlsruhe, germany. *IEEE Trans. on Vehicular Technology*, 69(6):5933–5944, 2020. doi:10.1109/TVT.2020.2973597.

[27] Jesús Fraile-Ardanuy, Sandra Castano-Solis, Roberto Álvaro Hermana, Julia Merino, and Ángela Castillo. Using mobility information to perform a feasibility study and the evaluation of spatio-temporal energy demanded by an electric taxi fleet. *Energy Conversion and Management*, 157:59–70, 2018. ISSN: 0196-8904. doi:https://doi.org/10.1016/j.enconman.2017.11.070.

[28] Luca Cilio and Oytun Babacan. Allocation optimisation of rapid charging stations in large urban areas to support fully electric taxi fleets. *Applied Energy*, 295:117072, 2021. ISSN: 0306-2619. doi:https://doi.org/10.1016/j.apenergy.2021.117072.

[29] Jie Yang, Jing Dong, and Liang Hu. Design government incentive schemes for promoting electric taxis in china. *Energy Policy*, 115:1–11, 04 2018. doi:10.1016/j.enpol.2017.12.030.

[30] Muhammad Amjad, Muhammad Farooq i Azam, Qiang Ni, Mianxiong Dong, and Ejaz Ahmad Ansari. Wireless charging systems for electric vehicles. *Re-*

newable and Sustainable Energy Reviews, 167:112730, 2022. ISSN: 1364-0321. doi:https://doi.org/10.1016/j.rser.2022.112730.

[31] Aqueel Ahmad, Mohammad Saad Alam, and Rakan Chabaan. A comprehensive review of wireless charging technologies for electric vehicles. *IEEE Transactions on Transportation Electrification*, 4(1):38–63, 2018. doi:10.1109/TTE.2017.2771619.

[32] Chirag Panchal, Sascha Stegen, and Junwei Lu. Review of static and dynamic wireless electric vehicle charging system. *Engineering Science and Technology, an International Journal*, 21 (5):922–937, 2018. ISSN: 2215-0986. doi:https://doi.org/10.1016/j.jestch.2018.06.015.

[33] Grant Covic and John Boys. Modern trends in inductive power transfer for transportation applications. *Emerging and Selected Topics in Power Electronics, IEEE Journal of*, 1:28–41, 03 2013. doi:10.1109/JESTPE.2013.2264473.

[34] Young Jae Jang. Survey of the operation and system study on wireless charging electric vehicle systems. *Transportation Research Part C: Emerging Technologies*, 95:844–866, 2018. ISSN: 0968-090X. doi:https://doi.org/10.1016/j.trc.2018.04.006.

[35] Lawrence Ulrich. Curbside cab charging: Wireless power tech keeps evs on the go - [news]. *IEEE Spectrum*, 57(10):8–9, 2020. doi:10.1109/MSPEC.2020.9205536.

[36] G Mohan, F Assadian, and S Longo. Comparative analysis of forward-facing models vs backwardfacing models in powertrain component sizing. In *IET Hybrid and Electric Vehicles Conference*, pages 1–6, 2013. doi:10.1049/cp.2013.1920.

[37] Chiara Fiori, Kyoungho Ahn, and Hesham A. Rakha. Power-based electric vehicle energy consumption model: Model development and validation. *Applied Energy*, 168:257–268, 2016. ISSN: 0306-2619. doi:https://doi.org/10.1016/j.apenergy.2016.01.097.

[38] Benedikt Jäger and Markus Lienkamp. Cofat 2014 – smartphone-based energy consumption simulation for electric vehicles. 03 2014.

[39] David Wenzhong Gao, Chris Mi, and Ali Emadi. Modeling and simulation of electric and hybrid vehicles. *Proceedings of the IEEE*, 95(4):729–745, 2007. doi:10.1109/JPROC.2006.890127.

[40] Mobi.e. Encontrar posto. https://www.mobie.pt/redemobie/encontrar-posto. Accessed: 2022-08-09.

[41] Jinhao Meng, Lei Cai, Daniel-Ioan Stroe, Guangzhao Luo, Xin Sui, and Remus Teodorescu. Lithium-ion battery state-of-health estimation in electric vehicle using optimized partial charging voltage profiles. *Energy*, 185, 07 2019. doi:10.1016/j.energy.2019.07.127.

[42] Abraham Savitzky and Marcel JE Golay. Smoothing and differentiation of data by simplified least squares procedures. *Analytical chemistry*, 36(8):1627–1639, 1964. doi:https://doi.org/10.1021/ac60214a047.

[43] Hesham A. Rakha, Kyoungho Ahn, Kevin Moran, Bart Saerens, and Eric Van den Bulck. Virginia tech comprehensive power-based fuel consumption model: Model development and testing. *Transportation Research Part D*, 16(7):492–503, 2011. doi:10.1016/j.trd.2011.05.008.

[44] Carl Johan Rydh and Björn A. Sandén. Energy analysis of batteries in photovoltaic systems. part i: Performance and energy requirements. *Energy Conversion and Management*, 46(11): 1957–1979, 2005. ISSN: 0196-8904. doi:https://doi.org/10.1016/j.enconman.2004.10.003.

[45] Michele De Gennaro, Elena Paffumi, Giorgio Martini, Urbano Manfredi, Stefano Vianelli, Fernando Ortenzi, and Antonino Genovese. Experimental test campaign on a battery electric vehicle: laboratory test results (part 1). *SAE International Journal of Alternative Powertrains*, 4(1):100–114, 05 2015. doi:10.4271/2015-01-1167.

[46] Jornal de Notícias. Táxis só podem ter até 10 anos de idade e têm de ser pretos e verdes. https://www.jornaldenegocios.pt/empresas/transportes/detalhe/taxis-so-podem-ter-ate-10-anos-de-idade-e-tem-de-ser-pretos-e-verdes. Accessed: 2022-09-22.

[47] Fleet Magazine. O táxi elétrico: 15 mil quilómetros depois. https://fleetmagazine.pt/o-taxi-eletrico-15-mil-quilometros-depois/. Accessed: 2022-09-23.

[48] Kotlin Foundation. Kotlin. https://kotlinlang.org. Accessed: 2022-09-22.

[49] Giovanni Malnati Marco Torchiano Luca Ardito, Riccardo Coppola. Effectiveness of kotlin vs. java in android app development tasks. *Information and Software Technology*, 127: 106374, 2020. ISSN: 0950-5849. doi:https://doi.org/10.1016/j.infsof.2020.106374.

[50] Victor Oliveira, Leopoldo Teixeira, and Felipe Ebert. On the adoption of kotlin on android development: A triangulation study. In *2020 IEEE 27th International Conference on Software Analysis, Evolution samernd Reengineering (SANER)*, pages 206–216, 2020. doi:10.1109/SANER48275.2020.9054859.

[51] Bruno Góis Mateus and Matias Martinez. An empirical study on quality of android applications written in kotlin language. *Empirical Software Engineering*, 24(6):3356–3393, jun 2019. doi:10.1007/s10664-019-09727-4.

[52] Kotlin Foundation. Kotlin - comparison to java. https://kotlinlang.org/docs/comparison-to-java.html. Accessed: 2022-09-22.