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Master degree course in Automotive Engineering

Master Degree Thesis

The Mobility as a Service business model

Is the Mobility as a Service business model a possible replacement to the private car ownership? A detailed analysis and cost model comparison

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Abstract

Development of a multimodal transporatation cost model for a smart city in the United States in the 2030 timeframe. The objective of the thesis consists in evelauting the different transport modes and, defining for the most likely a cost model, evaluate the economic aspect. The result of this analysis will subsequently be compared with a TCO model for several passenger vehicles and different powertrains. Finally, a comparative analysis is conducted and the main considerations are presented.

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Chapter 1

Shaping the way to smart mobility

This chapter describes the identified key global megatrends and explains what does that signify for the automotive industry, in terms of next challenges and trends. It also introduces the reader to the impacts arisen in cities, as a consequence of these megatrends, presenting also for this problematic next challenges and trends.

1.1 Global Megatrends

Megatrends are global, sustained and macro economic forces of development that impacts business, economy, society, cultures and personal life, thereby defining our future world and its increase pace of change. The Oxford English Dictionary defines a megatrend as “an important shift in the progress of a society or of any other particular field or activity” (oed.com). As cited in [1], Ilbury and Sunter note that the term megatrend is frequently used within the scenario planning literature, especially as a particular step in scenario planning methodology, where it is commonly understood to mean those global influencing factors which have a high degree of certainty but over which there is little control. Megatrends therefore refer to trends that are global and call for strategies for adaptation, rather than strategies for effecting change to the trends themselves. Consequently, as several of these megatrends have started since many years having an impact on the automotive industry, it is now critical to identify what they are and define what approaches and solutions are already available.
Since the academic literature on megatrend is limited, the approach focused on carrying out an internet research rather than looking into academic databases. The outcome of our research yielded to different reports recently produced by global accounting and management consulting firms KPMG[2], EY[3], Price Waterhouse Coopers[4], Deloitte[5], and Arthur D Little[6], as well as research organization such

as the European Environmental Agency [7]. Despite consulting reports and agencies white papers are not to be considered peer-review papers, they arguably reflect the main priorities for regulators and leading global players of the industry, which are the principal scenario planners and responsible of the resource allocations. In order to define which megatrends are reaching most consensus and should obtain more focus, the matrix shown in Table 1.1 was prepared, listing also our sources against the megatrends identified. A total of 16 global megatrends were identified during the research, suggesting some level of consensus, or at least convergence of ideas. The analysis identified the following six categories of key global megatrends to be the more common among the source review, namely: i) rapidly changing demographics, ii) rapid urbanization, iii) climate change, iv) resource scarcity, v) power shifts and vi) accelerating technological innovation. Each of these is introduced in more detail below. What is worth noticing, is the nature of these megatrends being political, societal, technological, environmental or economic but also the mutual exclusivity of each of this megatrend. For example, power shift could not exist without accelerating technological innovation, and we would not have a rapid urbanization if there was not any rapid change in demographics, and vice-versa. As it is also noticed in [1], it has to be considered that although megatrends have consequences on the entire globe (therefore defined global), they normally differ widely between regions, as it can be seen for urbanization and demographic trends that were already perceived years ago in several emerging countries.

International megatrends	Selected megatrends literature					
	Deloitte [5]	European Environmental Agency [7]	PWC [4]	EY [3]	KPMG [2]	Arthur D Little [6]
1. Rapid changing demographics	✓	✓	✓	–	✓	✓
2. Rapid urbanization	✓	✓	✓	✓	✓	✓
3. Accelerating technological innovation	✓	✓	✓	✓	✓	✓
4. Power shifts	–	✓	✓	–	✓	✓
5. Resource scarcity	✓	✓	✓	✓	✓	✓
6. Climate change	✓	✓	✓	–	✓	✓
7. Global health risks	–	✓	–	✓	–	✓
8. Continuing economic growth	–	✓	–	–	✓	–
9. Ecosystem pressure	✓	✓	–	–	–	✓
10. Increasing environmental pollution	–	✓	–	–	–	–
11. Diversifying approaches to governance	✓	✓	–	–	–	✓
12. Individualism	✓	–	–	–	✓	–
13. Economic internconnecteness	✓	–	–	✓	✓	✓
14. Public debt	–	–	–	–	✓	✓
15. Entrepreneurship rising	✓	–	–	✓	✓	–
16. Technological convergence	✓	–	–	–	✓	✓

Table 1.1: Megatrends matrix analysis

1.1.1 Rapidly changing demographics and rapid urbanization

Rapidly changing demographics and the rapid urbanization are the two megatrends that were identified by almost the totality of the papers reviewed (Table 1.1), and, as these two megatrends are considered not mutually exclusive, we have decided to analyze them together. From an estimated 7.7 billion people worldwide in 2019, the medium-variant projection indicates that the global population could grow to around 8.5 billion in 2030, 9.7 billion in 2050, and 10.9 billion in 2100 ([**UnitedNations.**], [4], [5]). More than half of the projected increase in the global population up to 2050 will be concentrated in just nine countries: the Democratic Republic of the Congo, Egypt, Ethiopia, India, Indonesia, Nigeria, Pakistan, the United Republic of Tanzania, and the United States of America. However, more developed countries exhibit different demographic trends where life expectancy has increased significantly, and birth rate markedly fallen. In 2018, for the first time in history, persons aged 65 years or over worldwide outnumbered children under age five [8]. Consequently, the populations of 55 countries or areas are projected to decrease by one per cent or more between 2019 and 2050 because of sustained low levels of fertility, and, in some places, high rates of emigration. Despite all, this rapid demographic change, has also to be considered from the perspective of urbanization. Reflecting the rapid urbanization trend, the 100 year period 1950 to 2050 is sometimes described as the "age of city building" [1] and hence, it is not surprizing that all six sources identified rapid urbanization as a key megatrend. Indeed, rapid urbanization is closely related to the three dimensions of sustainable development: economic, social and environmental, which all three have improved greatly since the beginning of the XXI century. Today, 55% of the world's population lives in urban areas, a proportion that is expected to increase to 68% by 2050. However, according to the United Nations [9], future increases in the size of the world's urban population are expected again to be highly concentrated in just a few countries, as, for instance, India, China and Nigeria. All them together are expected to account for 35% of the projected growth of the world's urban population between 2018 and 2050. Such trends mean that the process has already started, and only a well-managed urbanization, with the appropriate policies and share of information, can help to maximize the benefits while minimizing environmental degradation and other potential negative impact. Actions, especially in low-income and lower-middle-income countries, must be taken now, as most the most rapid urbanization is expected between now and 2050. The key is all in the timeline.

1.1.2 Climate change and resource scarcity

It is commonly acknowledged by the scientific community that the increase in global average surface temperature is caused by the anthropogenic increase in the greenhouse gas (GHG) concentration.This last one have continued to increase over 1970 to 2010, with even larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies [10]. Among all GHG, the only carbon dioxide (CO_2) is proven to contribute for about 78% of the total GHG emissions increase from 1970 to 2010, therefore it is in general considered the main cause of global temperature increase and climate change. Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 and the period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere [10]. In the only United States (U.S.), average temperature has increased by 1.3°F to 1.9°F since 1895 [11]. Furthermore, climate change involves many other dramatic events which, over the past 50 years, have been observed more and more frequently. For instance, the U.S. has experienced higher intensity, frequency, and duration of North Atlantic hurricanes since the early 1980s [11]. In addition, sever storms, extreme weather events, heavy downpours and in general precipitations, have also occurred more frequently and intensively. According to the National Center for Environmental Information (NCEI) which tracks U.S. weather and climate events that have great economic and societal impacts, during 2016, weather and climate event generated losses exceeding $46 billion. Although, this is only the 2nd highest annual number of U.S. billion-dollar disasters losses, behind 2011, when 16 events with losses exceeding $1 billion each occurred across the United States [12]. Climate change and its strictly related abnormal weather patterns are therefore expected to have effects not only on the environment but also on our socio-economics, demographics, crop production, food security, and political landscape, in unprecedented ways [5]. The era of strong global economic growth made possible by accessible and cheap resources is nearing an end for many countries [13]. The consequences of the environmental degradation will lead to price increases on key natural resources and the economic slowdown, as a consequence of population growth, will limit the available resources, increasing social conflicts. Water scarcity is already a problem in many areas in the world [6], and, by 2050, 60% more food is necessary, but with 52% of agricultural land being already affected by moderate to severe degradation [14]. According to the International Energy Agency [15], global energy demand will increase by more than a quarter by 2040 taking into account for continued improvements in energy efficiency, a powerful policy tool to address energy security and sustainability concerns.

The 2015 Paris Agreement, an agreement involving 195 members of the United Nations Framework Convention on Climate Change (UNFCCC), aims to keep the global temperature increase to well below 2°C above pre-industrial levels, but most experts predict already that global heating will exceed the threshold [16]. In 2020, all signatories are schedule to update their national commitments to the United Nations pact and the issue related to this matter will be further discussed [16]. In a report submitted in 2019 by the Global Commission on Adaptation, was concluded that $1.8 trillion in investments are necessary by 2030 to mitigate the cost-related effects of climate change. The investment would be concentrated in five categories - weather warning systems, infrastructure, dry-land farming, mangrove protection and water management - and would yield $7.1 trillion in benefits.

1.1.3 Accelerating technological innovation

Technological breakthroughs have characterized the human's history over the centuries since the discovery of the wheel. However, the rate of technological progress over the past 100 years is unprecedented in human history and has laid the foundation for much of the dominance humans are exerting over the planet [1]. Indeed, over the last 30 years, Information and Communications Technology (ICT) has significantly transformed our society. ICT not only ushered in the information age, but ICT based technologies have also been instrumental in enabling the research, development and growth of technologies in many other fields such as applied science, engineering, health and transport [2]. "Moore's Law" dictates that the capabilities of many digital devices such as microprocessors, memory capacity, sensors, and screen resolution have been improving at roughly exponential rates for decades, and is expected to continue to increase rapidly, albeit not necessarily at such rates [17]. More recently, further additional innovations as nanotechnologies and artificial intelligence (AI), allowed for new business opportunities and the emergence of new player in the industrial space. Big players face more and more compelling challenges and needs for adaptation, including new competition, changing customer engagement and business models, privacy concerns and cybersecurity. Disruption is taking place across all industries and in all geographies due to the enormous opportunities created. In addition, technology is also changing the ways that people work, and is increasingly enabling machines and software to substitute for humans. By 2020, the robotics industry could reach a market volume of $100bn, creating 3 million additional jobs, but also major issues to the today's US workforce. Overall, enterprises and individuals who can seize the opportunities offered by digital advances stand to gain significantly, while those who cannot may lose everything [3].

1.1.4 Power shifts

As we pointed out earlier in the introductory paragraph, each of the sixteen megatrends in Table 1.1 is very much dependent upon the others. However, the "power shifts" megatrend is to be considered as directly dependent upon each of the other

fifteen megatrends analyzed beforehand. The expression "power shifts" is referring to the global migration of power from a dominant central government, to a more decentralized situation where different entities, with different interests, are interdependent and interconnected. First of all, this is reflected by the structure of the global economy and especially the global financial system that shapes power relations. The reliance of countries on each other is further entrenched through global trade and lending. According to IMF, global debt in 2017 has reached an all-time high of $184 trillion in nominal terms, the equivalent of 225% of it Gross Domestic Product (GDP). Comparing these numbers with those before the global economic crisis, we see that global debt has grown by $47 trillion in nine years [18], with all bigger economies recording higher level of borrowings than their smaller counterparts. Particularity of the system is the involvement of foreign economies in the national debt. For example,as of June 2019, the United States total debt was $22.03 trillion, and approximately 39% of it is owned by foreigners, with China and Japan having the largest shares [19], establishing significant economic interdependence and interconnectedness. One additional aspect is related to the world military expenditure in emerging economies. Although global military expenditure increased 75% over the past 20 years, it stands at around $1.7 trillion annually since 2009. Nonetheless, in the past decade, China increased its military spending by 83%, while the USA's spending decreased by 17%. By 2030, the countries with top defense spending are expected to be: USA with over 1 trillion, China with $736 billion, and India with $213 billion. As it can be expected, this tense situation creates uncertainties for the future development and will affect the decision-making of the tradition global powers, or even a total re-balancing.
Result of the globalization and the open global economy developed throughout this last decades, now is common to see several multinational corporates, which have revenues bigger than some of the world's countries, with offices and legal entities spread allover the world. These companies all choose locations for personnel, factories, executive suites, or bank accounts based on where regulations are friendly, resources abundant, and connectivity seamless, making them diverge from the tradition of corporation taking pride in their national roots, and become more "nationless". In addition to that, connectivity and access to information are contributing to the human empowerment. By the end of 2018, more than 50% of the global population was using the Internet, according to the ITU [20]. Women empowerment is also in the United Nation agenda and Women's Empowerment Principles (WEPs) have already been rolled out in various enterprises worldwide. Finally, urbanization and the rise of megacities defines new political entities that will have an impact on the global development. Indeed, the points presented here will affect the role of governments over the upcoming years. Cities and regions will become increasingly significant public funders of research and innovation, government will increasingly partner with businesses, NGOs and philanthropist, which will in turn influence public research agendas. But also, whoever is the leader at

the moment, it is not sure that it will still be in the future.

1.2 The mobility implications

As it can be expected from the previous section, the global megatrends are influencing the automotive industry and in general how mobility will be offered in the future. Mobility is a key aspect of our modern societies. Indeed, it can be said that our well-being and economic development is quite connected to it. However, it is common knowledge that the automotive industry is responsible of most of the anthropogenic GHG emission of the entire transportation sector. As stated by the United States Environmental Protection Agency (EPA), in the time frame between 1990 and 2017, GHG emissions in the transportation sector increased more in absolute terms than any other sector, due in large part to increased demand for travel [21]. According to this same agency, in the U.S. the transportation sector (including cars, trucks, commercial aircraft, and railroads, among other sources) accounted for the largest portion (27%) of the total GHG emissions in 2017. Within the sector, light-duty vehicles (including passenger cars and light-duty trucks) contributed for the 59% of GHG emissions, while medium- and heavy-duty trucks made up the 23% [21]. Since years, regulators in different regions worldwide issued policies to limit the CO_2 emissions of light-, medium- and heavy-duty vehicles and governments around the world are acknowledging the importance of zero-emission vehicles (ZEVs) in achieving their climate, air quality, energy security, and economic development goals [22]. Additionally, the digital transformation made possible by ICT technologies, the exponential increase in computing power, and furthermore the recent progresses and innovations in nanotechnologies and AI are shaping a complete different future for the automotive sector. Therefore, the personal mobility is about to face four major innovations that have a high disruptive potential: electrification, connectivity, shared mobility, and autonomous driving.

Electrification Climate changes and pollution are the main reasons for the numerous announcements from most of the major car manufacturers of new electrified models, with some of them committing to offer all their models with an electrified version in the next five years. Following the same approach used in many research papers, we have considered electrification of motor vehicles at different levels depending on the power supplement and the propulsion devices [23]. For the sake of simplicity, in this paper, only three different types of electric vehicles will be presented, avoiding the further classification related to the level of hybridization and possible combinations for hybrid electric vehicles (HEV). Hence, the most broad definition defines electric vehicle (EV) a road vehicle which involves with electric propulsion. As illustrated in Figure 1.1, EVs may include battery electric vehicles (BEVs), hybrid electric vehicles HEVs), and fuel-cell electric vehicles (FCEVs).

However, among the three types outlined, the only ZEVs are BEVs and FCEVs.
Overall, adoption of EVs is still marginal at global level, but expanding at rapid

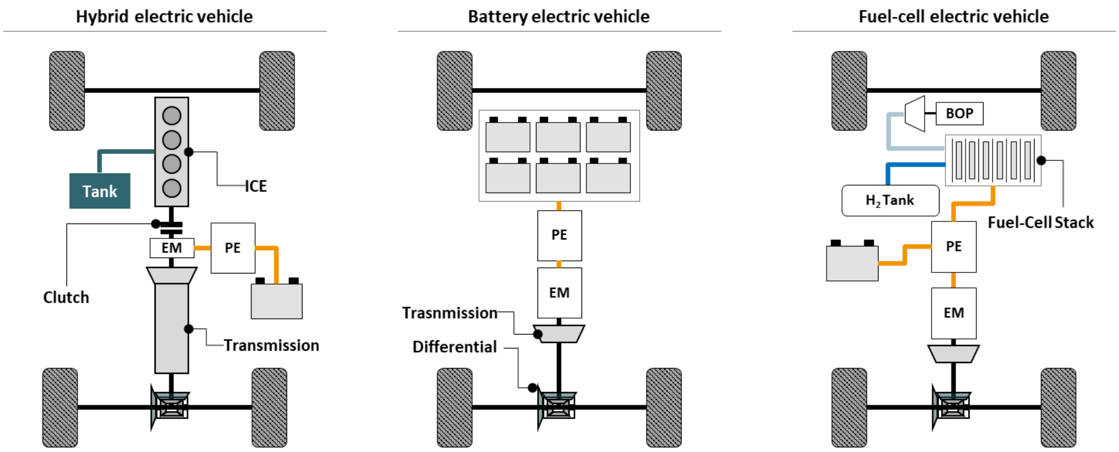


Figure 1.1: Electric powertrain classification - graphic by author

pace. In 2018, global electric fleet exceeded 5.1 million, up by 2 million since 2017 and almost doubling the unprecedented amount of new registration in 2017 [24]. In some regions, where policies, incentives and the deployment of charging stations have been taken more seriously, kick-started demand and faster adoption have happened. Technology developments made possible substantial cost reductions, even though the high price and development of battery technology is still recognized as one of the main challenge [24]. Demand for precious materials needed for the battery chemistry, are expected to be solved with scale and less dependent cathode chemistry to cobalt, such as NMC 811, NMC 622 or NMC 532. Moreover, other developments as complete redesign of the vehicle's platform, simpler designs which take advantage of the compact dimension of electric motors, and adapting battery sizes to the travel need will help achieve cost parity between EV and ICE vehicles. Initially, the role of regulations is fundamental as has already been proven but crucial is also the responsibility of manufacturers and technology innovators.

Connectivity Connectivity is in general defined as the exchange of information between a vehicle and its environment. Throughout the past two decades, the world got more and more connected and the automotive space was no exception to that. The survey conducted by McKinsey & Company in 2015, showed that customers are enthusiastic about connectivity features in their cars, and willingness to pay additional money for better connectivity rose significantly [25]. Still major acceptance issues need to be solved, as for instance privacy and data sharing, which will remain a focal point of interest for consumers and regulators, but the opportunity is for sure available. To understand more clearly the impact that connected vehicles have, I collected the five main trends within the automotive industry that are associated with connectivity: i) browser on wheels, ii) artificial intelligence, iii) entire different transportation value proposition, iv) car as a mobile virtual operator (MVNO), v) wireless network role in vehicle safety. The first trend means nothing less that driving has become the equivalent of online search with all the monetizing implication that this new driving behavior involves. Artificial intelligence, is considered most of the time an enables, more than a trend. Indeed, AI is allowing cars getting smarter at understanding what humans are doing and helping them at, for instance move and arrive to their destination accurately and safely. The new value proposition will play out over a much longer timeline and drastically revolutionize the traditional car ownership with profound impacts on car makers, car dealers and the supporting transportation and wireless infrastructure. In addition, as part of this transformation, car companies are looking to become MVNOs in their own right as they seek to achieve a carrier-independent business-model. Last, wireless networks will also play an essential role in combatting cybersecurity threats and supporting real-time map updates for AD and software updates. Manifestation of this connected world has already manifestation - C-V2X - and many more opportunities can be offered with the onset of 5G in just a few years. The good news is that automotive industry is finally working with the wireless industry to develop common standards and protocol [26], but further works are still needed and a major involvement of governments to build the required infrastructure is crucial.

Shared mobility Shared mobility refers to the shared used of a vehicle, bicycle, or other transportation mode. Since the early 2000s, advancements in social networking, location-based services, and mobile technologies made possible by the acceleration of technological innovations (see subsection 1.1.3), have contributed to the spreading out of the shared economy. The sharing economy is a customer trend where users rent and borrow goods and services, instead of owning them. This sharing economy can occur among peers (e.g., BlaBlaCar sharing, AirBnB, etc.) or through businesses (e.g., Car2Go, Yerdle, etc.) and it is perceived as more affordable, convenient, and better for the environment. Shared mobility, on the other hand, is seen as a promising way to reduce traffic congestion, and the CO_2, replace the private car ownership and, in the case of shared autonomous vehicles (SAV) of the burden of driving. Little is know about potential users of SAV and implications that such an economy can have on the transportation industry are not clear yet. Overall, the disruptive potential of the AV technology, connectivity, and shared mobility, is undeniable; the goal of this is thesis is in fact to contribute to provide an answer to some of those questions and a more comprehensive analysis will be presented in the next sections.

Autonomous driving According to the State of California, Department of Motor Vehicles “Autonomous mode is the status of vehicle operation where technology that is a combination of hardware and software, remote and/or on-board, performs the dynamic driving task, with or without a natural person actively supervising the autonomous technology's performance of the dynamic driving task". An autonomous vehicle is thus operating or driving in autonomous mode when it is operated or driven with the autonomous technology engaged. Due to the very vague definition, it is very common to find article and press announcements where autonomous vehicles (AVs) technology and connected vehicles technology are misunderstood and referred as likewise. Some experts see a high level of connectivity as a condition for the successful implementation of the AV, while others think autonomy can be achieved solely based on sensors ([27], [28]). Despite these considerations, in this thesis the term AV refers to the approach where the convergence- and sensor-based technology deliver better safety, mobility, and self-driving capability. As the autonomous technology is being released allowing step-by-step different stages of autonomy, the SAE classification system is in general adopted [29]. A key distinction can be made between SAE level 2 and 3 where the driving systems obtains the ability to perform a dynamic task whereas it only is an ADAS beforehand, relying on the human driver for the dynamic elements, as graphically represented in Figure 1.2. The functions of the different levels are described as follows [29]:

SAE Level	0	1	2	3	4	5
SAE Name	No Automation	Driver Assistance	Partial Automation	Conditional Automation	High Automation	Full Automation
Execution of Steering and Acceleration/ Deceleration	Driver	Driver and System	System	System	System	System
Monitoring of Driving Environment	Driver	Driver	Driver	System	System	System
Fallback Performance of Dynamic Driving Task	Driver	Driver	Driver	Driver	System	System
System Capability (Driving Modes)	N/A	Some driving modes	Some driving modes	Some driving modes	Some driving modes	All driving modes

Figure 1.2: Autonomous driving level classification by SAE [29] - graphic by author

- **Level 0: No Automation** The human driver is in complete control of all functions of the car

- **Level 1: Driver Assistance** One function is automated

- **Level 2: Partial Automation** More than one function is automated at the same time (e.g., steering and acceleration), but the driver must remain constantly attentive
- **Level 3: Conditional Automation** The driving functions are sufficiently automated that the driver can safely engage in other activities
- **Level 4: High Automation** The car can drive itself without a human driver but limited to a geofenced area
- **Level 5: Full Automation** The car can drive itself without a human driver

1.3 The city consequences

We have discussed so far, about what, at global level, is occurring (see section 1.1), the subtrends related to these megatrends, presenting the electric, connected, shared and autonomous vehicles (see section 1.2), consequently the next section introduces the implications on urban mobility.

Congestion Congestion is the consequent effect related to the following root cause: traffic influencing events (traffic incidents, work zones), traffic demand (fluctuations in normal traffic), and physical highway features (traffic control devices, physical bottlenecks) [30]. INRIX, estimated that in 2018 nearly \$87 billion have been lost by the U.S. citizens due to traffic congestion, an average of \$1,348 per driver. Taking into consideration the impact on cities, the picture is even darker: in the U.S. alone, congestion costed cities \$305 billion in 2017, an increase of \$10 year-over-year [31]. Cost of congestion, is moreover expected to rise over time: in another report from the same consulting firm INRIX, the cumulative cost over the 17-past year period in 2030 is projected to be \$2.8 trillion - the same amount American collectively paid in US taxes in 2018 [32].

Health Additionally to the climate change, the smog hanging over cities to the smoke inside the home, poses major threat to the human health. According to the study in the Proceedings of the National Academy of Sciences, about 107,000 fatalities occur each year in the U.S. due to traffic pollution [33]. Considering the situation in cities, where the concentration of $PM_{2.5}$ and harmful particulate is higher, even short-term exposure to traffic pollution can cancel out the positive effects a two-hour walk would otherwise have on the heart and lungs of older adults [34]. Hopefully, modern pollution control technologies and measures have been implemented all across the U.S. and has resulted in dramatic improvements of the air quality over the last several decades. A report shows that deaths due to pollution in the U.S. from 2008 to 2017 have decreased, which is of course a positive sign [35]. However, this doesn't show the big picture: the report still shows that in different pockets of the country and more specifically in numerous Californian cities, under the Trump administration, regardless the progresses made in recent years the situation is still critical.

Space The issue related to space is something that cities have more recently started dealing with. Cities, as New York and San Francisco where population density is among the highest in the world, are already struggling with problems related to housing shortages and soaring rents, therefore the gain of public space would be staggering. For instance, San Francisco sketched out a forward-looking plan about their vision on how a "city of the future" should look like and they came up with the idea that, exploiting new technologies and business models, the city can have back space from cars which can then be used for affordable housing, small parks and pedestrian amenities. According to their report, San Francisco claimed that they would be able to move the same amount of people with one tenth of the vehicles [36]. The way San Francisco is addressing the problem is actually logic: besides all major advantages that such a system can have in terms of sustainability and improvements on the current system, it is proven that car take away a lot of public space with parking and streets ([37], [38]). Green spaces such as parks and sports fields as well as woods and natural meadows, wetlands or other ecosystems, represent a fundamental component of any urban ecosystem and therefore have to be preserved.

1.4 Smart city

It should now be clear that actions are needed, and are needed as promptly as possible. Among all possible solutions, it is now identified that one major organization that can lead the change towards a more sustainable, reliable, and improved system is the city, which will initially create collaborations and co-operations to improve the quality of life of its inhabitants, but subsequently, will spread out these initiatives and extend them to neighborhoods, cities, and finally entire countries. Coming out from the XX-century models, characterized by uncontrollable population and city growth, economic boom, and unbelievable opportunity creation, inequality is skyrocketing. We're now in a situation wherein the political, economic and social environment is fractured, many citizens distrust elected officials to act on their behalf, and government bureaucracy is unable to provide efficient and effective services. In other words, we build cities that have contributed to the problem instead of mitigate it. The megatrends and subtrends illustrated above imply that the we need to transform out cities, not just once, but continuously.

1.4.1 Definition and characterization

The term "Smart city" refers to the global phenomenon put in place by city's organizations to counteract the effects due to overpopulation and fast urbanization presented in the section devoted to the megatrends (see section 1.1). Smart city is therefore a strategy that focuses on using the most innovative technologies, data, and leveraging the wielded power with government to improve the quality of life of their citizens. In our era, the word "smart" can be found related to many and unlikely substantive. We often find the adjective "smart" used to define even our mother planet Earth. According to Samuel J. Palmisano, Chairman, President and Chief Executive Officer at IBM Corporation, this substantial change toward a "smart everything" is because the precondition for real change now exists: people want it [39]. In the paper, the author provides a very specific definition of a smart city, defining it as an instrumented, interconnected and intelligent city [39]. 'Instrumented' refers to the capability of capturing and integrating real-time data using sensors, meters, appliances and an entire range of personal devices. 'Interconnected' refers to the integration of these data into a computing platform that allows the communication of such information among the various city services. 'Intelligent' denotes the inclusion of sophisticated analytics, modeling, optimization, and visualization services to make better operational decisions [40]. Hence, its main focus seems to be on the role of the ICT infrastructure but a city's smartness reflects upon more than mere technology. A second element characterizing many smart cities is the underlying emphasis on business-led urban development [41]. A smart city is therefore shifting form a managerial to a more entrepreneurial form, where cities are being shaped by the presence of big-businesses and/or corporations. The two cities taken as example by Holland [41], San Diego (USA) and Edmonton (Canada), expressed clearly this concept mentioning in their web-pages 'business-led' or 'business-friendly' criteria. A sudden change from managerial to entrepreneurial forms of urban governance is visible and seeks to leverage the nexus of competitive advantage by growing industries and generating, retaining and attracting the best talent. Nonetheless, overemphasis on technology and a heavily instrumented approach to urban placemaking, ignore the role of communities and local institutions who shaped cities over the years [42]. Consequently, the approaches to defining the smart city have become more diversified and humanized. For this reason, it is possible to find in literature different papers that merge the technology-driven definition with some human aspect related to the smart city. In fact, people benefit form the cultural heritage of a city and the smart city concept acquires the meaning of a mix of education, culture, and business. Smart city focus on education signifies that a high density of higher education institutions are necessary to promote the supply of adequate skilled workforce.

The combination of the three elements of smartness (as outlined above) is also emphasized by Caragliu et al. [43]. The authors state that a city is believed to be smart "when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance". To clarify, this definition seems to not only indicate what a smart city is envisioned to be, the authors also emphasize the aim of the smart city.

1.4.2 Technology roadmap

As outlined in the previous paragraph, modern information and communication technology (ICTs) systems are critical to the development of smart cities ([40], [43]). Consequently, the smart city concept is rapidly gaining popularity due to the emergence of new IoT-related technologies such as RFID (radio frequency identification), environmental sensors, actuators, smart phones, wearable sensor and cloud computing [44]. Broadly accepted by the literature is also the relationship between the feasibility of smart city initiatives and the expansion in big data and these IoT technologies. For the seek of completeness, this thesis will provide in the current section the reader with a literature research covering the latest available research papers that involve technology roadmapping in smart cities. Subsequently, some exemplary case study will be introduced where it will be possible to link the expected developments with the current status of the technology. A technology roadmap highlights the relationships between markets, technologies and products, considering current technologies and market requirements, and provides an overview for the expected implementations, and the key takeaways. These relationships are used to match short- and long-term goals to the development of certain technology that will help realize the business goal [45]. The framework for smart city technology can be divided into four layers: sensing, integration, intelligent, and application [46]. The sensor level is the lowest technology level, which is defined by sensing devices and will enable to detect and monitor environmental and biological data. The integration level will provide the communication of the information collected by the sensing layer. Subsequently, the intelligent layer uses methods such as data analysis and algorithms to make decision or prediction based on the integrated information. In the last layer, the application layer, the previous three technology layer are connected into a wide range of smart applications [46].

Sensing layer It must be clear that even the simplest smart city solution solution will involve a large number of connected devices and sensors [47]. Thus, the overall design of the infrastructure of a smart city is dependent upon the extensive use of intelligent sensors. Such sensors, provide on-site and in real-time physical parameters which can play a role in protecting human and environmental resources against harmful agents. In general, the sensors considered for smart city applications will be capable of monitoring environment, odor, water quality, air quality as well as security application [48]. Among the *environmental monitoring* sensors the most common are electrochemical or bio-sensors [48]. An electrochemical sensor relates any variation o different chemical parameter to electrical quantities, whereas a bio-sensor is typically an hybrid device which combines biological sensing components with an analytical measuring element. Both sensors, however, are able to provide the users with the concentration of pollutants detected in a specific sample of soil, water, or air. The *air quality monitoring* sensor detects gaseous compounds in the air and is inevitable for air pollution controls [48]. Depending on the required sensitivity of the results, a common type uses selective sensing membranes and a coated quartz resonator to detect dangerous gasses such as toluene, acetaldehyde and ammonia. Another important application for sensors is water quality monitor for drinking water distribution systems, industrial uses and surface water quality. The *water and wastewater quality monitoring* sensor monitors various water quality parameters using an electrode- or luminescent-based sensors [48]. The coming of digital, more reliable, more sophisticated and long-lasting sensors is eliminating the need of high time demanding laboratory analysis and novel molecular biology technology, such as fiber optic biosensors, nucleic acid probes will improve the usage even more. Sensor technology can also be implemented for counter-terrorism task and *security applications* [48]. Explosive detectors sensors are based on ion mobility spectroscopy, nuclear quadrupole resonance and infrared (IR) spectroscopy and can provide more cost effective and faster response than the common used canine detector. Within the *security application*, our research revealed a strong focus in the industry on developing the next generation of Global Positioning System, Recognition and Testing technology and Online Video Surveillance which are expected to play a crucial role in the city administration [46].

Integration layer Connectivity and access to the Internet have already contributed to the technical evolution of the world and improved out lifestyles, but to boost the proliferation of smart cities the development of a new wireless cellular technology with global standards is required. Today's IoT devices are mostly connected though low power wide-area networks (LPWAN) which allow for a low cost module, low power consumption, extended battery life, and improved wireless coverage. In fact, LPWAN is a type of wireless telecommunication designed to allow long-range communication at a low bit rate among things (connected objects), such as sensors operated on a battery. It provides long-range communication up to 10–40 km in rural zones and 1–5 km in urban zones. In addition, it is highly energy efficient (i.e. 10+ years of battery lifetime) and inexpensive, with the cost of a radio chipset being less than 2$ and an operating cost of 1$ per device per year [49]. In summary, LPWAN is highly suitable for IoT applications that only need to transmit tiny amount of data in long range, as shown in Figure 1.3. From the same figure (see Figure 1.3) is possible to deduce the general rule of thumb valid for wireless communication: among speed (how fast you want to send the data), distance (are you want to cover), transmit power (how fast you drain the battery), reliability or latency (how long it takes data to transmit), you have the possibility to choose three out of four. Nevertheless, considering the potential applications

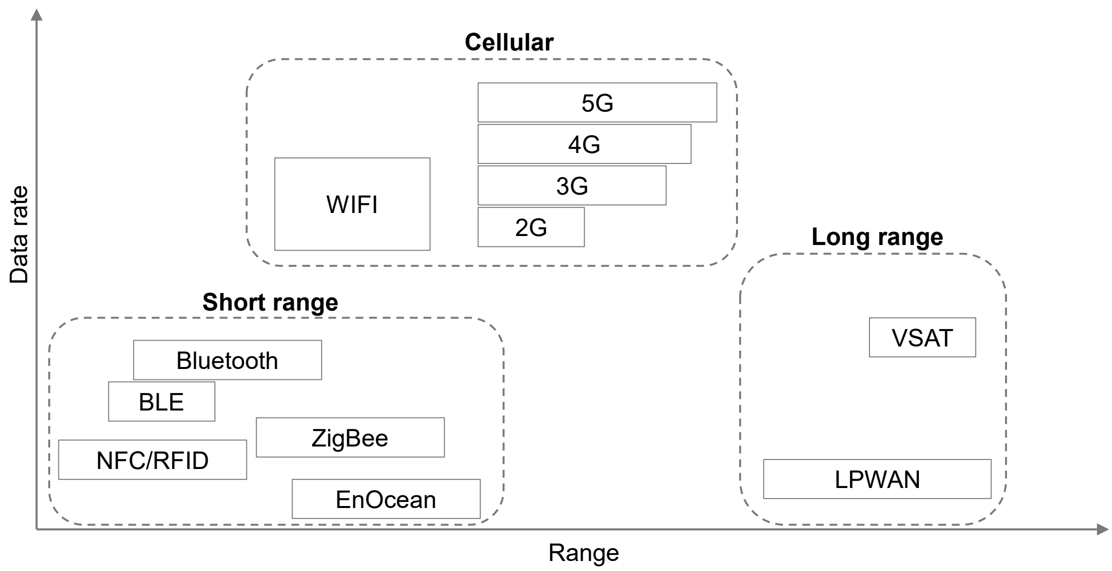


Figure 1.3: Required data rate vs. range capacity of radio communication technologies - graphic by author

in a smart city, already different solutions have been developed based on LPWAN telecommunication technology and almost certainly many more are going to impact this market in the next few years. Sigfox, LoRa, LTE-M, and NB-IoT are the four leading LPWAN technologies that compete for large-scale IoT deployment, where NB-IoT and LTE-M are two most likely to appear first in smart city, and each of them has advantages and drawbacks [49], that are not going to be presented in this thesis. Figure 1.4 presents also some exemplary use-cases that are already in use in some cities around the world, but are going to pop up all along the 2020s due to wide deployment of this technology.

A promising technology that promises high bandwidth and low latency network is the fifth generation cellular network technology, or better know as 5G. NGMN [50] has developed the following vision for 5G "5G is an end-to-end ecosystem to enable a fully mobile and connected society. It empowers value creation towards customers and partners, through existing and emerging use cases, delivered with consistent experience, and enabled by sustainable business model". This technology is expected to experience widespread commercial adoption, as the 5G business context is characterized by changes in customer, technology and operator contexts, but its application to smart cities is impactful and extensible. The manifestation of 5G in the marketplace can be visualized as the product of three core elements: massive Machine Type Communication (mMTC), enhanced Mobile Broadband (e-MBB),

Figure 1.4: LPWAN use cases - graphic by author

and Ultrareliable Low-Latency Communications (URLLC) [47]. Massive machine-type communications extends LTE Internet of Things to support huge numbers of devices with lower costs, enhanced coverage, and long battery life. The principal use cases are in IoT, asset tracking, smart agriculture, smart cities, energy monitoring, smart home, remote monitoring. eMBB is the most obvious extension of LTE capability, providing higher speeds for applications such as streaming, Web access, video conferencing, and virtual reality. Highest speeds will occur in small cells with limited movement speed of end users, such as with pedestrians. Of the three categories, URLLC enables wireless applications never before possible. Driven by high dependability and extremely short network traversal time, URLLC, also referred to as "mission-critical" communications, will enable industrial automation, drone control, new medical applications, and autonomous vehicles. This category is also referred to as critical machine-type communications (cMTC) [51]. Figure 1.5 shows how the different use cases have different requirement for throughput, latency, and reliability. The phase 1 of 5G commercialization is targeted for 2020 and will include requirements, and deliver speeds that approach fiber-like solutions (expected throughput of 5 Gbps) with grater spectral efficiency (3.5x of LTE) [47]. An important component of the communication infrastructure surrounding smart cities will be the cloud network. One of the key advancements in cloud design will be the co-engineering of hardware and software, defining the next generation of processor design. This approach will provide a number of benefits, including better integration efficiency, platforms that are capable of supporting deep learning, and

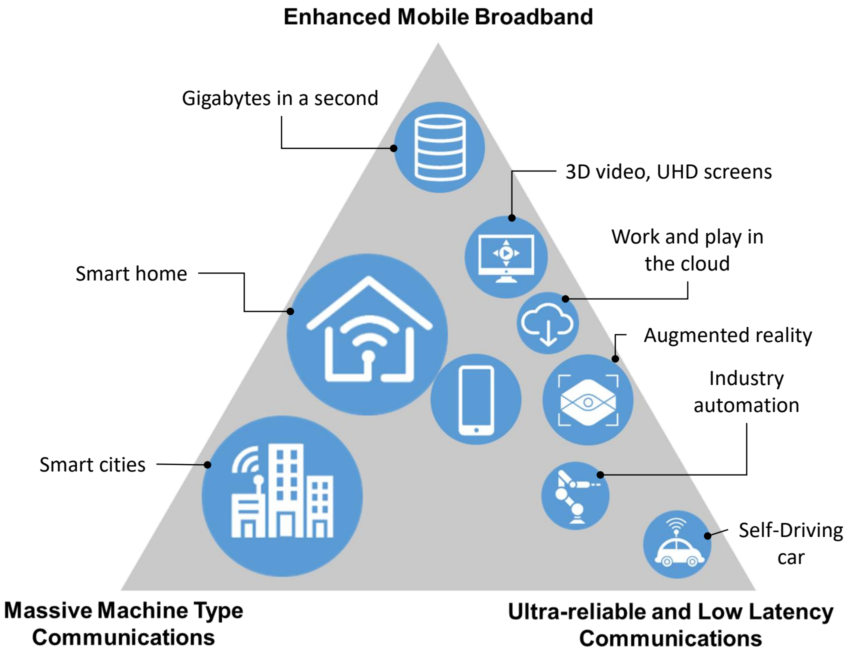


Figure 1.5: ITU use case model for 5G technology [51] - graphic by author

improved security. Moreover, improvements in data protection and access control will be made possible by incorporating designed-in security. Consequently, smart cities will need to evaluate a number of different cloud approaches, based on their specific needs. One of the cloud alternatives that will offer new opportunities to smart cities planners is hybrid cloud. This technology will utilize a combination of private cloud and public cloud resources to create an organized computing platform that can adapt to changing workloads and offer higher efficiency and resiliency. By deploying hybrid cloud solutions, smart cities can also defer some infrastructure investments by leveraging public cloud solutions and develop edge processing and data analytics which will further discuss in the next paragraph about the intelligent layer.

Intelligent layer The connectivity and communication technology plays a fundamental role in the distribution and exchange of data within the smart city boundaries, but the additional management and integration provided by the intelligent layer, will be decisive for the smart city success. Applications of advanced analytics, as machine learning and AI, data integration platforms, and augmented reality/virtual reality platforms are going to provide end-to-end value for users of the smart city ecosystem and act across the two previous explained layers as a technology enabler [47]. As it was mentioned before, during the smart city expansion there will be opportunity to migrate legacy IT/OT to new devices and platforms, such as the cloud networks creating the cloud computing. The improved connectivity network, will offer similar benefits around performance and integration, but with enhanced improvement in resiliency and safety. Thus, this intelligent connectivity system is a near-term opportunity for municipal planners and is defined by a well-established communication system (asset-to-asset, asset-to-sensor, and asset-to-human), interconnected with the gateway or the cloud (for processing and analysis of the large amount of information) and equipped with mobile edge computing (MEC) capability. The key idea beneath MEC (Figure 1.6) is to place storage and computation resources at the network edge, closer to where the user is. In the same way, the data processing will be located closer to where the data was produced. By processing data locally and accelerating data streams, MEC reduces the traffic bottleneck toward the core network. Besides, it helps shorten latency, improving the response of the system and the overall user experience [52]. These capabilities are well-suited for the smart cities environment, which rely upon

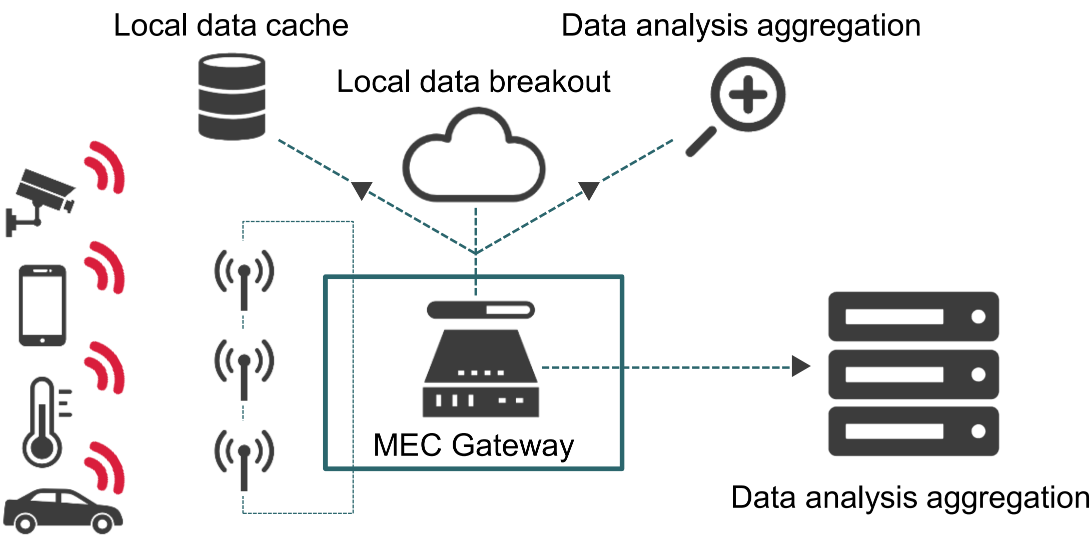


Figure 1.6: Schematic of Mobile Edge Computing - graphic by author

distributed sensors and the need to manage and filter large volumes of data. Although the service response and capabilities can be emphasized using 5G, MEC can also be applied the current existing 4G LTE networks [52]. Given its potential, MEC has begun gaining a lots of momentum among industries and within the researcher community, but there are still question that still need to be answered, as for instance, which entity is best positioned to deploy and maintain the system. Possibilities include existing cloud vendors (Amazon, Google, Microsoft, etc.), but also cellular operators, and private enterprises for their own applications might have a share in it. Among the applications that will benefit of MEC are ones that require server-side processing but are location specific as for instance, augmented reality, virtual reality, cloud/edge-based game hosting or connected cars. Artificial Intelligence is one further technology that will support and enable the full-fledged smart city ecosystem. AI could optimize the network, controlling in real-time connections and, for instance hand off users from Wi-Fi to cellular, handle increasing network complexity with an increasing number of cell sites, number of devices, and speed of operation. AI functions will be distributed among centralized clouds, edge clouds, and devices. Centralized clouds will be best for AI training and content not sensitive to delay, whereas edge clouds, with much lower latency, will support real-time interaction about the environment. The automotive application unleash opportunities integrating on-board AI applications providing major safety improvements, as well as user-centric new features enriching the entire journey experience [53]. AI will also allow for improvement over time due to the data collection made possible by the smart city system. Thus, not only the data collection, but also data management, and usability will be areas that can be leveraged in the near terms and provide measurable benefits. Meanwhile, the data-based concept of a smart city introduces challenges related to privacy, efficiency of the data management, and demand of greater resiliency and operation continuity at the edge of the network. Indeed, data and analytic can be intended as a four steps process made up of: i) sensors and connected devices, ii) edge processing, storage, and analytics, iii) centralized data computing resources, iv) data enabled applications. Ergo, the data will be first collected, and securely delivered by IoT-enabled devices. Subsequently, the data will be treated in real-time, possibly on-site, at the gateway with cloud computing and MEC. After, the data will be sent to the nearest data center for back-up, analytics management and possibly AI training. Finally, the data is considered completely processed, hence it will be ready for real-world application, enhancing user experience and integrated applications [47].

Application layer The smart application for a smart city are multiple and diverse and will primarily depend on the vision of the specific city. According to Hsi-Peng Lu et al. [46], which conducted an inventory analysis of applications in six fields (government, economy, environment, mobility, people, and living) that can be improved with the implementation of the technologies presented in this section, in most smart city cases Smart Mobility and Smart Environment were considered the primary directions of development, followed by Smart Government and Smart Living, with Smart People and Smart Economy seen as relatively less important [46]. In the following subsection, the Dubai case study will be presented, where the first four principal applications will be outlined.

1.4.3 The Dubai case study

Dubai's initial plans towards a smart city transformation started back in 2007. At the time, the world was just about to get hit by the financial crisis, however

Dubai was committed to take on the challenge therefore, the Government initiated a study on the transformation to a "Digital City" [54]. Led by Smart Dubai, the city has transformed itself into a model smart city, revolutionizing the way government services are delivered to its people by launching over 100 smart initiates and more than 1000 smart services, only in the last three years. The Smart Dubai 2021 strategy is an ambitious roadmap to prepare the city to embrace the future and emerge as a world-leading city by 2021, in celebration of the nation's golden jubilee [55].

Smart Mobility Dubai as many other cities around the world has set its highest priorities on developing smart mobility for its smart city vision. This is simply the use of ICT technologies to support and integrate transport in order to make mobility easier, convenient, and more efficient. Dubai's goal is to embrace autonomous car as a transportation. Dubai want to be at the cutting edge went it comes to mobility, focusing on the offering new transportation modes, improve the traffic management, road infrastructure, promote sustainable transport modes and therefore also non-motorized solutions. RTA (Road & Transport Authority) has started this transformation in 2015 with solid goals, they have developed a new mobile app, built the Enterprise Command and Control Center (EC^3) which is the a true multimodal multi-agency center and improved its public transportation to help ease traffic concerns. It's transportation system will include sea, land, and also air (Urban Air Mobility projects) with seamless integration and connection among them. Smart parking, smart toll and smart traffic light will all contribute to enhance the mobility experience and ensure fast flow of people.

Smart Environment The challenge of water and air quality is for Dubai fundamental to ensure citizen happiness. The zero CO_2 ambition of the city is evolving at fast pace, with electric car charging station popping up and smart sensor have been installed over the last years. Energy production is expected to move to solar energy, and water reuse and efficient irrigation system will be employed. Environmental friendly project solutions are promoted and will keep being in the future, via smart financing mechanisms and public and private partnerships. For instance, to underline its commitment, the government has pledged to invest $27.2 billion in a Green Fund to provide easy, low-interest loans to clean-energy investors. Renovation of buildings and amenities, green buildings and green urban planning are also goals that will promote this sustainable vision.

Smart Government As part of their aspiration, Dubai wants to improve the way government and citizens interacts, making it more seamless and efficient. In concrete, the aim is to conduct all government services and transactions in paperless and cashless manner without the need for visiting government offices. An integrated platform will encourage collaboration between public and private sectors.

The Dubai Open Data Law will increase sharing of non-confidential information between government agencies and the public, building relationships with the citizens and promote transparency. Moreover, smart governance will focus on citizen's participation and involvement using ICTs, data sharing and enabling smart processes and inter-operability. Engaging citizens in the decision-making will be crucial, therefore crowd-sourcing mechanism will be implemented and easily accessible.

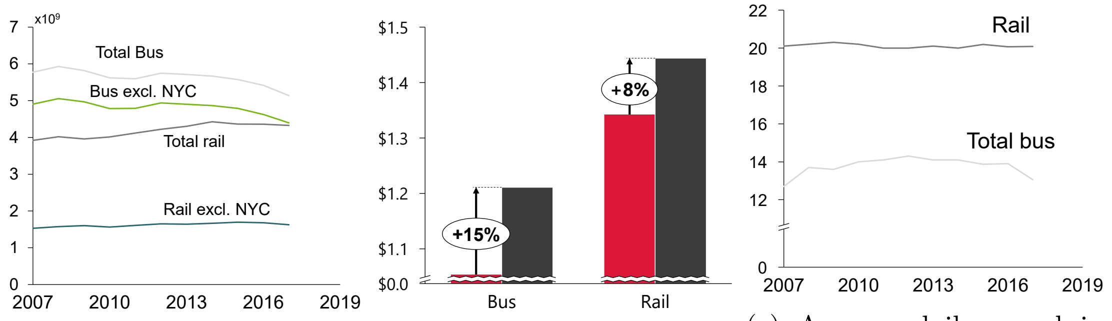
Smart Living Smart Living is related to the design of systems where people live, by investing in public services, such as education or healthcare systems, boosting the city to be more attractive for dwellers and visitors, and at the same time getting more security and safety for particular layers of their inhabitants, such as children or elderly people. Consequently, the quality of life is among the primary criteria that must be satisfied by a smart city. Dubai will address this issue improving connectivity and access to the information, cybersecurity for accessing city services and for conducting online transactions, and safeguard sensitive and private information. In addition, IoT-enabled sensors will facilitate asset management and water or electricity outages will be immediately sensed and faster service recovery will be made possible. Citizens will be able to monitor their resource consumptions, such as water and electricity, and AI will provide customized solutions to reduce it. Disaster mitigation can also improve citizen safety feeling and response and recovery time for such incidents if they happen. Dubai has also begun implementing Smart Home, a revolutionary application of smart health technology that uses a network of smart sensors to monitor health information and give prescription reminders. In a nutshell, Smart Living is simply the opportunity to use smart technologies to make lifestyles comfortable and easy. This affects behaviors, social habits, and may then encourage citizens to become more enabled/involved, resulting in likely additional source of feedback to the city government. Crowd-sourcing and open data opportunities will enable citizens to develop their own ideas, improving even further appreciation and earlier mentioned benefits. Smart living will eventually enables healthy and safe living in a culturally vibrant city with diverse cultural facilities, which incorporates good quality housing and accommodation.

Chapter 2

Mobility as a Service

2.1 Definition

Our current private car based transport system is inefficient and unsustainable. Urbanization is increasing traffic volumes, and the need to decrease the GHG call for new solutions for daily transport. A sustainable and consumer-centric transportation system should be in the centre of the solutions, where private car ownership can be easily replaced by a convenient system, flexible and capable of making the everyday traveling from place to another, serving users' needs. In addition, the actual public transportation system is not capable anymore of satisfying the consumers, and is resulting in decreasing utilization, increasing costs for the users, with minor or negligible infrastructure improvements over time. This is clear looking at Figure 2.1, which shows that while in the U.S. ridership has risen about 3% over the past decade, that increase is due largely to strong gains in the New York area, which accounts for about 40% of all transit riders [56]. If the New York region is excluded from the data, national transit ridership decreased by 7% over the same period. Some of the reasons related to this ridership decline (see Figure 2.1) are, first due to the transportation system itself, which has presented rising prices (8% and 15% for bus and rail respectively in the last ten years, taking into consideration also dollar inflation over the same timeframe) without offering any advantage to the consumers (see Figure 2.1c). But then also factors as the low gasoline price and the more important growing popularity of ridesourcing company such as Uber and Lyft, are moving the public away from the conventional mass transit transportation, damaging even more the entire urban mobility system. Competitive choices for private cars and the mass transit are called for, and Mobility as a Service (MaaS) is considered as one option as it offers a new paradigm by placing user's needs in the centre of the transport system. As stated by the first movers in this environment [57, 58], Mobility as a Service aims to combine different transport modes (e.g. car-sharing, UAM, ride-hailing, bicycles, taxis, public transportation)



(a) Unlinked passenger trips (b) Fare in 2005 and 2017 (c) Average daily speed in mph

Figure 2.1: Public transportation statistics and trends [56]

in a way that it will be seamless and integrated over one user interface. The combination of public and private operators is the key of such a transportation that will consequently offers alternatives and flexibility for traveling. The paradigm of multi-modal transportation system is nothing new, indeed the revolutionary change is coming from digitalization of such a transportation mode, which will allow to book and pay with a mobile application. In addition, the new concept is not just going to integrate the existing transport modes, but also offer better offering e.g. higher service level, or lower costs [59]. It is expected that due to cost reduction and future improvements of the service, i.e. autonomous vehicles, it will be possible to provide a solution to disabled passengers' difficulties, which under the current system hardly can be defeated. Again, one key aspect to reach such an ambition

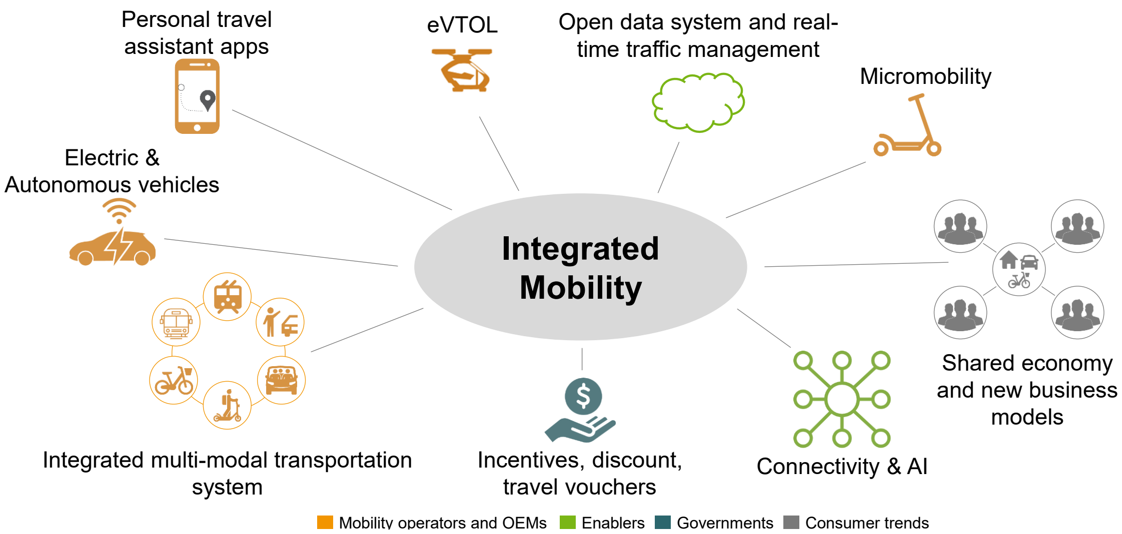


Figure 2.2: Mobility as a Service: the key elements and characterization - graphic by author

is the technology surrounding and supporting the entire ecosystem. In order to provide integrated services, which enhance daily mobility options, real-time data is necessary. Vehicle communication (V2X), is necessary to provide the consumers information about the traffic condition, estimated time of arrival, the location and much more, making the vehicles smart and capable of interacting with the users [60]. Not only traffic information have to be available but also information from other source (consumer locations, weather condition, etc.) must be pushed into this integrated network of data sharing [60]. Flexible and customer specified trip chains require a wise Maas ecosystem. As it is represented in Figure 2.2, MaaS consists of the MaaS provider, data providers, transport operators, customers and technical solutions and infrastructure (e.g. ticketing and payment solutions, journey planners and ICT infrastructure) [61]. The MaaS provider is going to be capable of organize the cooperation between all actors, taking advantage of the mobility data to effectively manage the ecosystem. The digital platform is the basis for all the interactions within the ecosystem' actors [62]. Anyhow, it is not clear yet if the system has to be better controlled by private or public entities, but the majority of the research papers agree that only the joint development and administration can lead to the optimal system, where the public sector provide the necessary infrastructure and regulations, while the private sector can find its opportunity in the new value creation [59, 63]. To ensure that integrated transport services direct user behavior to more sustainable transport modes, public administration need to monitor the planning, pricing and consumer protection of MaaS ecosystem. It should be ensured that the roles, responsibilities and collaboration regarding mobility operators and institutes that are in charge of the whole system are appropriate from mobility services' point of view. If regulation of transport will be updated to meet the operating conditions of MaaS, the service supply is expected to expand considerably. Consequently, the public administration itself could act as an upper level organizer and thus would be responsible for the collaboration of operators or a private company could have the role of the central MaaS operator. Anyway, as public transport is expected to play a key role in the new paradigm, the public transport authorities are key stakeholders as one of the upper level MaaS organizers [59].

2.2 The role of cars in MaaS

As it has been discussed intensively by industry and the research community, Mobility as a Service will be disruptive from many point of views. Disruption describes a process whereby a smaller company with fewer resources is able to successfully challenge established incumbent businesses. Specifically, as incumbents focus on improving their products and services for their most demanding (and usually most profitable) customers, they exceed the needs of some segments and ignore the needs of others [64]. In the disruptive scenario, the new-comers seeking to gain a foothold and delivering more suitable functionality, move upmarket and eventually overcome the traditional players that have earlier overlooked them. For the automotive industry this is now depicted by this revolutionary change represented by MaaS and the related new-players entering this sector. What is expected to happen is related as a direct consequence that is implied by the Mobility as a System paradigm. As it has been discussed in Section 1.2, the personal mobility industry is already facing a major change, related to electrification, shared mobility, autonomous vehicles, and connectivity. Per se, these changes might not have the potential to truly disrupt the transport system, however the combination of these four innovations, i.e. connected shared autonomous electric vehicles (CSAEV), are expected to change the game [65]. Moreover, if this situation is contextualized in a scenario where MaaS is highly adopted, it results in a major challenge for the traditional automotive OEMs. First, the combination of these revolving technologies, and the development of the required component result in a significant investment for the automakers, leading to decreasing or even nonexistent profits. The management consulting firm AlixPartners in its Global Vehicle Outlook 2019 estimated a total spending of $225 billion from 2019 trough 2023 only for the vehicle electrification (i.e. electric powertrain development and battery technology). The same amount is spent roughly in a year at global level for the combined expenditure on capital expenditures (CapEx) and research and development (R&D) [66]. While electric vehicle alone are not expected to affect the annual global sales, autonomous and shared vehicle have to potential to lead to increased travel, vehicle usage, and energy consumption, reducing the number of vehicle on the roads and create a completely new transportation system and business model [65]. Also, vehicle utilization in a shared economy will increase drastically, with researches showing that each shared autonomous vehicle (SAV) replaces up to 11 conventional vehicles [67]. In addition, the combination of these factors with the increased service offered by the MaaS ecosystem will lead to an even stronger decrease in vehicle sales due to the drop of private car ownership. Adoption of these new technologies and the shift to smart mobility is still the issue that keeps such worrisome reports away from the mind of automotive manufacturers but the research community and most of the leading management consulting firms, believe that the time is not too far away in the future. Arbib and Seba predict that the automation of vehicles will make vehicle ownership obsolete mainly based on costs, leading to 70% fewer passenger cars and trucks manufactured each year by 2030 [68]. According to the authors, these sale's drop is mainly led by the lower cost of autonomous vehicle compared to conventional that will outweight the advantages and psychological attachment to the private owned vehicle [68]. However, the cost projections and assumption used by Arbib and Seba [68] are very optimistic, and in this thesis will be presented more realistic assumptions and more factors will be taken into consideration, which can result in a less drastic effect. Nevertheless, with no doubts, the role of car in MaaS will change from the traditional business-model. The fundamental of this new mobility service is the possibility to seamless and reliable mobility without the

need of owning a car, yet not completely eliminating car ownership. In MaaS, it is still unclear who is going to own the cars in the future but certainly someone has to be the owner [69].
Changes in car ownership would probably mean more popular times for car-sharing as offers a similar offer to private cars but without ownership and encourages to

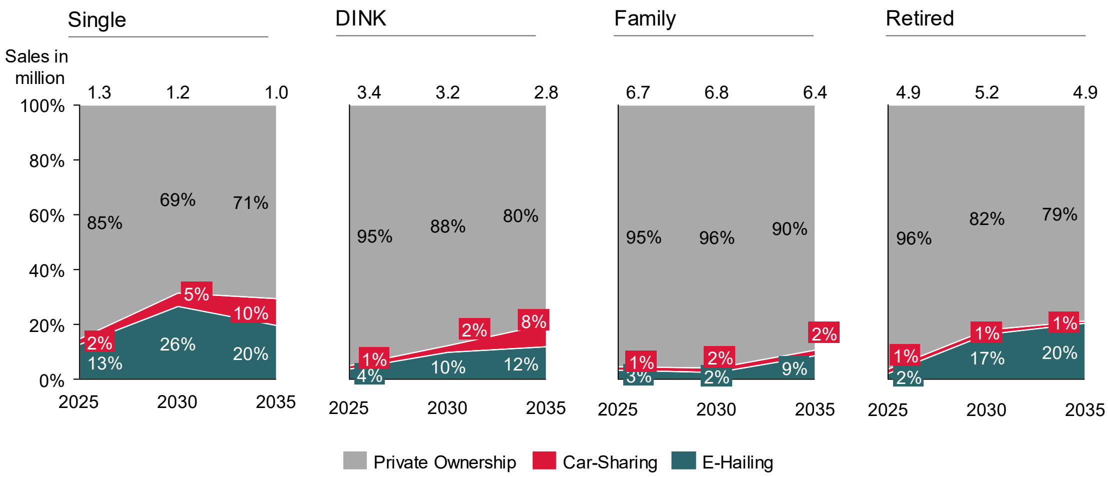


Figure 2.3: FEV sale forecast per mobility solution per household type in USA

try alternative modes. Recently, the traditional station based car-sharing business model has evolved toward a more convenient free-floating service,which enables to pick up a car anywhere within the operation area as long as the car is free, and to drop off the car within the same area. Car-sharing is therefore the preferred transport mode that can replace the traditional car ownership. In case of heavy good to carry, or many children to take with, car-sharing is to be preferred. Ride-hailing, on the other hand, which made its appearance into the market only some years ago could change significantly the role of the car. As point-to-point transportation mode, it will the preferred transport mode by all classes in the society but especially for those who considers cars as a simple transport mode, a commodity. In Figure 2.3 it is represented the internal FEV forecast developed using the dynamic market model (DDM) for the U.S. and considering four household types. The outcome of our model shows that for the market considered, private car ownership will remain strong in all household types, however adoption of new mobility services is expected to increase strongly through 2035. E-hailing will be the preferred mode for retired and single persons, not relying anymore and private cars, and car-sharing will fit better families (double income no kids, in particular) and single persons.

2.3 The role of public transport in MaaS

As it has been presented in the chapter's first section (see Section 2.1), the current public transportation mode has suffered from the introduction of these new mobility solutions, and combined with the increasing use of private car, has resulted in a decrease of the number of passenger trips during the recent decades (see Figure 2.1). The recent technological developments and investments on digitalizing the service made the use of buses and trains easier as electronic payment, web based route planning and real-time information has been introduced. However, it is clear that the conventional public transport needs to adapt to MaaS as the current model in not flexible enough to offer customer-focused mobility and result in increasing adoption [70]. Different studies show that the public transportation system is the backbone of MaaS [71], but in order to be considered at its maximum potential the entire system has to be updated trough a mix of new and existing solutions, and shaped around the emerging societal trends in public and private domains. The adoption of MaaS must sustain the transition from a public transportation system coordinated by the government to a multi-faceted system where exert coordination through the help of other actors [70]. Smith et al. [72] considered three development scenarios, i.e. market-driven development, public-controlled development, and public-private development, where the public transportation system is coordinated by the private sector, the public sector, or jointly by private and public. On a broad scale, they differ upon whether the public or private sectors adopt two new roles in the value chain: MaaS integrators and MaaS operators. The finding, is that all developing scenarios would provide benefits to the end-users and in all upsides and downsides were noticed. The important point according to the author is related to the establishment of the regulatory "sweet sport", which mean that neither too much regulation (that impede the private sector's ability to innovate), nor too little (that might lead to MaaS that does not serve the public sector), has to be developed [72]. A considerable improvement of the system would be in offering a point-to-point service, which could be offered using demand-based system, together with conventional service with timetabled routes. Such flexible public transport mode may lead car drivers drop cars for the more attractive public transportation system [69]. The future of public transport is dependent on how efficiently the traditional system can be integrated to the other modes. Hensed [69] described two scenario that are applicable already in the current system, where the typical bus-service is made more flexible combining it with the point-to-point service type offered by Uber. In the first scenario, the point-to-point transportation is offered combining conventional taxis with public transport at higher cost than the traditional service. In the second, ride-sharing would offer a point-via-point-to-point service which is not much similar to the traditional system, but with the advantage that cars or small-buses could be interchanged depending on demand. It is however still unclear how these solution would affect the system and how the bus contract can be managed in the MaaS paradigm [69]. At it was depicted, the first-/ last-mile problem is one of the main constraints to public transportation adoption. Zeller et al. developed an agent-based approach to model how much can the last-mile problem push drivers to drop their cars and use the established transportation system [73]. In the model, a shuttle bus service, cost incentives, and an infrastructure improvement (as crosswalks and bike-lanes) are implemented and all together resulted in a 40% decrease in driving. This suggests that policies can effectively reduce driving and shift commuters to other forms of transportation [73]. Consequently, public and private transportation have the potential to dramatically improve one another. Public transit hubs offer a steady stream of customers to new mobility service providers, and these service providers can make public transit a more attractive door-to-door experience. But the systems will have to be coordinated in order to be efficient and to make improve traffic and congestion in cities. Cities and transit agencies may need to take more control over how and where services are offered to avoid overloading areas with new services, and to ensure that access is available to all neighborhoods, communities, and travelers.

2.4 The role of bikes and e-scooters in MaaS

It is very uncommon to find literature that considers the role of cycling and scooter rides under the MaaS model [59]. However, bike-sharing and e-scooter or better described under the term “micromobility” is an important part of the paradigm of MaaS. The micromobility sector, has made its appearance into the marketplace only some years ago, but have experienced a rapid rate of investment, funding, and have been launched in several cities across the United States [74]. The two pioneer companies in the e-scooter ecosystem, i.e. Bird and Lime, are worth billions of dollar [75], and in less than a year, more than one million rides have been taken on Bird’s e-scooter [75]. Dockless e-scooter and free-floating bike sharing offer an easy way to tackle the problem of last-/first-mile, with an environmental friendly and fun solution. According to the National Household Travel Survey (NHTS), over 45% of the trips made in the United States are 3 miles or less [76], but, under the current system, 78% of those trips are made by personal vehicles. Hence, on short-distance trips, e-scooters and bike-sharing would provide an alternative to private cars, still ensuring the time competitiveness. Smith et al. [77] evaluated the potential benefit of shared dockless scooters in Chicago, and they find out that scooters can make mobility easier for 16% more people, allowing to reach their jobs within 30 minutes, which will be impossible to those using public transit and walking. Indeed, Americans overwhelmingly support these micromobilty services (70%), although there is a variation across regions, income groups, and other demographics [74]. While further data and analysis are needed to better understand the travel behavior decisions associated with electric scooters, given that they are relatively small devices (i.e. not cars), the question of whether or not they substitute for public transit trips or walking trips is somewhat irrelevant from an environmental or congestion perspective. Yet, there is still the constraint related to where such vehicles should be parked and what should they be considered, to ensure safety, public space utilization, and citizen's acceptability. San Francisco, Santa Monica and New York have already started working with the private sector to collect data and establishing the required regulation. The public sector must anticipate, and identify the boundary between innovation can deliver positive outcomes or generate risks. The main obstacles have been on the overnight launch and massive deployment of these services, which created concerns due to the improperly parked devices, and the use of devices on sidewalks. Thus, integration with local city strategy, agreements, regulatory rules with operational permit and licenses are required. Each city has to develop its singular approach, to maximize advantages and seize the opportunity considering also limitation as age fit, weather conditions, customer adoption and area of deployment. Overall, it is still unclear what the role of micromobility will be in MaaS as we are lacking proper know-how of larger scale MaaS schemes. On one hand, bike-sharing and e-scooter services could increase the amount of public transportation trips as such vehicles can be chosen for only one part of the trip leg and easily accessible by using a smart phone. On the other hand, car-sharing services offer already easy access to automobiles, and ride-sharing services should provide lower cost mobility. Finally, the success of such mobility solution is still dependent on the business model and the cost-convenience trade-off that can be offered the consumers. Analyses from several management consulting firms estimate massive market potential for a micromobility model and assure that it can be the panacea for numerous city problems [78, 79].However, this is strictly dependent upon the private sector being able to monetize the model and cities providing support to ensure its profitability [78].

2.5 The new mobility value chain

Mobility as a Service aims to bridge the gap between public and private transport operators on a city and envisages the integration of the currently fragmented tools a traveller need (planning, booking, access to real time information, payment and ticketing) into a smart shared platform. The disruptive potential of MaaS on the automotive industry has already been discussed, nevertheless it should be pointed out that the disruption will go along with an incredible economic opportunity for those that will be able to adapt to the new business model. The traditional automotive value chain, controlled entirely by only Tier suppliers and OEMs is going to be revolutionized with a complete new layer that will offer the mobility services. This value chain is the result of the consumer shift from a car ownership-centric transportation model to a hybrid model that blends car ownership with mobility services. As it has been presented by Karmargianni et al. [61], the business ecosystem of MaaS consists of several actors, including: i) transport operators (mobility

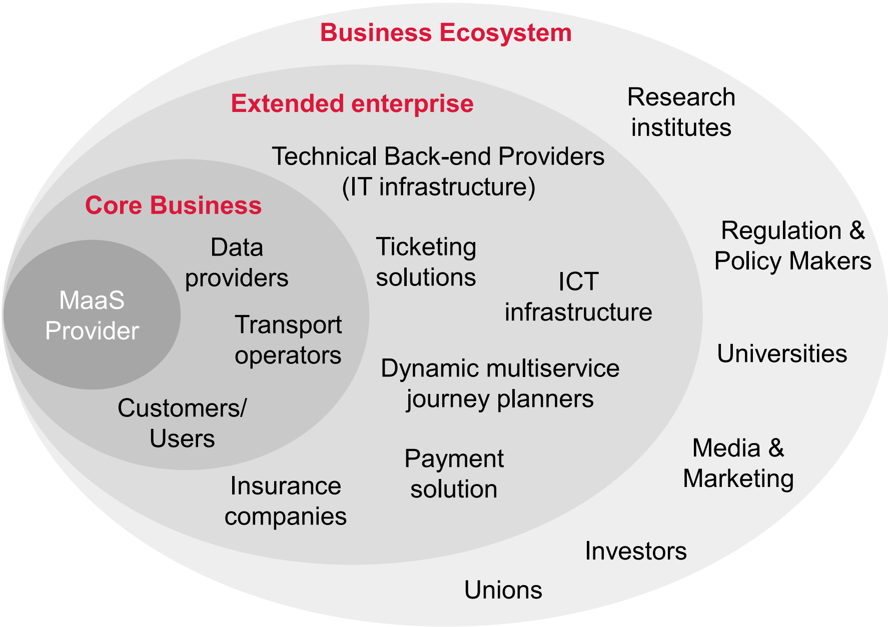
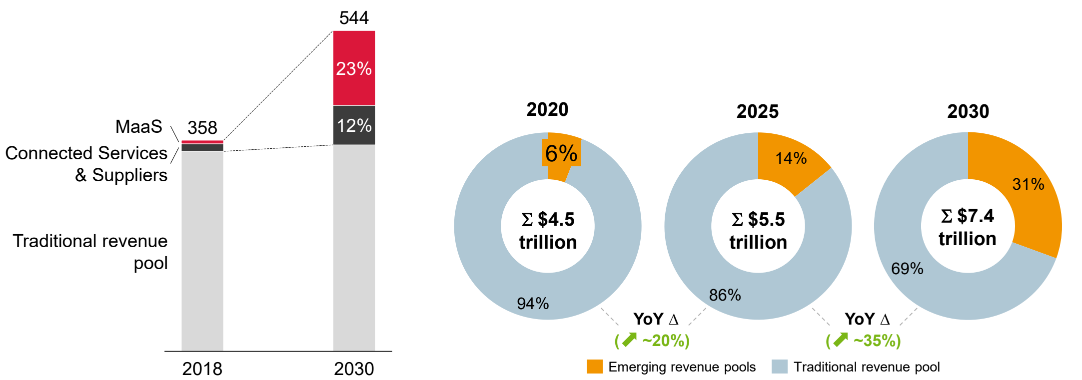


Figure 2.4: The Mobility as a Service Ecosystem [61]

service providers), ii) data providers, iii) technology and platform providers, iv) ICT infrastructure, v) insurance companies, vi) regulatory organizations, vii) universities and research institutions. The MaaS ecosystem is presented in Figure 2.4. For the seek of simplicity, such ecosystem will be broken down in three parts: the core business, the extended enterprise, and the business ecosystem. The core business parties are the transport operators, the data providers and the customers. The next layer, the extended enterprise, widens the view of the business supply chain to include the complementors and second-layer suppliers. In the MaaS ecosystem these are the technical providers (IT infrastructure providers), firms offering ticketing and payment solutions, ICT infrastructure, and insurance companies. The outermost layer, the business ecosystem, adds regulators, unions, universities and other research bodies, investors, and stakeholders to the business ecosystem [61]. Overall, this extended value chain will involve different stakeholders into the development but as well offers opportunities and shared value among all of them. The shared value is normally classified as involving primarily four main actor which are: the private sector, governments, consumers, and transit agencies. In the previous section, the shared value of governments, consumers, and transit agencies have been discussed and evaluated, consequently the added value that will be offered to the private sector is going to be illustrated. The consulting firm Boston Consulting Group (BCG) has nominated it the “MaaS Gold Rush” [80] referring to the revolutionary changes that are attracting investors, enterprises and users. Many and sometimes also improbable actors are trying to take a share of the cake, breaking the monopole of OEM at the top of the no longer existing pyramid. The investment banking and financial services company Goldman Sachs estimated that the only ride-hailing global market will eightfold to $285 billion by 2030 [81] and the opportunity is even higher considering autonomous fleets (up to three times more than the net ride-hailer revenue opportunity). Cities as San Francisco, where the Uber revenues are already more than three times larger than the local taxi market, will grow and lead the ride-hailing market development. The 'pay-you-go' mobility system, will give the opportunity to aggregation services to emerge; the mobility service providers will create the point of contact with the consumer through the app which will integrate the different mobility options. According to the management consulting firm Accenture, by 2030 revenues from mobility services are projected to soar to almost $1.32 trillion [82]. FEV Consulting has developed also an internal analysis, where the global automotive value chain revenue and profit pool are estimated through 2030 (Figure 2.5). According to the analysis, by 2030 it is estimated that Mobility as a Service and new emerging technologies, i.e. software, autonomous driving, and battery technology, will make up the 35% of the total profit generated in the automotive industry (Figure 2.5a). Moreover, the au-



(a) Global automotive industry profit [$ billion]

(b) Global automotive industry revenue [$ trillion]

Figure 2.5: FEV global automotive value chain revenue pools

tomotive revenue pool will significantly increase and diversify towards on-demand mobility services and data-driven services. This could create up to $ 2.9 trillion (or 64 percent more) in additional revenue potential in 2030, compared to $4.5 trillion from traditional car sales and aftermarket products/services. Other drivers for this major change are the growth of the automotive market in the new emerging economies, with complementary aftermarket opportunity. The aftermarket revenue is yet affected by the upcoming electric powered vehicles in all the major automotive markets (China, U.S., and Europe) where approximately 20-30 percent lower maintenance will be required, and even more by the autonomous vehicles, which also will lower the crash occurrence pulling down up to 90% of crash repair revenues. To wrap up, the economic advantage that will result from the new mobility services is staggering and should be in the focus of traditional player, but also new emerging players. The global revenues, as the profit for the automotive industry will strongly be dependent upon how it will be possible and how fast will company adapt to this new demand of mobility. The emergence of new players in the ecosystem will happen very quickly, as it is already been experience for company as Tesla, Uber, Rivian, and VinFast, hence rooted companies should watch them carefully and set up measures before reaching the point of no return.

Chapter 3

The private car cost model

In this chapter, the basic principles of the Total Cost of Ownership (TCO) model with an analysis of the different approach that can be found in the literature will be presented. Subsequently, the cost-model for a private vehicle will be illustrated and detailed, with also definition of the vehicles that were taken into consideration for our cost-analysis. Finally a TCO comparison of two different vehicles, and with different powertrains, will be shown, including a deep-dive on the purchase cost-comparison of vehicle in 2018 and 2030.

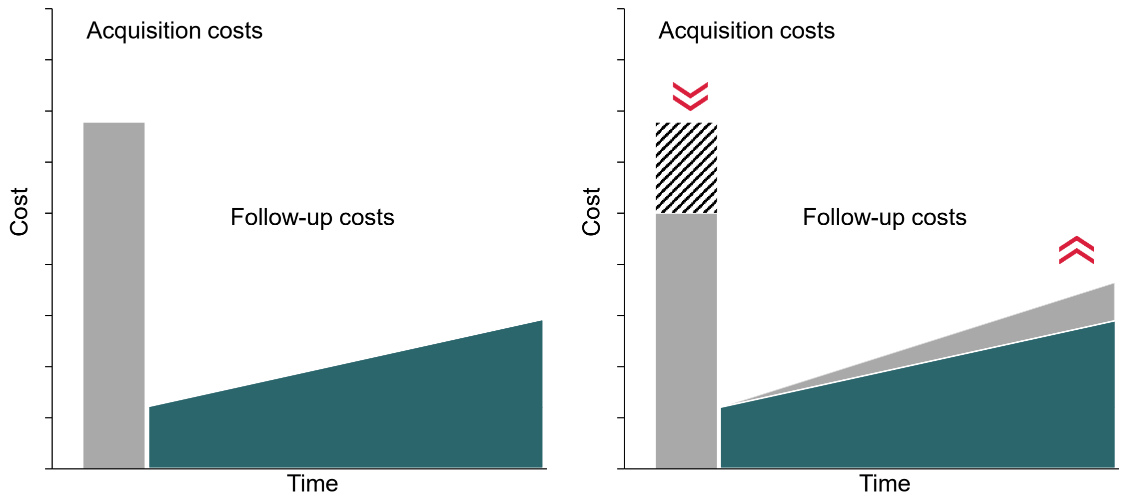
3.1 The TCO model

The Total Cost of Ownership is a concept which was originally intended as the analysis and explanation of the true cost of doing business with a supplier. In this section, the general principle of the TCO-model are going to be presented, with some illustrative methods and the general framework.

3.1.1 Introduction to the TCO-model

The expression "Total Cost of Ownership" appeared in the American literature for the first time in 1929 in the journal "American Railway Engineering Association" [83]. More recently, TCO has become a clear and effective instrument that companies use to asses from a cost-perspective one component over one other, and even justify their choices. Between the years 1990 and 2000, the major use of TCO-model was in business decisions, where the choice for a particular supplier was dependent on the total cost the buyer had to face over the lifetime of a component. Therefore, further investigation started and different literature works were published [84, 85], with the aim of developing a common framework "*to quantify all of the costs related to the purchase of a given quantity of products or services from a given suppliers*"

[84]. Related to the automotive industry, the principle of the TCO-model has become of primary interest to compare the different powertrains options that have been developed (illustrated in Section 1.2) over the last decade, and on base of this result, predict customer preferences and adoption curves. Indeed, the same principle followed for the supplier choice, can be applied in the purchase of a new vehicle, being it for private or commercial usage, offering the customer the opportunity to examine all costs it will face depending on the powertrain type he/she is going to prefer.
The TCO-model addresses the problematic that psychologically affects a substantial fraction of consumers which consider investment and purchase costs of higher relevance than total costs. The logic behind a TCO-model is therefore to present the entire picture related to costs considering that a higher purchase cost, is not related necessarily to higher total costs. Figure 3.1 is the graphical representation of this logic. As it has been represented, the total costs are composed of two parts,



(a) Alternative A (b) Alternative B

Figure 3.1: Problem logic acquisition and follow-up costs

the first one named purchase costs, and a second one named follow-up costs. The TCO-model will allow to take into consideration both parts, to assess which one is going to be most cost-effective option. For instance, although Alternative A (Figure 3.1a) has the highest initial cost and will therefore require the biggest investment, is not sure that it will be the most costly options among the two. Alternative B, indeed, will offer a lower initial costs, but will result in higher costs over its lifetime (Figure 3.1b). Consequently, the objectivity of a TCO-model lies in the fact that within the analysis, the consideration related to both purchase costs and follow-up cost, will be developed and investigated, providing a structured analysis where fixed costs, variable costs and total costs are obtained. However, as was

pointed out, a major part of the cost assessment in a TCO-analysis is based on cost estimations or price forecasts based on literature researches, promoted by industry relevant experts, or estimation based on common understanding. Hence, reliability in a TCO-model is always a major limit that must be kept in mind, and in general is addressed including in the results also different price evolving scenarios [86] or Monte Carlo analyses [87] which provide the reader with a more extended view on the analyzed component and related biases.
In the literature exist several approaches to determine the TCO of a certain component, where the two major ones are the dollar-based and value-based approaches [88].

Dollar-based approach A dollar-based approach focuses on gathering all actual cost data for that compose the TCO of the component under investigation. The dollar-based approach indicates the dollar value ($) of the component and of each of the item that make up the total cost. It is therefore relatively straightforward in its explanation as it is possible to evaluate monetarily how much each parameter contribute to the final result. However, it is not always elementary the determination of all dollar-values for components and especially, it is sometime trivial to take into consideration the full-fledged range of items. In general, the price allocation are based on the effort or resources needed to carry out a certain activity. Such activities will then be included in the TCO analysis and, particularly in a repetitive model, will simplify and speed-up the entire process, as they will simply be summed up every time the activity is planned to be done over the component lifetime. The above explained approach is often referred also as activity-based costing, which means that for each level of activity, a cost allocation will be attributed.

Value-based approaches The value-based approach combines cost/dollar data with other performance data that are often difficult to “dollarize”. The advantage but at same time the disadvantage consists in the fact that qualitative and quantitative data will be pulled together, making the result more precise but more complex to assess. This process is often considered very time consuming, as requires very lengthy explanations of each cost category. Moreover, the total cost derived following the value-based approach is not directly traceable to dollar spent, and does not allow consequently to make any cost-related forecasting. However, the assessment of supplier’s performances with scores instead of dollars gives the organizations a more clear representation of upsides and downsides and reflects more the various performance discrepancies for the analyzed component. In such a way, “weighting” of cost factors, which are in general corresponding to the companies priorities, can be changed without the need of a new model. In general, the value-based is a more complex yet complete approach to evaluate TCO of a component, which requires a great iterative process of fine tuning of the weights and point allocation, but offers also an easy and precise tool to use for repetitive decisions.

3.1.2 TCO framework

During the determination of which cost elements are critical for the decision of a particular supplier, the firm should always look for the significant cost items associated with pre-transaction, transaction, and post-transaction flows [89]. The first, refers to all cost that are related with investigating and qualifying sources, or adding a new supplier to the firm's system. Then, the transaction costs are the true cost of the purchase, including delivery, inspection, and a variety of other costs. The third, the post-transaction element, includes the line fallout, the eventual rework of parts if defective, and the associated costs (as return, warranty, etc.) [85]. One effective method to evaluate all these costs presented, is actually the TCO-model, hence a well-structured framework for its development and implementation is necessary. The TCO framework that is going to be illustrated was developed by Ellram in 1993, in its journal publications "*A Framework for Total Cost of Ownership*" [85] and was developed on the basis of seven firms with successful TCO approaches. As illustrated in Figure 3.2, the process includes eight stages which can be divided in two macro-groups: the preparation phase and the core phase. In

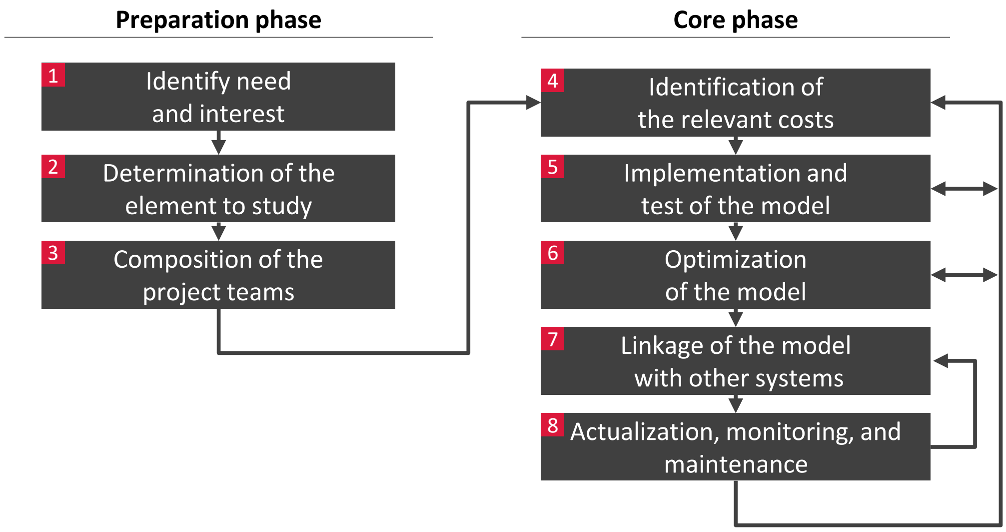


Figure 3.2: Framework for Total Cost of Ownership model development [85]

the first stage it must therefore be identified the reason why it is needed to develop a TCO-model. According to the author, the cause can be internal or external. For instance, during the research came out that some companies have actually develop TCO-models, to figure out cost related issue, while some others, saw TCO as a way to help ensure that the customers, whether internal users of final consumers, get the most of their money [85]. In other world, the driver that pools companies to start developing a TCO can vary greatly, but the common thread should be the need to understand the true costs, not just the price, behind a given purchase. During the second stage, the item of interest should be determined. The item can be one defined during the first step, or one that is relatively important to the firm in terms of dollar purchases. This step is very critical, and if not managed with care, will result in merely time and resource wasting. Indeed, it is sometimes defined a team responsible for the investigation and decision of the item to analyze. Step three involves the formation of a TCO development team. The advantage related to use a team in TCO modeling is in the expertise of the people involved, which positively affects the final results. The team should be led by a leader, and should include people from different departments and with different functions. In the forth stage the real model development begins. In this stage, several step are included. First, relevant costs must be identified. Second, the team determined which of these costs are important . Third, the team identifies which cost are available or have to be determined. Forth, data sources are documented for future reference. Stage five involves the test and implementation of the model build. By this time, all data have been gathered and the team is ready to test, discuss, and verify if the scope has been reached. This stage is iterative, therefore, if any important elements were left out, they must return to the previous stage. In addition, it must be clear which are value calculated, real-data, or educated guess, and in case any of the elements included are inappropriate, these elements should be removed. During stage six, the fine tune of the model will incorporate analysis of the results, identification of the TCO scope, and incorporation of changes. The team must sit down again and analyze the results of the TCO model. The model must be stress-tested during this stage and sensitivity analysis can help make the model more robust. As soon as the team is comfortable with the results, the model is ready to use for decision making. Stage seven is the link of the TCO model to other system. There are normally three types of systems that a firm should consider linking with TCO modeling: firm's supplier system monitoring, firm's education and training system, and the firm's computer systems. This stage should be for obvious reasons automated, and can increase the value of the TCO as will make available data into other systems that can use and take advantage from it. However, the effectiveness of the TCO-model can be ensured only with efficient updates, monitor, and maintenance. A resident expert should be the "owner" of the overall system and should be provided with concerns and suggestions by the users, and update the system accordingly.

Cost component definition As illustrated earlier in this section, the cost determination is a fundamental step during the screening of the possible suppliers. The transaction sequence presented initially, made up of *pre-transaction*, *transaction*, and *post-transaction*, offers a systematic approach for its definition. Costs are, according to Ellram classification [89], ordered chronologically and though a simple three steps approach. This simple chronological model can also be used in the TCO-model for vehicles and powertrains. In this case, the majority of costs will fall under the the transaction and post-transaction phase, however, in a much

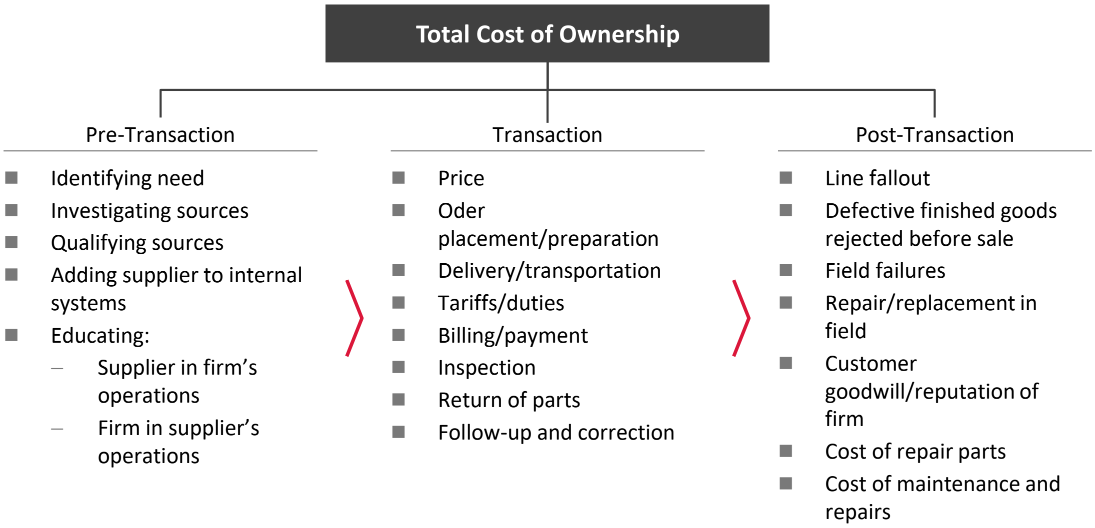


Figure 3.3: Major categories for the components of total cost of ownership [89]

broader context, the pre-transaction costs can be, for instance, the costs related to the infrastructure development (charging station, fuel station, parking), the establishment of the required dealers, and service points. The MaaS cost-model, as will be presented in the next chapter, is also following a similar framework, where the necessary platform development, the cost investment, and many more other parameters are contributing to the final cost of the transport mode.

3.1.3 Vehicle TCO: perspective from literature

As presented in Section 1.2, the need to curb CO_2 emission in the transportation sector has become in the recent years a major challenge for both industry and regulators. Therefore, new solutions regarding powertrain technology have been developed and its adoption is expected to surge rapidly through 2020s. Consequently, with the intention to increase transparency related to these new technologies and present an economic assessment for future adopters, the TCO-model has become a common topic in the automotive literature. The TCO-model is an useful tool to compare from an economic point-of-view the costs related to the conventional ICE, opposed to the one of electrified powertrains. HEVs, BEVs, and FCEVs are all an important pathway for de-carbonizing transportation and reducing petroleum dependence but, one barrier to adoption is still the higher purchase price associated with these technologies. Consequently, the TCO-model, outline the sometimes not considered implication related to lower fuel consumption, less maintenance, and in general lower variable costs, which can make EVs more economically advantageous over time than conventional powered vehicles. Consumers tend to underestimate long-term savings [90], as they are perceived of second importance compared to the purchase cost, therefore a consumer education is often seen as a low-cost tool for encouraging EVs adoption. Fuel cost savings, in particular, can go directly to the mind of consumers and are then emphasized by educational websites and cost calculators form governments, utilities, environmental groups, automakers, and universities. The literature, on the other hand, aims to develop cost-estimations and cost-models, arise observations and critics depending on the geopolitical situation, remarks on the future cost extrapolation, take into consideration different vehicle classes, powertrains, use cases, and techno-economic/economic parameters. Wu et al. [87], for instance, carried out a total cost of ownership comparison of electric vehicles and conventional vehicles using a probabilistic analysis and a projection across different markets. Using Monte Carlo simulations, they identified both the lowest TCO/km and the inputs parameter with the highest effect on the TCO/km, showing the strong dependence of EVs on the annual distance traveled and the vehicle class. Among the results presented, the authors point out the potential influence and thus the importance of policies, suggesting three measures that would make EVs more appealing. The underlying principle, according to the author, is the uncertainty proved by the probabilistic results, which do not exhibit a clear cost-efficiency among technologies. Therefore, the first recommendation imply involving customers and educate them about the TCO fitting to their respective vehicle preference and driving distance. In addition, governments should support the shift toward smaller vehicles, which are expected to be more suitable as an electrified version. Second, they address the issue related to “range anxiety” building the required infrastructure. Third, promote grants and bring investors willing to contribute to the technological development of electric components is of crucial importance to lead to mass adoption. Furthermore, the authors recommend for future researches in the field of EV, to include probabilistic parameters in techno-economic analyses and emphasize on vehicle classes and use cases, as the result are highly sensitive to these parameters. A more comprehensive EV TCO forecasting was developed by van Velzen et al. [111] where a framework of thirty-four (34) factors that affect the future TCO of EVs was used. In the TCO, they have been used parameters collected through an analysis of the existing literature and a total of seventeen (17) interviews. The interviews were used to validate the data from the literature analysis and to verify whether all information were taken into account. In the results, the authors show a list the of thirty-four (34) factors that may directly or indirectly influence the total cost of ownership of EVs. This means that the development cost of EV for the next decades is not a simple cost calculation, where manufacturing cost and experience curve can be used. Many qualitative factors, reinforcing cycles, will play a role as well and hopefully tip the balance to a more mature market for EVs. Moreover, the authors brought the attention on one consideration that is characterizing the current automotive industry and it is

Table 3.1: Literature overview of different vehicle TCO

#	Year	Author	Model type	Powertrain types	Future extrapolation	Government incentive	Component costs	Battery replacement	Battery residual value	USA specific
1	2019	Moon et al. [91]	Mainly economic	ICEV, BEV	✓	✓	✓	-	-	-
2	2006	Delucchi et al. [92]	Techno-economic	ICEV, HEV, BEV	-	-	✓	✓	-	✓
3	2016	Bubeck et al. [93]	Mainly economic	ICEV, HEV, BEV, FCEV	✓	-	✓	✓	✓	-
4	2017	Levay et al. [94]	Mainly economic	ICEV, HEV, BEV	-	✓	-	-	-	-
5	2016	Hagman et al. [95]	Mainly economic	ICEV, HEV, BEV	-	✓	-	-	-	-
6	2017	Mitropuolos et al. [96]	Mainly economic	ICEV, HEV, BEV	-	-	-	-	-	✓
7	2013	Al-Alawi et al. [97]	Techno-economic	ICEV, HEV	✓	-	✓	-	-	✓
8	2018	Breetz et al. [98]	Mainly economic	ICEV, HEV, BEV	-	✓	-	✓	✓	✓
9	2018	Danielis et at. [99]	Mainly economic	ICEV, HEV, BEV	✓	✓	-	-	-	-
10	2014	Hou et al. [100]	Techno-economic	HEV	-	✓	✓	✓	✓	-
11	2013	Lebeau et al. [101]	Mainly economic	ICEV, HEV, BEV	-	-	-	✓	✓	-
12	2015	Coffman et al. [102]	Mainly economic	ICEV, HEV, BEV	-	✓	-	✓	-	✓
13	2017	He et al. [103]	Mainly economic	BEV	-	-	-	-	-	-
14	2015	Gnann et al. [104]	Techno-economic	ICEV, HEV, BEV	✓	-	✓	-	-	-
15	2017	Letmathe et al. [105]	Techno-economic	ICEV, BEV	-	✓	-	✓	✓	-
16	2014	Le Duigou et al. [106]	Techno-economic	ICEV, HEV, BEV, FCEV	✓	✓	✓	-	-	-
17	2013	Gilomore et al. [107]	Mainly economic	ICEV, HEV, BEV	-	-	-	-	-	✓
18	2018	De Clerk et al. [108]	Mainly economic	ICEV, HEV, BEV	-	-	-	-	-	-
19	2015	Rousseau et al. [109]	Techno-economic	ICEV, HEV, BEV	-	-	✓	✓	-	✓
20	2019	Carley et al. [110]	Mainly economic	ICEV, HEV	-	✓	-	-	-	✓
	Sum				**6**	**10**	**8**	**8**	**5**	**8**

specific for this period: the authors identified the profit margin as a new direct factor influencing current and future TCO for EVs, that was not incorporated in previous frameworks. According to their estimation, due to the massive investments that OEMs are facing at current times and will have to face also in the next years for the technological shift to CSAEVs, at some point in the future they will want to recoup their funding. In the paper it is showed that even in a future scenario with high scale and learning effects, which lead to a decline in EV production cost , does not necessarily result in lower BEV retail price. One additional section was then dedicated to government recommendation, as deemed to be crucial in the development of EVs, especially by kick-starting the adoption rate (presenting the exemplary cases of China and California).
Table 3.1 presents the literature research that has been carried out as a stating point for the vehicle TCO developed in this thesis. The papers were classified based on the following selected features:

- Model type
- The powertrain types included in the TCO-model
- Future extrapolation of the component costs based on experience curve or technical papers
- Government incentives and subsidies for the vehicle purchase
- Direct manufacturing component costs
- Battery replacement over the vehicle lifetime
- Battery residual value separated to the vehicle residual value
- Specific market investigated by the authors

In total, twenty (20) peer-review papers and reports were consulted, including among them mainly economic and techno-economic models. It is considered a “mainly economic” model if primary economic aspect of the vehicle are considered. On the contrary, a “techno-economic” model considers technical aspects as affecting the economic model of the vehicle. During our research it was clear, that the majority of the papers available followed an economic model. Only seven (7) of them, were considering the technical specifications of the vehicle assessed while evaluating its costs. This literature research focus was on evaluating available vehicle TCO capable of highlight the economic advantages of electrified vehicles compared to the traditional ICE powered options. Although this thesis will include only BEVs and HEVs, it is worth pointing out that the papers found showed that both current but older authors as well, put a stronger focus on comparing HEVs and BEVs than FCEVs. At current stage, although the development of fuel-cell technologies has been investigated since several years and some OEMs have even considered launching some of these vehicles, their application is still predicted to be be only for niches and rare applications with only marginal adoption [112]. Six (6) papers have presented cost extrapolations for EVs and expected evolving scenarios. Cost extrapolation are always difficult to find in literature, as reliable sources for

techno-economic information cannot easily be found. In this thesis a cost assessment will be proposed for electric vehicles based on internal (FEV Consulting cost estimation based on expert interviews), as well as external estimation, where the powertrain component costs in 2018 and 2030 are presented. The consideration on whether offer subsidy and incentives for EV purchase was treated in ten (10) papers, presenting the different remarks and recommendations. The determination of the vehicle purchase costs starting from the direct manufacturing cost of the powertrain component was proposed by eight (8) reviewed papers and some of them were considering also the battery replacement over the vehicle lifetime. Indeed, eight (8) of the analyzed peer-review documented was considering the technological limitations of the battery and the eventual cost of replacing it during the lifetime of the vehicle. One more consideration regarding the vehicle's battery was on separating the residual value of the vehicle to the battery residual value. It is still not completely clarified how this will be handled in the future, as battery recycling and a battery second-life value chain is not established yet. Inevitably, only five (5) authors considered in their model the this feature, which might strongly affect the result. Last, in our research we included papers that were both from the U.S. and not, were the different fuel prices, taxes, and government incentives were showing varying results.
As it was presented, in the literature different approaches and parameters are considered, but the general understanding of a vehicle TCO is common among all. As will be illustrated in more details in the following section (Section 3.2), in general terms a vehicle TCO is dependent on two groups of costs, called fixed costs and

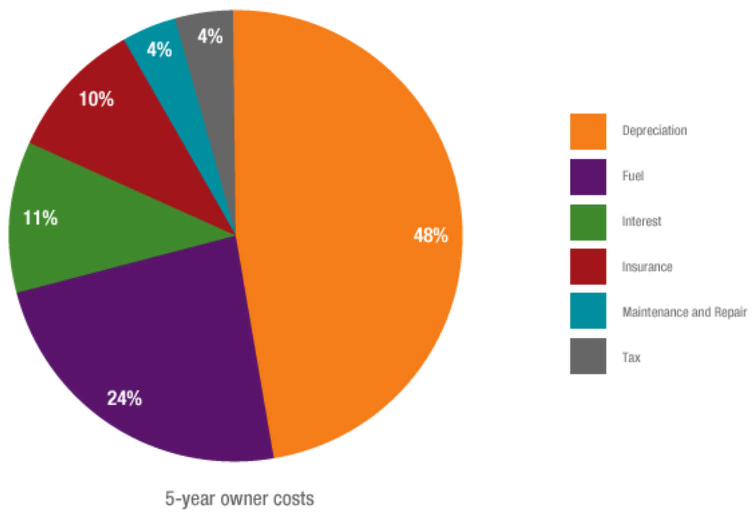


Figure 3.4: TCO for a typical newly bought vehicle in the US [113]

variable costs. The broad definition says that fixed costs are costs occurring only once over the vehicle lifetime, whereas the variable costs (which are also defined recurring costs) are dependent on the users and the usage of the vehicle. Figure 3.4 indicates the relative size of each cost factor for the average new vehicle in the US over a 5-year ownership and have been added for illustrational purposes. The categories that are showed in the illustration (Figure 3.4) are the most common in the literature and also in this thesis will be presented following the same categorization. However, is shall be noticed that in the pie chart the fixed costs (i.e. depreciation) count for approximately the 50% of the total costs, which is not the case of all TCOs. For this reason, a vehicle TCO interpretation must be always evaluated singularly, as very unlikely general conclusions can be drawn.

3.2 The private car cost model

Having explained the importance and basic principles of a TCO-model and presented some examples related to vehicle TCO, in the following the private car cost model will be illustrated and analyzed. The entire model is based on the assumption that, even though different powertrains will be mounted inside the vehicles, the other parameters will remain the same. Therefore, what affects the cost of the vehicle and the purchase price that the customers have to face, is only dependent on the components and the direct manufacturing costs (DMC) of these lasts. In this section, after a brief introduction of the methodology of the model, the underlying assumptions and relevant component costs will be explained. Finally, a critical discussion related to biases of those assumption is provided where also a comparison of component costs between 2018 and 2030 will take us to the conclusions.

As was illustrated in Figure 3.3, the vehicle TCO follows in general a chronological approach where the total cost of ownership can also be represented by the pre-transaction, transaction, and post-transaction costs. However, we have presented at the end of previous section (see Section 3.1.3) that a total cost of ownership framework normally tries to compute the fixed cost and the variable cost that a consumer faces over the lifetime of a vehicle. In this thesis, such structure will be used as it is also the preferred in the literature we considered [87, 92, 111]. Figure 3.5 is the representation of the structure of the TCO used within this work and it will be illustrated with more details along this section. As represented, the total cost of ownership structure used in this thesis involves computing the costs of three main macro-groups: *the vehicle price*, *the operational costs*, and *the resell value*. Within each macro-group, the costs will add up considering for the vehicle price the cost of powertrain components and the glider, for the operational costs the fixed and variable costs, for the resell value the residual value of glider, battery and powertrain. For the vehicle price, we have considered different vehicle classes, represented by exemplary vehicles, where the costs of the glider will be constant, as well as the cost of all the components that constitute it. Nonetheless, the differentiation will be created by powertrains and the attributed costs of the main components that

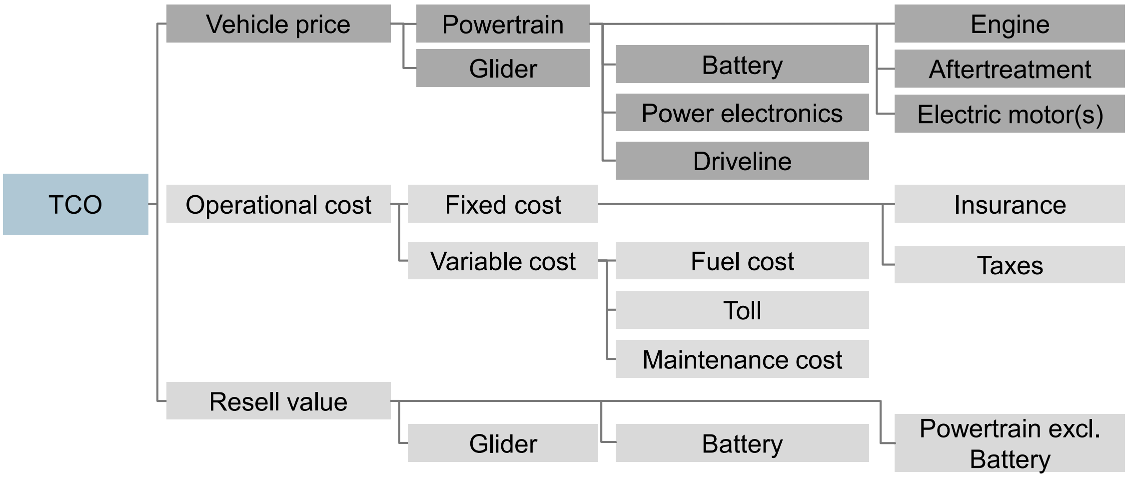


Figure 3.5: Structure of the total cost of ownership of a private vehicle

characterize it. For the electric powertrain, we have estimated direct manufacturing costs for battery, power electronic, and electric motor, while for the combustion engine, we have estimated the DMC for the engine, the aftertreatment system, and the driveline. For what concern the operational costs, among the fixed costs we included the insurance and the annual/sale taxes. Instead, the variable costs are maintenance costs (i.e. tire change, repairs, maintenance, cleaning), toll costs (i.e. parking and road tickets), as well as the fuel cost, which will be gasoline for ICE and electricity for electrified powertrains.

3.2.1 Definition of the exemplary vehicles

This vehicle TCO has the intention to be the most possible representative of the cost that a city's citizen living in a U.S. city, in downtown, would have to face using his vehicle on a daily basis for his personal needs. Therefore, two reference vehicles were taken into consideration as supposed to be the most representative of the customer choice herein detailed. Furthermore, to provide also a more transparent view about this topic to the reader, the vehicle analyzed in this thesis can be reconnected to true real world automobiles that at current times are sold in the North American market with the powertrains under investigation. Consequently, the choice fell on one compact city-car and one medium sedan.

The compact city-car exemplary vehicle Among the passenger cars, the compact city-car is generally classified in the Class A/B segment [114]. This classification was introduced by the European Commission and is the most widely accepted denomination for passenger vehicles. In 2019, due to the introduction of new road vehicles as for instance mopeds and electric scooters, the European Union amended this classification using a slightly different nomenclature. Among the new classification of motor vehicles, therefore, the category M1 refers now to the class of vehicle that are designed and constructed for the carriage of passengers, which comprise no more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 3.5 tons. In Figure 3.6 and exemplary passenger vehicle of this category is showed.

In the TCO model, the vehicle specifications were defined to assess the cost of each component in two different powertrains, i.e. ICE and BEV, where for the latter, two battery sizes are considered. Considering two battery sizes, allows the

Figure 3.6: Exemplary compact city-car [115]

reader to compare a cheaper option, to an option suitable also for longer distances. This latter configuration can be, indeed, better suited for customers that decide to buy a vehicles not only for the daily commute to work, but that are also looking for higher flexibility and more freedom. In fact, the strategy to offer full-electric vehicles with different battery sizes is already adopted by many OEMs, to better tailor to the needs of customers [116] and address the so called "range anxiety". As a matter of fact, different literature papers have found that adoption of BEVs has been so far limited, as user's psychology is fighting back the range limitation associated with full-electric vehicles. Conventional ICE vehicle accustomed consumers to ranges, but especially fueling times, that will hardly be achievable by BEVs. Therefore the question is now how manufacturers will be able to offer a similar experience to the users, or otherwise, how the users will be keen to accept this trade-off. In this thesis, no information related to the adoption will be provided, as the TCO-model considers only costs of a specific vehicle with defined specification. What will be included however, is the consequence that a battery choice lead from a cost perspective. In particular, general questions can be on what is cost of a battery replacement, how is it affected by the charging behavior, the number of charging cycle per day and where charging of electric vehicles will occur.

The specifications of the vehicle are included in Table 3.2. This specifications are

	Unit	**Value**
ICE		
Displacement	L	1.5
Power	kW	70
Aspiration		Naturally aspirated
Primary energy carrier		Gasoline
Efficiency improvement in 2030		Cylinder deactivation, lightweight, Miller Cycle
Transmission		
Type		6-AT
Electric powertrain		
Power	kW	Small battery: 50 Large battery: 70
Battery size	kWh	Small battery: 24 Large battery: 41
Full electric range	miles	Small battery: 80 Large battery: 150
Lifetime - cycles	#	2,500
Lifetime - distance	miles	150,000

Table 3.2: The vehicle specifications

the inputs used for the assessment of the costs component. In the line *efficiency improvement 2030*, the technology that will be implemented in 2030 are listed, which will result in a cost increase for the ICE powertrain. Moreover, indication on the battery lifetime are also part of the specification. For the future estimation, we assumed that the technical specification of power for the engine/motor and the energy included in the battery will be kept constant, i.e they will not change over time as further improvement on the vehicle's performances are not fundamentally necessary. On the other hand, the technological improvement will be made on the efficiencies and the costs of the components, as will be better explained in the next sections. As it is possible to see, the lifetime of the battery in the electric powertrain is considered a relevant technical specification in the TCO-model, and therefore included in the table above (see Table 3.2). The lifetime cycles, or distance are the parameters that determine if the battery has to be replaced during the vehicle's lifetime or not. This point is stressed, as we presented in our literature research section (see Table 3.1), by several authors in this field. The battery replacement, the battery second-life, and eventually the battery recycling are hard topic that still have to be clarified by the industry and a complete new value chain has to be developed to solve this issue. The important aspect worth to mention, is how the battery replacement affects the final result of the TCO and can change entirely the outcome of the analysis. The battery manufacturing cost is, at current times, the most costly element of the entire system counting for up to 60-70% of the total lifetime cost. If the battery does not last for the entire vehicle lifetime, its replacement will result in a burden that hardly can be compensate by only the minor operational costs, making electric vehicles strongly cost inefficient. Manufacturers, research and governments, are working to solve this very uncomfortable issue, and great progresses have been made already. Some promising technology that will increase battery lifetime are being tested and according to many developers, is not anymore a matter of if but only of when. The U.S. Government announced that will grant $ 2 million to General Motors for the development of solid-state lithium batteries [117]. Toyota, the world's second larger auto manufacturer, considers solid-state lithium battery a game changing technology and believes that they can be introduced as early as 2020, which would be two years earlier than they originally planned [118]. Many others, of which also cell supplier Samsung SDI, are investigating also other ways to increase battery lifetime. Therefore, the aspect related to battery replacement has to be discussed and its importance must be underlined.

The medium sedan exemplary vehicle According to the European classification, medium sedans are normally part of the Class D segment [114]. This is the second vehicle segment that will be presented in this thesis. The importance of this segment is linked to its relevance in the North American market. Indeed, the mid-size sedan is often described in North America as the typical "large family car" including a wide range of prices and specifications. In Figure 3.7, an exemplary vehicle from the manufacturer Toyota is illustrated.
Mid-size sedan are not only one of the preferred vehicle's class among consumers, but are in general also a valid option for all shared and rented cars for most of the private companies in this space. As will be explained with further details in the section related to the ride hailing and car sharing cost model, the mid-size sedan is going to be the reference vehicle used for the cost estimation computation.

In Table 3.3 the technical specifications of the reference vehicle are presented. A turbo-charged gasoline engine is in general the baseline engine used for this vehicle's segment. However, in this case we have decided to considered an upper mid-class engine, as the typical entry level version is less likely adopted in the U.S. market. The same type of transmission has been considered, as in the compact city-car and no improvements are expected for these vehicle classes. The future evolution of this powertrain has been discussed within the FEV expert [120] network, and more technically advanced efficiency improvements have been considered. Engine downsizing, dynamic cylinder deactivation, e-boost, and lightweight measures are

Table 3.3: The vehicle specifications

	Unit	Value
ICE		
Displacement	L	2.0
Power	kW	170
Aspiration		Turbo-charged
Primary energy carrier		Gasoline
Efficiency improvement in 2030		Downsizing, dynamic cylinder deactivation, e-boost, lightweight
Transmission		
Type		6-AT
Electric powertrain		
Power	kW	Small battery: 150 Large battery: 150
Battery size	kWh	Small battery: 38.3 Large battery: 64
Full electric range	miles	Small battery: 125 Large battery: 230
Lifetime - cycles	#	2,500
Lifetime - distance	miles	150,000

Figure 3.7: Exemplary medium sedan [119]

expected to be included in the future to meet the always more stringent emission regulations. Also the ICCT agrees on these measure [121], where they estimated that by 2025 still 90% of U.S. light duty vehicles can avoid electrification thanks to advances on the combustion engine. However, these technology improvements will lead, as in the case of compact city-car, to an incremental price increase. In the same report, ICCT has assumed that to achieve the 2025 and 2030 emission CO_2 emission standards, an incremental price increase of approximately 4-6% must be expected. ICCT also points out that the efficiency improvement cost estimations presented in the paper, will be hardly dependent on the supplier and engineering technology developments, and consequently cost might widely differ from the estimated ones [121]. Overall, a key point of the ICCT white paper is the possibility of achieving tighter emission standards through 2025 with only combustion improvements, although greater electrification with hybrids and eventually plug-in electric vehicles is very in the 2030 time frame. Regarding the electric powertrain, it can be noticed that the battery size is substantially increased, principally to allow for a longer full-electric range. With this class of vehicle, range is a key technical aspect that will affect the customer decision, as you have to expect that this vehicle will have to meet several customer needs in terms of driving range and power demand. As it has been explained in the compact city-car paragraph, the battery lifetime has been considered also in for this vehicle class an important technical parameter, and significantly affecting the vehicle TCO.

3.2.2 The vehicle purchase price

As was introduced in Section 3.2, in this model the purchase price of a the vehicle under investigation will be defined by the DMC of the components that constitutes it. However, the DMC are only a fraction of the real vehicle cost that the customer have to face. Indeed, vehicle manufacturers typically show prices as made up of two broad categories: the direct manufacturing costs, and the indirect costs. Direct manufacturing costs include manufacturing labor and direct material costs, which can be estimated via reverse engineering or other approaches. Indirect costs include research and development, corporate operations, dealer support, and marketing and are difficult to estimate. Because of the difficulties of estimating indirect costs associated with new technologies, the automotive industry has often applied scaling factors to changes in estimated direct costs to capture changes in indirect costs and, hence, predict the full impact vehicle modifications will have on the final selling price. A commonly used scaling factor is the retail price equivalent (RPE) multiplier, which is historically based and compares direct manufacturing costs with all other factors that influence the final price of a vehicle. Conceptually, RPE multipliers provide the relative shares of DMC and all other items tha affect the business of auto manufacturing. According to U.S. Environmental Protection Agency [122]:

$$RPE = (\text{direct + indirect costs + profits})/(\text{direct manufacturing costs})$$

Within this work, it will be used an RPE multiplier suggested by FEV experts [120] where a factor of 1.2 is attributed to the assembly cost and a factor of 1.4 is attributed to all indirect costs including transportation, marketing, R&D, depreciation and amortization, overhead costs, and profit of both OEM and dealers. A RPE factor of 1.6 is also in-line with the literature, as we found during our literature research [111], even though some have considered bigger factors. As we have presented in 3.1.3 Van Velzen et al. [111], pointed out that this factor is expected to increase with EVs adoption, as the manufacturers will want to recoup their investments. Nevertheless, from our perspective we have estimated the factor to be constant, as the return of investment will be possible thank to the more favorable economy of scale and the lower assembly cost of the electric powertrain compared to the conventional ICE.
At this point is possible to define the vehicle purchase price 3.1:

$$C_{Vehicle} = (C^{Base} + C^{Powertrain}) * RPE \tag{3.1}$$

Where C^{Base} is the glider cost and $C^{Powertrain}$ is the powertrain cost, and their sum constitutes the component costs, as explained in the following paragraph.

The component costs The component costs are the underlying input parameters used to define the purchase price of the two vehicles investigated. The purchase cost of the vehicle have been assumed as made up of two parts: the glider and the powertrain. The glider is the part including all the structural components (i.e. the body frame, the suspensions, the interiors, accessories, etc.) and it will be shared and exactly the same in the ICE and BEV versions. The powertrain, therefore, is what differentiate the purchase price of the vehicle and is defined by the DMC of the components that constitute it. In particular, for the ICE powertrain we have assumed DMC costs for the engine, the transmission, the efficiency improvement component, and the aftertreatment system, whereas for the full-electric powertrain we have estimated costs for the electric motor, the power electronics (including harnesses), the thermal management system, and the battery.
The computation of the battery cost C^{Bat} follows Equation 3.2 and uses as factor the specific battery price (k^{Bat}) and the nominal battery energy (E_{Bat}).

$$C^{Bat} = k^{Bat} * E_{Bat} \tag{3.2}$$

In this model Li-ion high capacity battery technology are considered and the assumption that the battery module costs and singular component, as for instance the BMS, scale up with battery capacity is accepted. As used in different literature papers [123], these components constitutes only a minor part of the DMC and therefore will be considered not affecting the cost-model.
The glider cost is computed as dependent from the weight of the vehicle as the linear relation between material used and cost is widely accepted [124]. In addition,

as we introduced in Section 3.2, the glider cost will be constant for the two different powertrains, as it generally includes the same components. From a different perspective, we can then consider the DMC glider cost C^{Base} of the two reference vehicles as difference between the vehicle cost and ICE powertrain components. Consequently:

$$C^{Base} = C^{Veh}_{ICE} - C^{EATS} - C^{Engine} - C^{Transmission} \tag{3.3}$$

However, lightweight measures, which are not going to result in cost reductions for the glider, have to be considered. Indeed, assuming a conventional steel unibody as the baseline vehicle body-in-white, lightweight material options, such as ultralight steel, aluminum, and carbon fiber composites will be used to obtain glider mass weight reduction up to 30%. Such measures needed to achieve higher fuel efficiencies will lead to a cost increase in order of 10% for the DMC of the glider as assumed in this thesis.
Finally, the cost of the BEV is then defined according to equation 3.4

$$C^{Veh}_{BEV} = C^{Base} + C^{Bat} + C^{EM} + C^{PE} + C^{TM} \tag{3.4}$$

Where the cost of electric motor (C^{EM}), the power electronics (C^{PE}), and the thermal management (C^{TM}) have been estimated with FEV experts [120] and validated with peer-reviewed papers and industry relevant white-papers [125, 126].

3.2.3 The operational costs

As represented in Figure 3.5, the operational costs are composed of two parts: the fixed costs and the variable costs. The first one, represent all costs that are related with the ownership of the vehicle as, for instance insurance and taxes, while variable costs are depending on the usage of the vehicle. The fixed costs used within this thesis are the national average costs provided by the American Automobile Association [127]. This costs have then been adapted to match with the Michigan yearly license, registration, and taxes provided by the Secretary of State. The variable costs are computed and determined according to the specific case that is analyzed. Indeed, the variable costs are dependent on the annual mileage, charging behavior, and share of the mileage traveled in highways or urban roads. The fuel costs consist of one part of the variable costs analyzed in this model. In the model the annual fuel cost is computed for the conventional and electric powertrain. In Equation 3.5 the annual cost of for the gasoline powertrain are presented.

$$C^{Fuel}_{ICE} = \frac{C^{Gas}}{FC_{Gas}} * L \quad \text{with} \quad FC_{Gas} = FC^{U}_{Gas} * S_U + FC^{EU}_{Gas} * S_{EU} \tag{3.5}$$

The fuel costs are computed trough the gasoline price (C^{Gas}), the average fuel consumption (FC_{Gas}), and the annul mileage (L), considering that the average fuel consumption will depend on the fuel consumption in urban and extra-urban context (FC^{U}_{Gas}, FC^{EU}_{Gas}) and the share of mileage traveled in each condition (S_U, S_{EU}). The energy cost for the electric powertrain is computed according to Equation 3.6

$$C^{El}_{BEV} = \frac{C_{El}}{FC_{El}} * L \quad \text{with} \quad FC_{El} = FC^{U}_{El} * S_U + FC^{EU}_{El} * S_{EU} \tag{3.6}$$

And:

$$C_{El} = C^{Home}_{El} * x^{Home} + C^{Fast}_{El} * x^{Fast} + C^{Slow}_{El} * x^{Slow} \tag{3.7}$$

Equation 3.7 computes the electricity cost considering the charging behavior and the different charging costs. Electric vehicles can be charged either at charging stations or simply at home. As it has been seen in the recent years, different types of charging stations with different charging power can be used as conventionally used gas stations. However, charging costs will be different for different the charging station types. Public fast charging station (C^{Fast}_{El}), due to the higher equipment cost, will have a cost that will be higher compared to public slow charging stations (C^{Slow}_{El}). However, charging stations are not the only possible solution to charge electric vehicle. Indeed, home charging at electricity home rating (C^{Home}_{El}), is expected to be the preferred charging mode for overnight charging as substantially more cost effective. The charging cost of electric vehicle can consequently be variable depending on the charging behavior of the users, more than the true energy cost. However, public charging stations have the fundamental role of contributing to fight range anxiety and encourage adoption of EVs. According to a survey from Volvo [128], the clear majority of the surveyed said that they would be more inclined to purchase an EV if there were more charging stations.

A considerable portion of the variable is represented by the maintenance and repair costs. Ordinary and extraordinary maintenance is carried out every year on vehicles, as oil and filter change, aesthetic repairs, and tire maintenance. To have again correlation between the number used, we have used the data from American Automobile Association report [127], which provides the average annual cost for maintenance in the U.S. for different vehicle classes. An additional factor for the tire replacement (k_{Tire})was considered occurring every 25,000 miles, along vehicle lifetime. For what concern electric vehicles, maintenance is expected to happen more rarely and be cheaper due to the less moving components and the lower complexity of the powertrain [120]. Consequently, the annual cost for maintenance was computed according to Equation 3.8.

$$C^{Maintenance} = L * (k_M + k_{Tire}) \tag{3.8}$$

3.2.4 The resell value

The resell value will allow to compute the real money flow related to the vehicle depreciation. In this thesis, due to the high sensitivity of the battery price we have considered depreciation for the battery, as well as the vehicle itself. Moreover, in case of longer vehicle's lifetime or higher utilization, the replacement of the battery in electric vehicle can be necessary. In Tabe 3.1 we have presented this thematic and we have discussed how the literature has so far dealt with this issue. In this thesis we will consider the battery replacement as an additional cost that would follow on the customers and therefore this will influence the TCO outcome. However, it has been already discussed that no defined or certified approach is available yet (see Section 3.1.3). For this reason, in this thesis a model for the battery depreciation is introduced and used. As a first step, it will be evaluated in the model through Equation 3.9, if the replacement of the battery is necessary and how often this even must occur.

$$N_{Bat} = \left\lfloor \frac{T * L}{N_{Cycl,max} * R} \right\rfloor \ , N_{Bat} \in \mathbb{N} \tag{3.9}$$

To compute the number of battery cycles (N_{Bat}), the annual traveled distance (L) is multiplied with the vehicle's lifetime (T), and divided by the maximum number of cycles ($N_{Cycl,max}$) and the design full electric range (R). To consider the capital cost necessary for the battery replacement, it must be also computed when the battery replacement is expected to happen and precisely, in which year (Y_{Bat}) the new battery will be acquired. Equation 3.10 show how this value can be defined.

$$Y_{Bat} = \left\{ \left\lfloor \frac{0 * N_{Cycl,max}}{S} \right\rfloor, \cdots, \left\lfloor \frac{N_{Bat} * N_{Cycl,max}}{S} \right\rfloor \right\} \ , Y_{Bat} \in \mathbb{N} \tag{3.10}$$

The difference cost for the battery replacement arising form the procurement of a new battery and sale of the used battery ($C^{CR}_{Bat,j}$) in year j can be determined using Equation 3.11.

$$C^{CR}_{Bat,j} = C_{Bat} * f_{retail} * (1 - x_{res}) \ \forall j \in Y_{Bat} \tag{3.11}$$

The variable x_{res} describes the fraction of residual value model for the battery lifetime until it reaches the maximum number of charging cycle ($N_{Cycl,max}$). In Figure 3.8 the battery residual value model is represented. The battery residual value model give the percentage of residual value of the Battery in dependence of the charging cycles that have been carried though on it. The battery residual value was computed from real publicly available data from the electric vehicle manufacturer Tesla [129]. The data was used to estimated the evolution of the battery SOH in dependence of the number of charging cycles. From this analysis we have then considered the residual value for the battery as following the same evolution of the SOH over time. The residual value of the battery is therefore assumed as the value that the battery has at the end of the life cycle in a motor vehicle and begins it second life in other application. The entire battery second life value chain has to be developed and established, therefore no available information were used to certify our assumption. According to different industry leaders, the battery value chain will play a crucial role in the automotive value pool, therefore many automakers are

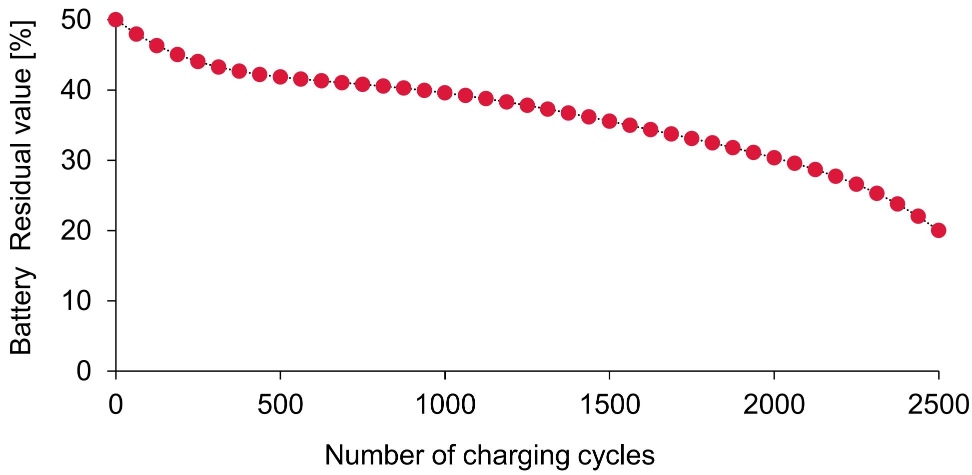


Figure 3.8: Model of the battery residual value

moving toward that space. At current times, the second life of a battery is estimated to be at the point when the SOH is below 80%, therefore many applications can still benefit from it and the opportunity has to be seize.
In addition to battery depreciation model, however, a vehicle depreciation will affect the TCO model. The vehicle depreciation will be considered from historical data publicly available. It is assumed that the vehicle depreciation will be the same if we are considering a conventional vehicle or the electrified counterpart. However, the model considers that the depreciation model for EVs is just affecting the glider cost, whereas electric powertrain and battery are following the battery residual value model. This differentiation was considered not necessary in the case of ICEVs as the historical data used, was based on this type of vehicles.

3.2.5 TCO computation

After the computation of the single cost parts described in the previous sections, the Total Cost of Ownership can be calculated. In Equation 3.12 will be presented the formula that has been used within this thesis for the computation of the capital and operational costs accounted in the TCO.

$$TCO_{tot} = C^{Veh} + \sum_{j=1}^{T} \frac{C^{fuel} + C^{Res} + C^{CR}}{(1+i)^j} \tag{3.12}$$

Furthermore, by calculating the capital value of individual cost categories, is possible to evaluate their contribution to the total cost. This approach allows a detailed analysis of each cost driver and meets the distribution of user costs explained in Section 3.1.2.

Other than representing the total costs over the vehicle lifetime, in this thesis we will present the results as cost over distance (mile). In this way it will be possible to define in comparison to the other transportation mode, what are the true costs of owning a vehicle for a fixed user (defined vehicle ownership and defined average annual distance) compared to the one proposed in a Mobility as a Service scenario. Furthermore, is possible to evaluate for different users which powertrain is expected to be the best option from the only perspective of costs. This consideration will be presented for a fixed annual distance and the additional purchase cost amortization is also explained. Indeed, as has been already presented, at current times the capital investment necessary for the purchase of an electric vehicle is higher in comparison to the conventional vehicle. However, our results show that the technological improvements expected in the next decade can bring manufacturing costs down and purchase parity can be achieved.

Chapter 4

The Mobility as a Services cost model

Within this chapter the mobility services will be first introduced and then the structuring of the cost model will be explained. The mobility services cost models developed within this thesis are the ride hailing, car-sharing, and the micromobility, where for the first two, the private-car cost model has been used as the preliminary input parameter. The mobility cost model was developed under the consideration of all the cost that the mobility providers have to propose to the users in order to make the business model reasonable. As a consequence, in the following sections the input parameter will be mostly estimated and collected from the available sources and will be for the most merely economic. One important parameter that has been taken into consideration is the development of autonomous driving technology as an enabler for the autonomous ride-hailing service by the year 2030. Many researches have been conducted by industry and the research community with the intent to understand the development of this technology and the impact that its development will have on the automotive industry. In Chapter 2 the Mobility as a Service concept was introduced, with current available forecasts, researches, and its expected uptake. In the following the parameters, enabling factors, and challenges will be thoroughly explained and discussed.

4.1 Ride hailing cost model

With the term ride hailing it is intended the transportation mode offering an unlicensed taxi service to its users. Pioneer in this space are for example the companies Uber and Lyft, which have started offering this services respectively in 2009 and 2012 [130, 131], and have since then expanded to more than 750 metropolitan areas worldwide. The main difference compared to the traditional taxi service is that the company is able to provide lower cost per trip, using a business model where the

drivers are not been payed by the number of hours they work but by the number of active time. Moreover, drivers of a ride hailing service are not experienced drivers, employed by the company. They normally are simple users, that they register in the ride hailing web site, provide the required information to the service provider, and are then enabled to start operating in the area they prefer. This allow for a cheaper on-demand transportation mode that has showed surprising adoption since its introduction.
This section will introduce the main parameters that will define this transportation mode in the year 2030. By that time, it is expected that the service will be most likely automated, where the need of driver in the car is not going to be necessary anymore affecting the entire cost model.

4.1.1 Vehicle characterization

The first component that is going to define the cost of this transportation mode, is related to the vehicle type and its specification. Indeed, the ride hailing cost model presented in this thesis was developed starting from the outcomes of the private car cost model explained in Chapter 3. As will be presented in Chapter 5, the cost per mile of electric vehicle over lifetime is expected to be more convenient compared to conventional ICE vehicles. Consequently, as the operators will want to offer the service at the least operational cost, it has been assumed that all the vehicles will be electrified. In addition, the requirement of offering more sustainable mobility services, is expected to lead the uptake and choice for such vehicles. It is already announced by different city governments, that throughout the next decades many city centers are not going to allow anymore circulation of ICE powered vehicles. ZEVs are therefore going to be the only option for all mobility services that will have the intention to operate in city areas and this consideration has been adopted also for this model.
One more consideration is related to the vehicle type. For the private car cost model, it has been assumed that vehicles operating within the city limits are going to be mostly small or medium segment vehicles, as more compliant with the city dwellers requirements. For what is expected regarding the ride hailing service however, the additional cost of medium segment sedan compared to the more cost effective compact city car will be easily amortized with to the improved service offered. Ride hailing, as is already the case for the current taxi service will have grater utilization by the business people. This class of people, are in general characterized by an higher income, and especially by the need of reaching destination in the fastest way. Ride hailing, consequently, has to offer a on-demand service with high availability, to cope with their requirement. Moreover, differently from the other transportation modes, the users are not required to drive the vehicle, as this operation is done by the ride hailing drivers. This will result in the clear preference of this transportation service over the other for this society class, since they will

have the possibility of carrying out other tasks during their trips. Medium segment sedan, due to the improved comfort, the bigger cabin space are not only the better solution for business travelers, but also in case more users will have interest of sharing the trip to the destination. Shared ride hailing is indeed one option that can be offered to the users of this service and will yield to a lower trip cost without affecting the journey experience. As will be presented in the following sections, ride hailing utilization is determining parameter for the cost model, and even though in the available business model, shared trip are rarely happening, it expected that car occupancy will significantly increase over time.

Fleet discount Fleet pricing is a special discount price offered for the purchase of multiple cars from a dealership. Many types of companies make frequent use of fleet pricing and purchasing, whether it is a car rental service rotating out old rental cars for newer ones, or commercial vehicles for official company use. Therefore, even for the ride-hailing business model a fleet discount is expected. A consideration regarding this aspect is however if the ride hailing will eventually operate a fleet or will continue its evolution following its current model. As a matter of fact, ride hailing as of today does not operate any owned vehicle. The vehicle that are used for its operations are propriety of the ride hailing drivers, which pay for all operating costs. A major advantage for the ride hailing company is that they do not have to own the assets to operate them, which yield to a much simpler operation of the service. However, on the other hand, this limits the development and the profit margin that they can make on the total trip costs. In our model, we assumed that the ride hailing business model will evolve toward a more asset based operations, much more similar to the current taxi business, where ride hailing companies are going to be also fleet operators. For this reasons, and the expected purchasing power of ride hailing company, will result in fleet discounts on the purchase prices of the acquired vehicles.

Automated and non-automated More than the vehicle type, the fleet discount, the vehicle powertrain or anything else, the real game-changer for the ride hailing business model is expected to be the introduction of autonomous driving cars. Autonomous driving cars have been in development for many years now, and billions of dollar are still invested every years by all major automakers to reach the stage of development when this technology can be unveiled to the world. The ride hailing business model will in particular advantage from this technology breakthrough as other that the enhanced safety, it will not be needed to have a driver to operate their vehicle's fleet. Autonomous driving will make the vehicle, more efficient, safer, and transforming them in always operative machines that do not have demands or complaints of all kinds. With autonomous vehicles it will be possible to improve the user experience, all for a cheaper price. Moreover, the complete vehicle design will change, as the entire cabin space could then be design with a

user-centric approach. Further services will be available for the users, as the vehicle will be able to customize the ambient to the preferences of the passengers, and the passengers needs. From a timeline perspective, autonomous driving cars are expected to make their appearance into restrictive geofenced areas, as soon as 2025, with a more widespread availability in 2030. As will be presented in this sections, some concerns are still to be clarified as for instance the increased empty miles traveled or the higher cost of cleaning of autonomous vehicles. Nevertheless, for this thesis it has been considered and developed a cost model for the automated and non-automated ride hailing services, supposing that AD technology will be widely adopted and certified by 2030.
In Figure 4.1 an autonomous vehicle from the computer service provider Google is shown, as is one of the more advanced autonomous driving project at current times.

Figure 4.1: Google self-driving car [132]

Vehicle lifetime Regarding the vehicle lifetime, in the specific case of ride-hailing model, we have assumed that the vehicle will not be kept until end-of-life. According to our research, this is a current practice for all companies involved with a fleet of vehicle to manage. This allow fleet managers to offer higher services, having higher reliability from the vehicles that are in operation, and more importantly benefit from the fleet cost reduction that is offered to fleet owners. We have indeed assumed that the fleet vehicles will depreciate at the same rate as private owned vehicles, however the vehicle depreciation is on the purchase price and not on the price affected by the fleet effect. In this way, vehicle depreciation contributes less to the vehicle operating cost and also allows companies forecasting the costs related to the vehicle ownership. In the model, a lifetime of approximately two years was assumed, which would correspond to a total distance driven over lifetime of 150,000 miles. The residual value of the vehicle is than expected to be half of the residual value of a vehicle with similar characteristic, due to the high utilization of ride hailing vehicle.

4.1.2 Vehicle utilization

One element that we have considered contributing to the ride hailing business model is the vehicle utilization. The vehicle utilization defines how the vehicle will be used, where, and how much, considering parameter as for instance localization, share of empty miles, and the relative charging behavior. In the following are therefore these costs defined and explained.

Driver cost The driver cost is a fixed cost that is related to the current ride hailing business model. Currently, the drivers is not a direct employee of the company, however the driver receives money for its service from the company. In the future, is not expected that ride hailing companies will continue with the current business model, as this result in low predictability and planning of the business evolution. Consequently, it is assumed that in order to have more control on their operations, companies will start employ drivers as similar to the taxi service. Depending on the vehicle utilization, the drivers will be paid, hourly, a fixed amount. We have assumed that the driver hourly wage, will be dependent upon two main factors: the localization, and the shift peculiarities. We have assumed a week-day sub-divided into three time slots: the peak, the non-peak, and night. For each an hourly wage was assumed. This value has then been adapted for four different localization. We have assumed that ride hailing vehicles would operate in different parts of the city. Depending on where the driver will be operating, he would be paid a different amount of money. It is also expected that the vehicle will be placed in certain zones of the cities and ideally operate within its borders. This will result in different operating cost for the operator that however cannot result in a different cost for the final customers. This aspect should be taken into account in evaluating the price proposition.

Localization To increase granularity to the model, we have sub-divided the city's borders into four operating zones. This made possible defining the utilization of the ride hailing service in different parts of the city and find the correlation to the operating costs. The four zones, which will be explained in the following, are downtown, urban, suburban, and exurban. The downtown zone is the part of the city where the utilization is expected to be the highest throughout the day, with very small down-time and shorter average trips. The urban, will be characterized by less frequent trips, longer distances, but still with very high utilization. Suburban is the area where most of the trips will have longer distances, but the down-time is expected to be high during the non-peak hours. Finally, the exurban zone is characterized by trips between different part of the suburban area, with low utilization, high average speed, and therefore with lower operating time.

Average occupancy The matter related to the vehicle occupancy is still not clear. For the entire ride hailing business model, but also for the entire transportation industry, to understand if and how people would share a trip in the future is crucial. Looking at the current service offers, the companies try to offer the opportunity to share the trip among individuals commuting toward the same destination. However, survey and data are showing that the adoption is very low. People don't like to share, what it is. The cost advantage consequent to the shared trip, is not considered beneficial enough at the moment.
In the model, we have therefore taken into consideration average occupancy, and as will be possible to notice from the results chapter, they will be presented in different scenarios occupancy dependent. Indeed, to provide the reader with a more clear effect of what is expected and how the results will change depending on this factor, a high occupancy and low occupancy have been developed and will therefore be presented in the results chapter (see Chapter 5).

Empty miles In Figure 4.2, the representation of the empty miles is shown. Empty miles are the additional miles that each ride hailing vehicle would need to drive to provide the service to the customer. In fact, each trip traveled with a ride hailing vehicle requires to drive additional miles. Just the concept of ride hailing, requires that the vehicle drives to the location where the pick-up has been requested, which is already an additional distance that would be needed in case a private owned vehicle would be used. Aspects related to relocation, multiple requests,

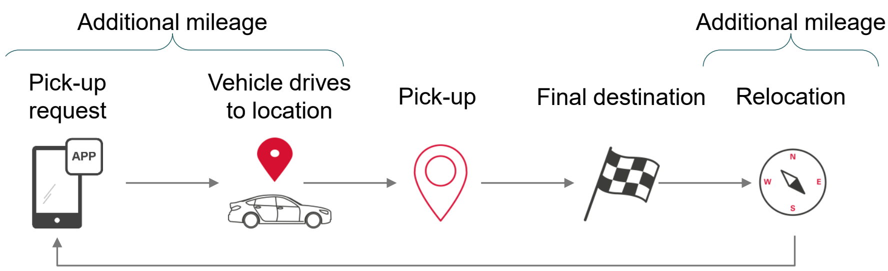


Figure 4.2: Ride hailing exemplary trip and empty miles

and difficulty in predicting pick-up demands are indeed major concerns that are normally mentioned among the drawbacks of this service. As a matter of fact, this additional empty miles are expected to contribute drastically to the increase in vehicle miles traveled (VMT) and therefore the energy demand. Concerns related to this increase in VMT can however be balanced by higher utilization of the vehicle, shared trips, as for instance having multiple pick-ups during one single ride, where people reaching a similar destination would share part of the trip, at a reduced final costs, but, more importantly, without having a significant impact in the energy demand. To the extent of the model developed in this thesis, the empty miles have been considered as percentage increase to the average trip distance. We have therefore supposed that the empty miles are a fixed amount on the average trip length and they would just be dependent on the number of trips that are carried out. Nevertheless, we have also considered the specific location of the trip and we have consequently defined four distances affecting the total driven mileage.

Charging behavior As we have considered only EVs in our model for the ride hailing service, the charging aspect has also been considered as a parameter influencing the results. To define the charging behavior and how the vehicles will be charged we have considered primarily two aspects. Initially we have considered the charging time that we expect the vehicle needing to completely re-charge the battery. As was illustrated in the previous chapter (see Chapter **??**), the charging infrastructure and primarily its development are one major factor that will foster the adoption of EVs. Therefore, ride hailing company will benefit from this infrastructure availability in different areas to provide on-the-ground and when needed fast charging, which allow to increment the range and time of operation of the vehicles. On the contrary, fast charging will not be the available solution. Fast charging will be primarily used in all situations when having energy in a short amount of time is actually beneficial to the business. In all other situation different charging methods will be employed. Slow charging station will be a better solution for the overnight charging of the vehicles. In the model, down-time where assumed and they have been estimated to be enough to allow for a complete battery charging cycle at a slow charging station. Moreover, electricity at industrial rate can be a possible solution to recharge the vehicles overnight. Electricity at industrial rate can be provided only through contracts with the energy companies and would requires also an investment for the installation of the infrastructure and having a sufficient space available to allow for the charging action. We do not expect to have vehicle charging all the time at industrial rate, however for vehicles operating outside the city centers, where big surfaces of real estate would be more likely available, deposits can be build and charging station installed. In general, a mix of different charging options have been considered to be the more precise and try to estimate with the more reliability the real case.

4.1.3 The additional costs

Other than the vehicle related costs and the operational costs, the ride hailing business model is affected by some additional costs that affect the normal vehicle utilization. In the following the aspects related to safety oversight of autonomous vehicles, the cleaning and additional maintenance required for autonomous vehicles, the parking costs, the cost of insurance for ride hailing vehicles, and the general overhead and profit will be extended.

Safety oversight A new Massachusetts Institute of Technology paper [133] was the first scientific paper to bring up the problematic related to safety oversight of AVs. In the paper, the authors point out that the AVs will still requires an operator with the responsibility to oversee their operation. In case of error, even though AV should be able to pull over and bring the vehicle to a full stop in complete safety, they will probably require of an operator to start over its operations. What was not clear is how many vehicles can be overseen by a single operator and if it is going to be a requirement from the regulators. However, according to the authors this aspect can affect negatively the business utilization of autonomous vehicles. In this thesis, the safety oversight has also been taken into consideration assuming that the operator will be able to supervise up to twenty vehicles simultaneously.

Cleaning and additional maintenance Cleaning of ride hailing vehicles is already an issue of the current system [134]. Despite, a driver is present in the vehicle during all the passenger trips, trash, odors, and much more require that the vehicle must be cleaned after every single shift. The question is therefore how this will be handled when the vehicles will be completely autonomous. Use cameras to remotely control the users behavior in the vehicle would go against the privacy policies. In addition, AVs are already to proven to create motion sickness disease to the passenger and result in even dirtier situation that would add on top of the already messy ride hailing vehicle. The question put as who will clean self driving vehicles is therefore an aspect that has to be considered also from a cost perspective. The industry expect to find a solution where the vehicle could have some self-cleaning fabrics that would decrease the efforts in the cleaning operation. However, the cleaning of vehicles, as recognized in the rental car business, contributes substantially to the fixed costs. Consequently, from this context we have estimated that vehicle's cleaning will be performed every certain number of trips, estimated to be forty passenger-trips in the case of driven vehicles, and 60% less for automated vehicles.
Strictly connected to the reason leading to a more frequent cleaning for ride hailing vehicles, compared to private owned vehicles, it is rule to consider a higher frequency for maintenance as well. Vehicles, as they will not be operated anymore by the owner, will requires more maintenance. Autonomous vehicles, for the most, will probably operated in a more controlled way, but the interior parts can be likely be subjected to acts of vandalism. In addition, autonomous driving technology and all the additional components required, will necessitate very frequent control to ensure that the safety standards are met by all means. Higher cost due to the additional maintenance are therefore expected for ride hailing vehicles., which will of course affect its cost model.

Parking Fleets operating vehicles need to be stored all the non-operating time. This non-operating time is partially considered as the required time to re-charge the vehicle's battery, but also as not necessary operating time from a business perspective. However, the parking space will result in a cost per vehicle that the fleet operators will face as a monthly lease. We have considered different cost for the vehicle operating in different areas of the city. We have considered that vehicles operating in downtown and close to the city center, would be parked in near their operating zone, as their non-operating time is low and the time to travel to the outside the city deposit might be too long and take away revenue increasing true operating time. Nevertheless, price per parking lot is considered more expensive than the deposit parking. Deposit parking thus considered only for the vehicles where industrial charging has been considered, meaning all vehicles operating in suburban and exurban areas.

Insurance benefit Due to the upcoming deployment of autonomous vehicles, insurance companies are among the related industries that might suffer a disruption in the next years. As the insurance for rented vehicle has always been considered a cash cow, due to the high fees that they were able to charge, for the higher risk related to the instance. Autonomous vehicle, on the contrary, will improve the vehicle's safety and therefore insurance fees have are expected to be subjected to a plummeting cost. The insurance benefit will only affect AVs, and a higher cost is still expected to affect human driven vehicle for the ride hailing cost model. However, it should also be kept in mind that the traditional insurance business model will be affected in general by vehicle's automation. If not completely autonomous, vehicles, will have at least some level of autonomy, which will be required by regulations or the preferred choice for the users. Therefore, also for not completely autonomous vehicle, at least a partial automation can result in cost benefit from a cost perspective. In our model, as the cost reduction is still uncertain, we have only considered a price benefit for fully autonomous vehicles, whereas a price premium is still present for the other vehicles, regardless the partial autonomy.

Overhead and profit Several additional cost matters are expected to still contribute in the real cost model, as for instance the customer services costs, assets acquisition, and many more. However, to count for their contribution, an overhead margin was estimated. Other than overhead additional costs, a fraction of the final costs will be requires for the company make it economically viable and, for this reason, a contribution for the profit margin has then been added on top of all the costs here considered and outlined.

4.2 Car-sharing cost model

Car-sharing is an additional transportation mode considered in the Mobility as a Service cost model. Car-sharing differentiate from the ride hailing business model primarily because the car is not operated by anyone, but instead you personally drive the vehicle wherever you prefer. The car-sharing environment has seen the appearance of several player from its first launch. Big players in this space are now for instance ZipCar and Car2Go [135, 136], but different business models have been developed. The two most common are the station based, and the free-floating services. In the former, the vehicles can be used allover a definite zone, but the vehicle will be picked-up and dropped off a predefined station where all vehicles will be stored. The latter, offer a more flexible service, where the vehicles can be used again within a limited zone as desired, starting the trip from they have been deposited by the previous user. The station based service, is in general more convenient for the operators, and can offer therefore lower prices, but set limitations in the flexibility for the users. Station based car-sharing is perceived to be the replacement to the current car rental. It is already possible to see commonalities between the two, where the traditional players in the car rental business are moving to this space [137]. Free-floating car-sharing is on the other hand expected to suffer from the increasing adoption of ride hailing. Nevertheless, one of the main benefits that the free-floating service provides, is in the very similar user experience to the current private car and can be a very compelling replacement to it.

Following the main parameters that characterize its cost models are outlined. However, it shall be noticed that also for the car-sharing cost model, the inputs are computed on the basis of the private-car cost model.

4.2.1 The vehicle characterization

The fundamental hypotheses behind the car-sharing business model are the same of the ride hailing business model. As was explained in Subsection 4.1.1, the intention of operators of car-sharing fleets is to be able to offer a certain service for the smaller operational costs. Therefore, in the definition of the vehicle used for such operation, it is obvious that here again fleets will be dominated by EVs. Other than being a more economically advantageous solution, BEV are also going to be the preferred solution for all users living the city center space. Tightening emission regulations will anyhow contribute to thriving of ZEV and, as outlined above, their emergence. Regarding vehicle type, the same consideration is again here valid for the car-sharing cost model. Led by the more comfortable solution of medium sedans, compared to compact city vehicle, will bring on the road fleets of medium size vehicle. As was presented in the introductory part, car-sharing aims to be the perfect replacement for all the current users of privately owned vehicle, who would still need to have the comfort and flexibility of it. Many use-case would benefit from having available a shared vehicle ready to use for their private travels. All users expected to give the private car would still desire to have a valid replacement for their commute to the grocery store or for the week-end trip with friends. For all similar situations, the medium sedan is preferable to the compact city car. In the model developed, therefore, the medium sedan vehicle has been considered as the preferred and only solution available for the car-sharing cost model. Finally, to provide the cost comparison between different battery sizes, the two battery sizes where considered separate and for both car-sharing solution. The operation time is a major requirement for the car-sharing business model, but the advantage of having the car all the time when is not in operation parked into a station or a defined area, allows for benefits in the charging related aspect. In Chapter 5 more details regarding the choice of battery for the car-sharing business model are shown and some conclusions are drawn.

Additional hardware The car-sharing vehicles requires the installation of some additional components for its operation. Hardware as a precise GPS, a keyless door lock, an ignition system that can be activated from remote and others, are necessary for each car-sharing vehicle. The acquisition of this component at a fleet level was considered and a corresponding price was estimated.

Fleet discount All consideration explained in Section 4.1 regarding the fleet discount are valid for the car-sharing model too. Car-sharing operation, however, require a bigger number of vehicles and consequently a bigger fleet. Therefore, we have assumed that the purchase power for these fleet operators is going to be higher, resulting in higher fleet discount. It was assumed that the fleet discount for car-sharing companies will be the same as the current applicable to rental companies. Moreover, car-sharing operation can be a valid value generation option for all OEMs that are approaching new mobility services. Different players are at current time present in this space, as for instance Daimler (https://www.daimler.com), PSA (https://www.groupe-psa.com/en/), BMW (https://www.bmw.com/en/index.html), consequently, higher concession could be possible and applicable for a few car-sharing services.

Lifetime Similarly to the ride hailing business model, for car-sharing companies will be more advantageous to own or lease the vehicle for a contractual period of time, which is going to be shorter that the normal average vehicle lifetime. A lifetime of three years has been estimated for the car-sharing transportation mode. In this way, the companies can benefit from the fleet discount on the purchase price that will not be applicable on the resale value. As a matter of fact, vehicle depreciation will be less affecting the business model and the economic benefit can be perceived.

4.2.2 Vehicle utilization

Car-sharing business model has to take into account of the utilization of the vehicle. For vehicle utilization, it is considered where and when the vehicle will be used, but also the charging behavior, and the additional empty miles necessary to improve the service quality.

Localization Regarding the operating zones of the car-sharing business, we have here again taken into account several ones, as estimating the operation time and utilization might be done in an easier and more precise way. The car-sharing service, was then considered for three major areas within the city borders, where, however, the option to travel between cities was only qualitatively estimated. The three zones are herein after named downtown, urban, and suburban. In the definition of the utilization of the car-sharing service, an additional differentiation was made for the station based, and free-floating services. The main difference between the two service is indeed in the utilization. Given that the free-floating model will offer more flexibility to the final users, it is expected to be used more frequently used than the station based counter part. This result in higher number of trips per day, especially in the downtown area, but with shorter distances traveled. The station based service, as replacement for the private-car, will present longer trips, higher average speed, but more importantly similar utilization in all the three areas considered.

Empty miles Empty miles for the car-sharing service are only due to relocation of the vehicles to allow for a better vehicle utilization in the predetermined zone of operation. This is different to what was earlier discussed regarding the ride hailing model, as there is not going to be any mileage increase due to the distance traveled before the pick-up. Empty miles for the car-sharing model are therefore less compared to ride hailing but still will count for an additional fuel consumption that should not be neglected. The relocation miles are necessary to improve the service quality and allow for a better vehicle utilization. This additional operation is necessary all the time vehicle localization is unbalanced, namely after peak hours where the vehicle are displaced mainly toward one direction. Relocation can also be an efficient way to charge the vehicle at a lower fare, moving them in places where electricity at industrial rate can be provided, as for instance at depots or external parking.

Charging behavior The effect related to charging behavior for car-sharing is less important than for the ride hailing service. Charging of car-sharing vehicles will however be different depending if we are considering the free-floating model or the station based. For the former, a mix of charging solutions have been considered depending on the localization of the vehicle and its primary operation zone. The latter, on the other hand, can benefit from the fact that vehicles, after serving the users, will be parked in controlled and pre-established zones, where charging station can be installed by the car-sharing operator. This enable the establishment of contracts with the energy provider, that can than offer cheaper electricity. For the seek of simplicity, it was assumed the electricity fare for station based car-sharing being at industrial rate.

4.2.3 The additional costs

Car-sharing is finally characterized by some other additional costs that have to be additionally added to the operating costs. Some of these additional costs are similar to the above explained costs for the ride hailing business model, but others are specific for the car-sharing one. In this section the additional costs related to insurance, parking, the cleaning and the additional maintenance, fleet management, and overhead will be illustrated.

Fleet management With fleet management shall be intended that additionally to the empty miles explained in Subsection 4.1.2, it is necessary that a person drives the vehicles from one location to the other. This operation, other than resulting in additional cost from the higher energy consumption perspective, it leads to an additional cost due to operating the vehicles. Therefore this accounts for an operational cost, linked to the fleet management practice, but also to a cost related to the relocation of the vehicle, namely the driver that moves the vehicles between locations. This is already a current practice done in rental companies and also in the current car-sharing business and it is expected to not change dramatically. Nevertheless, automation and better connectivity might lead to a more optimal fleet management and less costly relocation resulting in a clear economic benefit compared to the current business model.

Parking The car-sharing company needs to provide the users with accessible and multiple parking locations dispersed throughout the city. However, parking is one of the major cost driver and contributing significantly in the cost model of the service. In the specific consideration of a future city, in addition, the city trends will lead to less availability of public space for commercial use. Parking lots will decrease, and the cost per parking will consequently increase. In this thesis, one parking solutions have been considered for each car-sharing model where in the station based a lower cost can be accepted. Moreover, the city regulators will prefer shifting all vehicle outside the city, in less congested areas and where space is going to be a smaller issue. As a matter of fact, parking cost for downtown, and urban areas is estimated more expensive than in suburban spaces.

Cleaning and additional maintenance The underlying hypotheses for the cleaning costs are the same previously outlined in Section 4.1. Indeed, similarly to ride hailing vehicles, the issue related to vehicle cleaning is still not solved. The high frequency of passenger interchange, plus the consideration that vehicles are not owned by the private, means that vehicles need to be cleaned regularly. Differently from ride hailing vehicles, car-sharing do not need cleaning operations as often. The first reason is related to the passengers that are more likely to use car-sharing vehicles, i.e. DINK and singles, which should use the vehicle as replacement of their private car and longer trips. Secondly, as the car-sharing needs the vehicle to be driven, passenger will consider it a less recreational space, and resulting in lower opportunities to dirty the vehicles.
The additional maintenance for car-sharing refers to the additional costs that is necessary to repair the vehicles. Differently to what was presented in Section 4.1, the car-sharing vehicles is not going to reach complete autonomy, therefore being the driver still needed and being the driver not professional employed as in the ride hailing business, we have estimated that vehicles will break down more often than the case of private-owner vehicles. This is already noticeable looking at car rental companies and cars, where vehicles are regularly returned with scratches and dents after the renting.

Insurance add-on Unlike what was illustrated regarding the autonomous ride hailing, insurance companies will try to get the most out of car-sharing vehicles. Inexperienced drivers and lower level of autonomy are the primary reasons upon which insurance companies will leverage their remarks for the additional cost for the insurance bill. Despite the introduction of ADAS into the vehicles, which will decrease the likelihood of accidents, several aspects still make reasonable higher charge for car-sharing vehicles compared to the private owned counterpart. According to our expert interviews [120], the additional cost for the current rental car business can be up to five-fold the annual insurance fee for a private owned vehicle. This estimate was transferred to the car-sharing business model, expecting therefore a 500% increase.

Overhead The complexity of this transportation modes makes is hard to considered all cost components into the model developed. Therefore, a percentage increase referring to the overhead costs of the business is considered, where all additional operations shall be included. Compared to the ride hailing overhead cost, it is assumed that for the car-sharing operation more side costs have to be taken into account. Thereby, overhead is considered bigger and counting for a bigger share of the total cost. For instance, one key point that we consider worth to mention about the addition overhead cost, is related to the cost to enable passengers to utilize the service. Indeed, car-sharing users are also the vehicle's drivers, which yield to the need of certifying all documentation before he will be allowed to take on a vehicle.

For instance, an operator has to verify the validity of driving licenses, the criminal records, insurance coverage, and many more paperworks, for each users that signs in for the car-sharing service, procedure not needed in the ride hailing.

4.3 Micromobility cost model

Micromobility is the last transportation mode considered within this thesis. Micromobility is a relatively recent transportation mode, that, however, has the potential to improve the current transportation system and is already showing increasing adoption [74]. With micromobility it is intended the transportation mode that includes all mobility services covering the last/first-mile of a trip. In the Mobility as a Service business model, it is indeed discussed the relevance of bike sharing and e-scooters, which together contribute to solve the problematic of mobility for the initial part of the trip, but also the last leg of transportation. In the model presented for this thesis, the only e-scooter transportation mode was analyzed, as strictly connected to usage in a smart city in the United States for the year 2030.

Despite the fast adoption, the demonstrated advantages and improvements to the current transportation system, and the simplicity of its integration into the model, only very few data regarding the economy of these vehicles have been found. At present time, high uncertainty regarding the business opportunity and questions regarding how the business model should be developed make it hard to assess and develop a confident cost model for this transportation mode. Nonetheless, in the following sections the different assumptions and the defined parameters will be outlined.

4.3.1 The vehicle characterization

Micromobility vehicles often include bike-sharing, e-bikes and e-scooters. However, due to the lacking of data for such transportation systems, we have decided for this thesis to focus only on the e-scooter business model. To date, e-scooters have been largely regulated as personal consumer products, not as shared use fleet vehicles. As such, there are few equipment standards for features such as wheel size, center of gravity, platform size, acceleration and braking interface, and lights. Comparing the different solutions that have been employed in last recent years, however, we have noticed that some general terms can be defined. Although initially, e-scooters were produced by only a very small number of companies in the world, e.g. Xiaomi, all the major players in the micromobility space have started developing and producing vehicles by themselves. Other that the technical specification, which are more and more similar between competitors, the cost and lifetime characterizes the different e-scooters. Related to the cost model developed for the thesis, we have assumed a purchase cost for the electric scooter, which was subsequently discussed and endorsed by the FEV expert network [120]. After completing the cost model, the lifetime and purchase cost evolution over time have been assumed discussing the results with the some industry experts.

Additional hardware Additionally to the vehicle purchase cost, all e-scooters are equipped with a localization device. Most geofencing technologies use GPS, which as currently installed in most shared mobility devices is accurate to within 5-10 feet, making it more useful in delineating where bike and scooter use is prohibited or restricted (such as in speed) for larger areas such as beach boardwalks, popular shared-use paths, specific streets, campuses, or parks. Moreover, GPS technology allows to localize vehicles using your personal smartphone and related app, and improves the usage for the final users. Such cost component are normally marginal but not negligible, and have been assumed constant at the current market value.

4.3.2 The vehicle utilization

The peculiarity and also the main advantage of this transportation service is related to its utilization. E-scooter, but any vehicle that shall operate in the micromobility space, contributes in reducing the burden of first/last-mile for city citizens. Implementing micromobility services within the city borders and integrating it with the current transportation system has resulted in increase ridership for transit agencies, as already explained in Chapter 1. Some additional aspect are worth to be mentioned regarding micromobility vehicle's utilization and will be outlined in the next few paragraphs.

Regulatory and city permits It has to be clear that the micromobility service has advantages only if operated in high densely populated areas, where utilization of private owned vehicle is already discouraged or challenging. Such service can other than offer a compelling sustainable mode of transportation, can also contribute to further increase utilization of public transportation services, as already explained previously. Therefore, the location where this vehicles will be mainly deployed are city centers which lay under the supervision of city regulators. As it has been seen already in several cities all over the United States, e.g. San Francisco, to let these vehicles circulate, a city permit has to be issued. Regulations for micromobility vehicles still have to be implemented and certified and this process will probably involves also no traffic zones, parking zones, and much more. However, from a cost perspective, we expect that the only regulatory cost addressed to the service providers will be included in the herein explained city permit, and has been therefore estimated in the model.

Charging and relocation If we had to consider e-scooter and e-bikes, locations where such vehicles will be recharged have to be envisaged. Many options have

been investigated in the recent years, and possible compelling solutions are now available. The current preferred solution involves picking up the vehicles at different times of day, and subsequently charging the batteries in external location to the operating zone. Moreover, during the drop off of the vehicles, the operators will relocate them in location that are more strategically interesting for their utilization, improving therefore the service and the efficiency of the service. However, industry experts still consider this operation too costly and damaging the profitability of the business model. The opinion of subject matter experts and also considering the information collected during our literature research seems to be promising and optimistic, concluding that with time, a more optimal solution will be identified and developed, which can address this problematic. The business model cannot be mature before regulators and all players have entered the game.
To remain on the safe side, the cost estimation used in this cost model, has been estimated similarly to the one used in different literature papers and by industry experts. Therefore, more investigation is needed in the future to recheck these assumptions.

Utilization Data collected on one-way household trips by the Federal Highway Administration's National Household Travel Survey show that the majority (59.4%) of vehicle trips in the US in 2017 were less than six miles [138]. Consequently, other than the opportunity to replace this vehicle trips, is it obvious that micromobility target trips will be short and frequent. Data regarding micromobility utilization are already available, and researching into users and service operators as well, we found out that currently, the number of trips per day is is limited by vehicle availability and customer demand. Limitations such as battery capacity, number of vehicles permitted within the city borders, and customer adoption, result in low operating time and therefore low utilization of these services. At the same time, solving issues as relocation and charging outlined before, optimizing the service with collaboration with transit agencies and regulators, is expected to drastically affect this parameter.
In this instance again, we suggest to reconsider in future times all assumptions made for this cost model, to verify their validity when more data will be available. The results presented regarding micromobility are considered representative of the current solution. However, biases and uncertainty can affect the estimated result for 2030.

4.3.3 The additional costs

Similarly to what was explained for both ride hailing and car-sharing, some non-classified additional cost have been taken into consideration. Nevertheless, additional costs for micromobility are not computed as factor increase on a reference case, but are expressed with absolute values, depending on our assumptions and the information collected.

Customer support and insurance In the additional cost for micromobility, we have identified the necessity to illustrate potential improvement to the current services. Nonetheless, customer supports and insurances are already available in several micromobility service, we have noticed that they are still not reliable and not accounted enough by the service providers. Particularly with regards to insurance, it is still not clear how these electrified vehicles will be considered by the regulators and therefore what is the responsibility of service operators and users. As a matter of fact, insurance policies will need to adapt to regulators and, as we expect, the relative cost fringe will be affected. In the same way, as soon as regulation will be established, an appropriate customer support is needed to assist customers in registration, certification, solving issues and much more, as it is already the case for the car-sharing service.

Maintenance Finally, vehicle lifetime and maintenance are a key problem that keeps awake operators and has to be solved in order to reach profitability for this system. We have identified primarily two aspects related to this issue. The first is connected to the utilization of these vehicles, by the users. Scooters and bikes have been found in lakes, stolen, burned [139], which certainly diminish the fleet lifetime and shall be improved with time. The second instance that we have came across is on the design of the vehicles themselves. High maintenance cost and short lifetime are also linked to poor design and durability issue, problems of which micromobility operators are already working on. Thereby, we suggest to reconsider the cost estimation also for this point, as the business model will most likely change with time, and we expect issue to partially be solved.

Chapter 5

Discussion of the results

In this chapter, the final results and a general discussion of these will be provided. The results provided will be subdivided into two macro groups, to differentiate the outcomes from the private car TCO model and the Mobility as a Service cost models. Finally, a general discussion of the biases and possible next works is outlined, including a series of recommendation for city planners, and industry leaders.

5.1 Total Cost of Ownership for private cars

The TCO model helped us to define which powertrain is going to be the most cost effective for the future dwellers of a smart city in 2030. In the model two powertrains were simulated, however, we have included for the seek of completeness also the cost of the vehicle equipped with a fuel cell system instead as well as the BEV. Figure 5.1 represents the Direct Manufacturing cost for the compact city car considered in the model, equipped with a fuel cell system, an internal combustion engine, and the large battery system. The graph is structured in a way that the two zero emission powertrains are in comparison with the DMC of the ICE vehicle. As it can be noticed, we have assumed that from a vehicular standpoint, the components used in all three powertrains will be shared and therefore the same. The cost difference is only assumed to be related from the different powertrains that are installed on the vehicle. According to our assumptions and our sources, for compact city car the purchase parity cannot be reached yet also by the end of the next decade. Nonetheless, the cost difference could be accounted by government incentives, or lower profit margins for the automotive producers, being however less likely. On the other end, it is clear the still very high manufacturing cost of FCEV. The latter, still require the use of precious materials for the development of the fuel cell systems, which increase drastically the manufacturing cost, but also requires very costly tanks for the hydrogen storage on the vehicle. For all these reasons, we expect a very low adoption of fuel cell technology by that point in time and in the

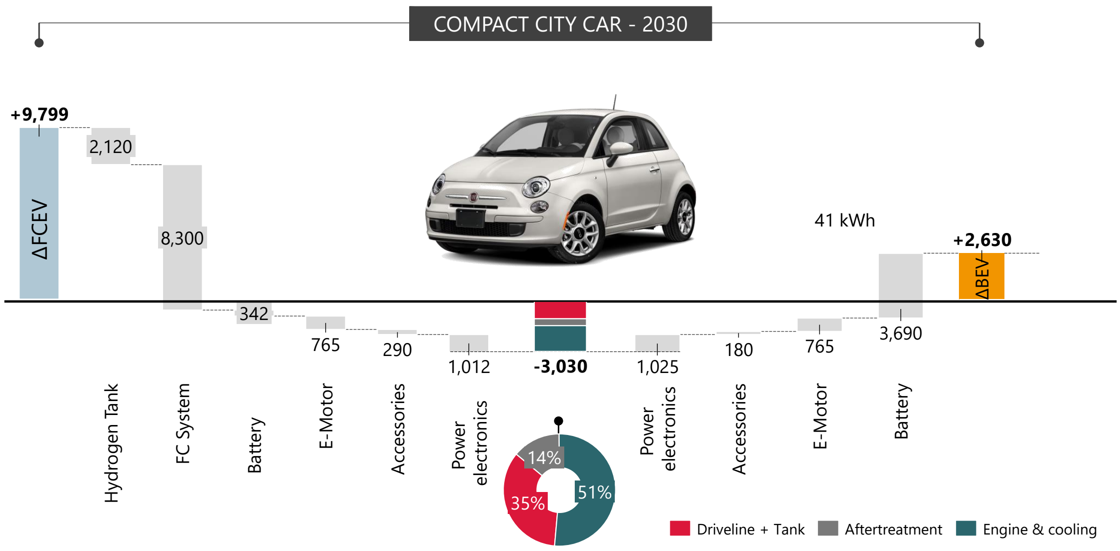


Figure 5.1: DMC for a compact city car in 2030

region considered.

Moving on to the second class of vehicle considered for this TCO model, we can see that the trend is very similar to what have been observed for the compact city car. In Figure 5.2, we notice that the medium sedan will also not reach the purchase

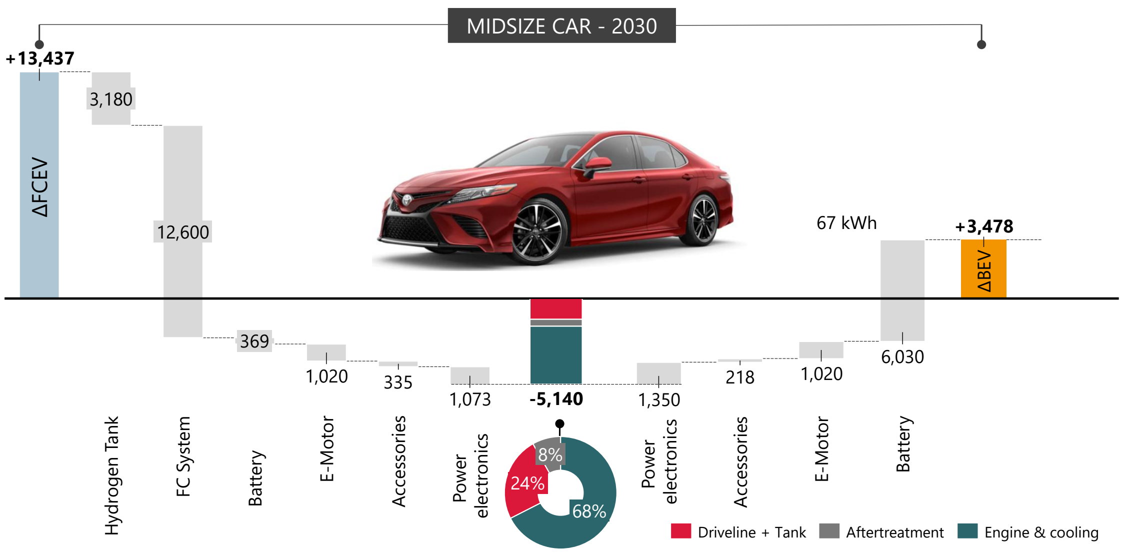


Figure 5.2: DMC for a medium sedan in 2030

parity between ICE and the full electric versions. The battery cost compared to all

other components still makes the vehicle more costly. Comparing BEV and FCEV, it is clear that the DMC difference still makes it not attractive for a city citizen, other that offering a solution which can provide a longer full electric range.
In general, we can conclude that full electric vehicles will still be more expensive than their counterpart with the combustion engine still in 2030. However, it is worth to mention that we decided to make cost assumptions that were the most conservative and to follow only the most reliable source of information. Indeed, some sources found were estimating battery price evolution stronger than the one used for this model, which would have made the purchase parity very close for both class of vehicles.

From a TCO perspective electric vehicles can be more cost effective than the ICEs. Figure 5.3 shows the TCO over different annual distances traveled for the medium sedan and holding period of eight years. The battery sizes are included in this analysis, to see how they related to cost and what is the trade-off with cost and range that has to be accepted. It is clear that over the vehicle lifetime, BEVs are more cost effective in both battery sizes. For the vehicle considered, with large battery, and fixed holding period of eight years, the TCO parity is reached at 7,000 miles per year. For the small battery vehicle, TCO parity occurs at even lower annual mileage. Therefore, all vehicles, or better users, that will use their vehicles for longer annual distances, will have even a greater cost advantage using full electric vehicles. Additionally, we have considered annual mileage up to 30,000 miles per

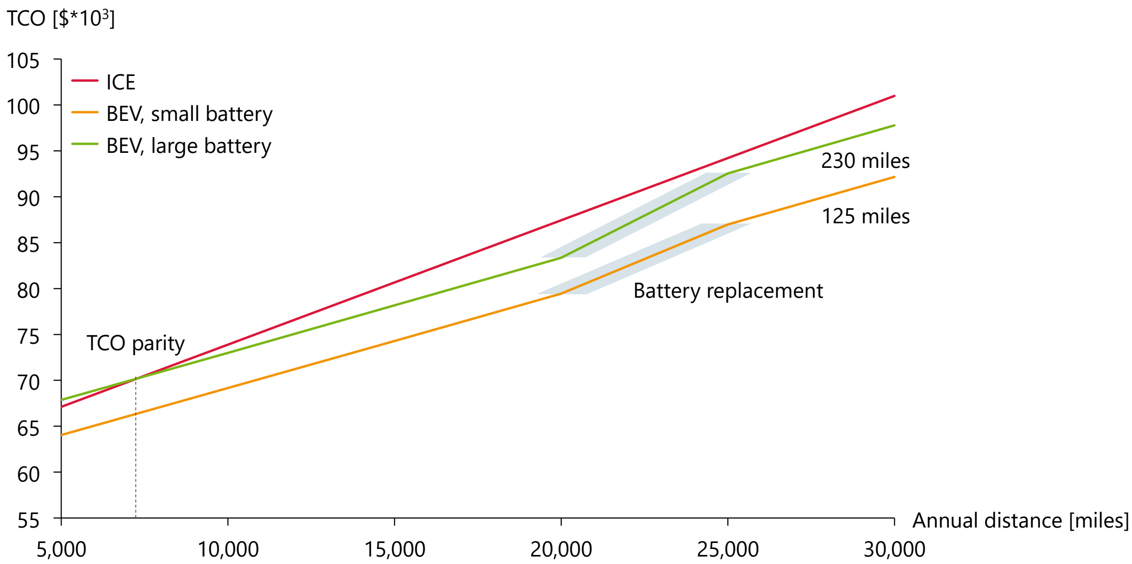


Figure 5.3: Total Cost of Ownership over annual distance traveled

year to also take into consideration a battery replacement over the vehicle lifetime.

In this regard, for a mileage greater than 20,000 miles per year, a battery replacement occurs, which affects the TCO. Despite all, even the battery replacement does not affect negatively the cost model, and BEV are still cheaper over lifetime than the gasoline counterpart. The model was able to consider different holding periods, and also greater annual distances, but even in these conditions the general output is not changed.

We have now understood that BEV will be more cost effective over lifetime compared to ICEVs. However, we have also seen that from a pure purchase perspective, the price parity by 2030 is not reached yet. This means that over the holding period, there must a be point in time when the BEV will break-even with the ICE. For this purpose, in Figure 5.4 we have plot the TCO over lifetime of the medium sedan, with the two powertrains analyzed. The TCO break-even occurs at two

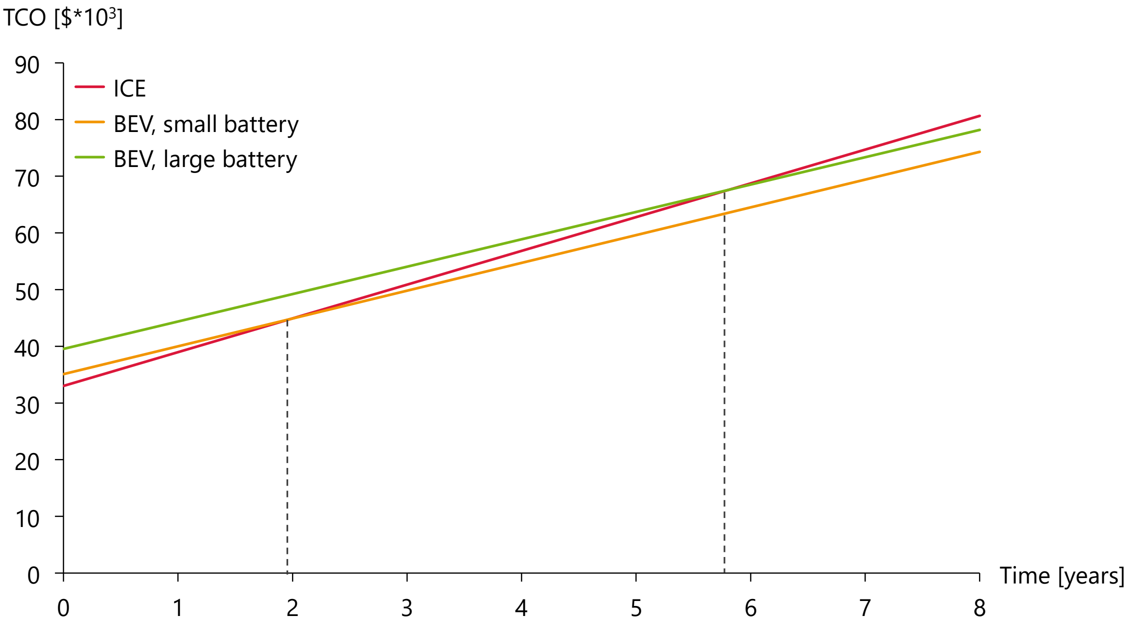


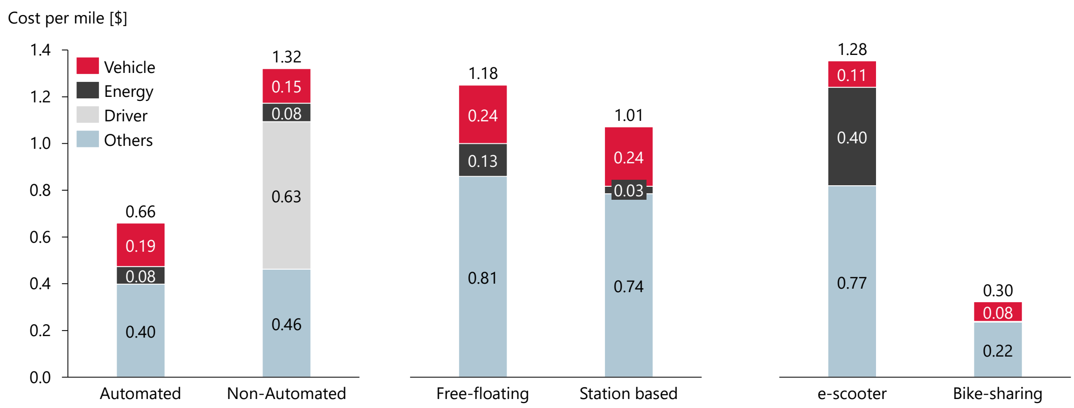
Figure 5.4: Total Cost of Ownership over lifetime

different times for the two battery sizes. In the example considered here, over a lifetime of eight years, for the small battery size it occurs after approximately two years of ownership. For the large battery option, it occurs slightly after the second half of the fifth year. Consequently, after this initial analysis of full electric vehicles, we can conclude that from a mere cost analysis will be less costly than ICE, with a return of investment of less than two years for the small battery version. For this reason, as was presented earlier in this thesis, we have decided to consider only BEVs for all mobility solution involving a motor vehicle in the Mobility as a Service business model, as will be further explained in the next section.

5.2 Cost of mobility in Mobility as a Service

Outlined and developed following several assumptions, the Mobility as a Service cost model was finally able to provide us with the average cost per mile the users shall face using any of these services. Therefore, the average cost per mile is what service providers, accounting for all the considerations explained in Chapter 4, have to demand to the users of the service. Consequently, other than being dependent on the accuracy and truth of the numerous assumptions made defining these mobility services, a further parameter that can affect these cost in positive way depends on how regulators and cities will act. We consider that the most likely scenario involves collaboration between transit agencies, OEMs, and cities to allow the smoothest service and improve the overall offering. Collaborations are thus the primary aspect, which all players should work on. Understanding the various business models, and the operations is necessary, but these can be determined only if all players have expressed their proper requirements. The opportunity can provide benefits in many areas and in many ways, but needs the participation and the co-operation of all.

Figure 5.5 shows the different cost per mile of the three mobility services evaluated. The different contribution to the final cost of Vehicle, Energy, Driver, and Others are also represented. The ride hailing cost in Figure 5.5a is quite partic-



(a) Ride hailing (b) Car-sharing (c) Micromobility

Figure 5.5: Cost per mile for different mobility services

ular. Looking initially to the non-automated cost structure, we notice that the main contributor to the final cost is the driver. The driver, as the necessary part of the equation that makes it possible to provide the service to the users, will be the most significant fixed cost of the business. Thus, the opportunity to remove it from the vehicle using automation is the target for most of the ride hailing companies. However, automation is not only removing the driver from the equation. It involves several other aspects that have been explained earlier in Chapter 4 and taken into account during the definition of the model. Indeed, safety supervision, additional costs for cleaning and the cost of autonomous vehicles itself re-balance the contribution of all cost instances. Figure 5.5b shows the cost per mile of car sharing, in the two modes free-floating and station based. The former is expected to be more expensive, as several additional parameters included in the Others have to be taken into account in return for additional flexibility of the service. This flexibility is required for several use cases, however we consider that both services can co-exist in the smart city environment. Moreover, the bigger contribution of energy to the final cost is due to the additional empty miles, and the higher recharging cost for the former service. Finally, Figure 5.5c shows the costs of e-scooters and bike sharing. As outlined in the relative chapter, the micromobility business model, is the one that might suffer of the biggest changes through 2030. Nevertheless, we believe that to some extent our model can be representative of the final solution. Indeed, we consider that e-scooter will still be an expensive mode of transportation, in particular compared to bike sharing. However, from the information that we have collected we agree with many experts, that adoption will rise significantly, in contrast to what will happen with its costs. E-scooters still need to address several problems related to the relocation, the vehicle lifetime, and the battery charging, which have been considered and simulated in our model and included in the presented results. Nevertheless, it is clear that the main cost contribution is related to the recharging cost of such vehicles. An appropriate business model can improve and eventually further reduce this costs, even though we don't expect it to be significantly different. Bike sharing, on the other hand, due to its cost advantage and hopefully the better integration into the smart city environment, should be kept in mind as a possible preferred mode of transportation by many people.

In Figure 5.6the cost per year for different mobility services is represented. In this way, the three mobility services analyzed, and the private car ownership can be compared and assessed. This private vehicle has been chosen as representative of the worst case scenario that can be simulated with the model from an economic perspective. Indeed, the private vehicle used for this comparison is the medium sedan vehicle, with the small battery electric powertrain. Additionally, on the x-axis, we have included several annual distances, that can be representative of the different users and needs of a city citizen. The results shown are quite interesting. Presuming that the three services will co-exist in equal number and usage in the city space, the average cost per mile has been plot over the different annual distances. Obviously, the cheapest transportation mode will remain micromobility, which will be followed by ride haling, and finally by car sharing. However, the main conclusion that can be drawn from this graph is that with a combined usage of these three, makes it up to 10,000 miles per year economically viable. In this range, are included many users, including in particular person that might be very beneficiary of such service as for instance, students and elderly people. Moreover, potential to further reduce this cost are possible, as already outlined earlier in this thesis. For instance, measures where people with higher requirements and more financial resources, might request improved services, which will then contribute to not only additional costs for operators, but also in bigger portion to the total cost. We have already several times discussed this aspect related to the users of a smart

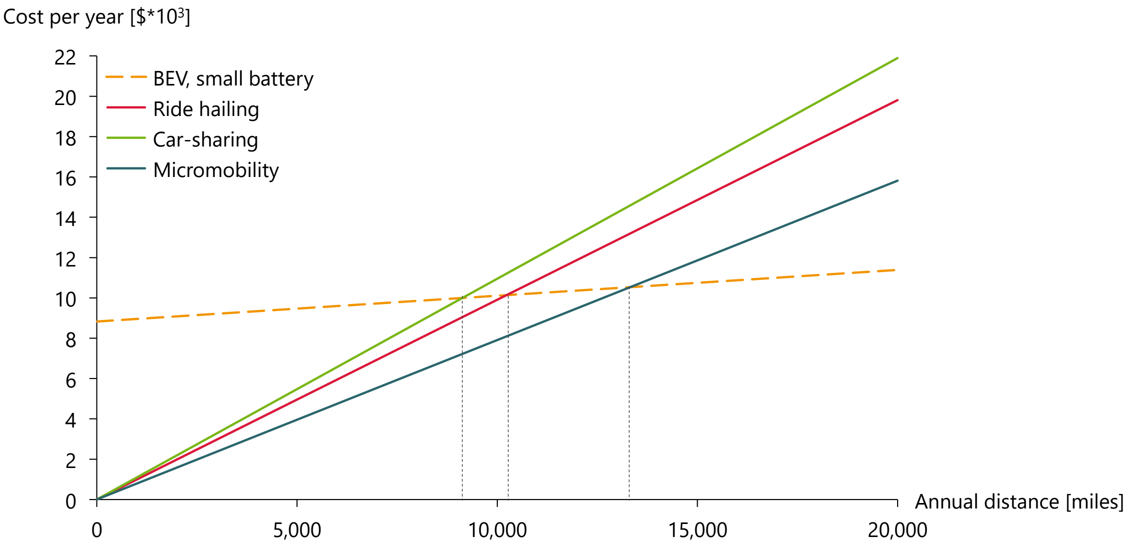


Figure 5.6: Cost per year over annual distance for Mobility as a Service vs. Private car

city earlier in this thesis. Nevertheless, we would like to point out that the key focus for the smart city is on the user needs and the target will be to improve the complete experience for the smart city inhabitants. Therefore, even when we discuss about smart mobility we should not forget that different users with different requirements shall have access to the service.
To summarize, the Mobility as a Service cannot be the only option, but for sure it can contribute providing enhanced mobility services, more sustainable, more cost efficient, and more convenient to a wide range of users. This is represented in Figure 5.7, where the expected cost for an average six miles trip is computed. In the Figure, the different transportation systems are compared in terms of cost and duration of the trip. This figurative representation makes clear what Mobility as a Service will be. Indeed, we have identified some key performance indicators that will be unique for Mobility as a Service. First, the time aspect, necessary to undertake the entire trip. As we can see, Mobility as a Service will be, faster than Private cars by a 10-15%. Secondly, the service can be completely sustainable, as shown in this thesis. Third, Mobility as a Service can be less costly than private car ownership for the majority of users. And also able to provide an end-to-end transportation system in the wast majority of trips. On the contrary, we expect Mobility as a Service to impact negatively on some aspects. For instance, a cheaper

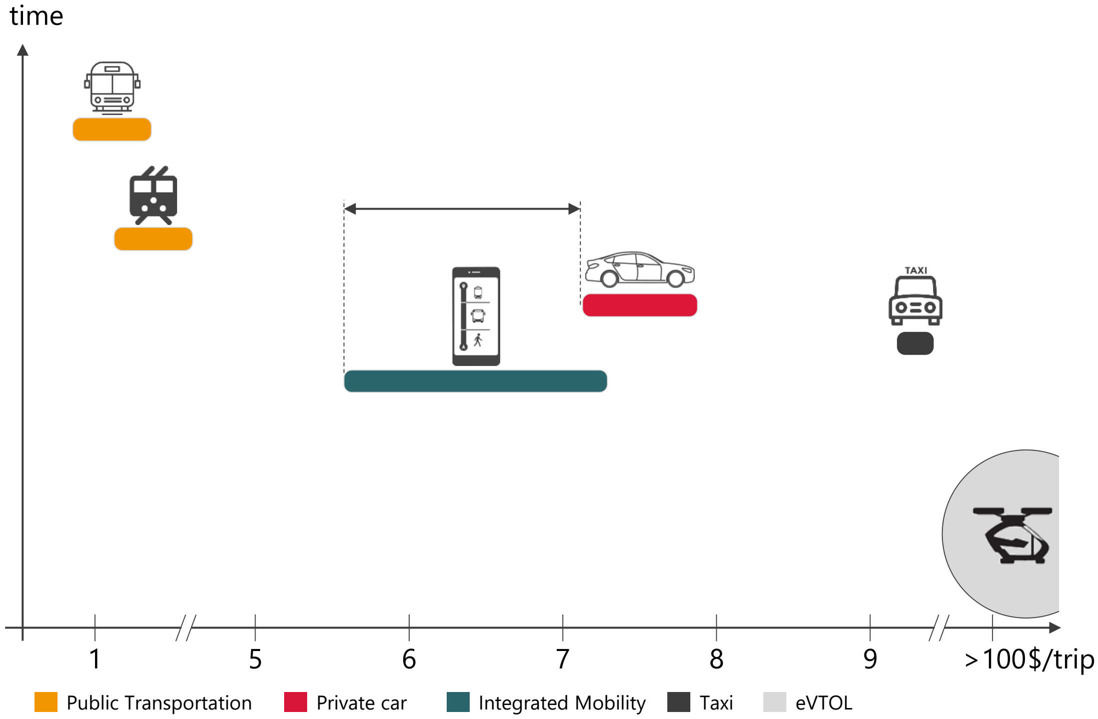


Figure 5.7: DMC for a compact city car in 2030

and come convenient transportation may result in an increase of transport demand. Higher transport demand can increase congestion but also the energy consumption, affecting even more the resource scarcity. Additionally, as explained earlier, Mobility as a Service would depend on adoption of the customer trend of a shared economy. As we discuss about smart cities, which might arise less than a decade from now, the shared economy that we hope might not be ready and influence the adoption and the development of this service.

To conclude this part, we want to add some general thoughts collected from some expert interviews. In Figure 5.8 we have represented the some key recommendations for both the private sector and but city regulators as well. From the side of regulators and city governments, we recommend to start collecting and sharing mobility data data with operators and other parties. This operation can help understand the requirements, the obstacles, and priorities, and also the motivate the choices. Secondly, the development of the required infrastructure is a government's responsibility. Connectivity, dedicated lanes, no-traffic zones and much more have to e built within the city borders, regardless the development of a specific mobility service, as is a pre-requirement also for many more use cases of a smart city. The power and influence that future smart city can have with governments should also be leveraged with vendors. Therefore, direct and specific instructions and key

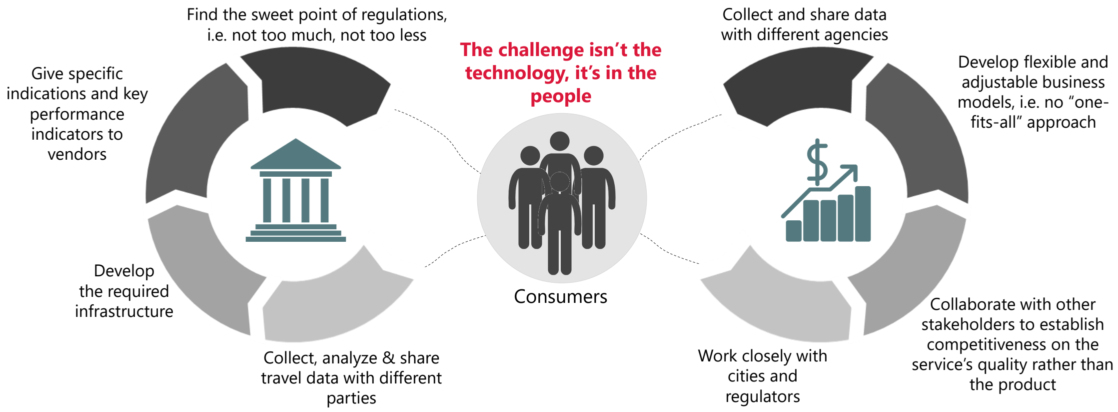


Figure 5.8: Representation of the user-centric approach in Mobility as a Service

performance indicators must be the focal points of all discussions, which shall also affect the final result. Finally, a regulatory sweet spot is necessary. Rules and regulations must be established, individually for each case, being it a smart city, or confined zone in it. The sweet spot is defined as the amount of regulation which improves the quality of the outcomes, and improve competitiveness between the industry players, without however affecting the normal developments and implementation.

On the other side, industry and in general the private sector has to comply with city boundary conditions and understand that only collaboration can lead to the desired result. First, then, take part to public meetings and start working closely with governments is fundamental. Follow their instructions and establish good relationships must be the initial priority. Additionally, the disruption due to this global megatrends, will affect all players and all sectors. Thereby, even collaborations among competitors can be advantageous. The winning strategy is not anymore about the technology but about the service provided. Consequently, flexible business models, developed singularly for the particular solution, tailoring it on the needs of the served customers and established collaborations is the only approach that can lead to organic growth. Lastly, mutual data collection and sharing is also useful. Both cities and vendors should collect data and share it among them.

Bibliography

[1] F. Retief, A. Bond, J. Pope, A. Morrison-Saunders, and N. King, «Global megatrends and their implications for environmental assessment practice», *Environmental Impact Assessment Review*, vol. 61, pp. 52–60, 2016.

[2] K. International, «Future State 2030», 2014.

[3] Ernst & Young, «Megatrends 2015», 2015. [Online]. Available: https://www.ey.com/Publication/vwLUAssets/ey-megatrends-report-2015/$FILE/ey-megatrends-report-2015.pdf (visited on).

[4] PrivatewaterhouseCooper, «Five Megatrends», 2016.

[5] Deloitte, «deloitte-nl-ps-megatrends-2ndedition», 2017. [Online]. Available: https://www2.deloitte.com/content/dam/Deloitte/nl/Documents/public-sector/deloitte-nl-ps-megatrends-2ndedition.pdf (visited on).

[6] Rick Eagar, Charles Boulton, and Camille Demyttenaere, «The Trends in Megatrends», 2014. [Online]. Available: https://www.adlittle.com/sites/default/files/prism/The_Trends_in_Megatrends_9.pdf (visited on).

[7] EEA, «Assessment of global megatrends — 2014 update», 2014.

[8] United Nations, Department of Economic and Social Affairs, and Population Division, «World Population Prospects 2019 Highlights», 2019. [Online]. Available: https://population.un.org/wpp/Publications/Files/WPP2019_Highlights.pdf (visited on).

[9] United Nations, «World Urbanization Prospects - The 2018 Revision», 2018. [Online]. Available: https://population.un.org/wup/Publications/Files/WUP2018-Methodology.pdf (visited on).

[10] IPCC, «Climate change 2014 - Synthesis Report - Summary for Policy Maker», 2014. [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/02/AR5_SYR_FINAL_SPM.pdf (visited on).

[11] U.S. National Climate Assessment, «Climate Change Impacts in the United States», 2014. [Online]. Available: https://www.globalchange.gov/sites/globalchange/files/NCA3-climate-trends-regional-impacts-brochure.pdf (visited on).

[12] Climate.gov, «2016_ A historic year for billion-dollar weather and climate disasters in U.S. _ NOAA Climate.gov», 2017. [Online]. Available: https://www.climate.gov/news-features/blogs/beyond-data/2016-historic-year-billion-dollar-weather-and-climate-disasters-us.

[13] ISSA, «Megatrends and social security - Climate change and natural resource scarcity», 2014.

[14] OECD Science, «Megatrends affecting science, technology and innovation», 2016. [Online]. Available: https://www.oecd.org/sti/Megatrends%20affecting%20science,%20technology%20and%20innovation.pdf (visited on).

[15] iea, «World Energy Outlook 2018», 2018.

[16] Bloomberg, *The Massive Cost of Not Adapting to Climate Change*, 2019. [Online]. Available: https://www.bloomberg.com/news/articles/2019-09-09/the-massive-cost-of-not-adapting-to-climate-change?utm_medium=social&utm_campaign=socialflow-organic&utm_content=business&utm_source=linkedin&cmpid=socialflow-linkedin-business+ (visited on).

[17] Ethan Mallick, «Establishing Moore's Law», *IEEE Annals of the History of Computing*, vol. 28, pp. 62–75, 2006.

[18] IMF, *IMF Blog - International Monetary Fund Blog*, 2017. (visited on).

[19] United States Department of the Treasury, *Debt to the Penny (Daily History Search Application)*, 2019. [Online]. Available: https://www.treasurydirect.gov/NP/debt/current (visited on).

[20] ITU, *New ITU statistics show more the half the world is now using the Internet*, 2018. [Online]. Available: https://news.itu.int/itu-statistics-leaving-no-one-offline/ (visited on).

[21] U. S. EPA, «Fast Facts: U.S. Transportation Sector Greenhouse Gas Emissions, 1990-2017 (EPA-420-F-19-047, June 2019)», 2019. [Online]. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100WUHR.pdf (visited on).

[22] ICCT, Rokadiya, Shikha, «Regulatory pathways for zero-emission vehicle mandates», 2019. [Online]. Available: https://theicct.org/sites/default/files/publications/ICCT_zev_mandates_India_20190703.pdf (visited on).

[23] C. C. C. IEEE, «The state of the art of electric and hybrid vehicles», 2002. [Online]. Available: https://core.ac.uk/download/pdf/37883668.pdf (visited on).

[24] International Energy Agency, «Global EV Outlook 2019», 2019.

[25] McKinsey&Company, «Competing for the connected customer - perspectives on the opportunities created by car connectivity and automation», 2015.

[26] Society of Automotive Engineers, *On-Board System Requirements for V2V Safety Communications J2945/1_201603*, 2016-03-30.

[27] KPMG, «Self-driving cars: The next revolution», 2012. [Online]. Available: https://staff.washington.edu/jbs/itrans/self_driving_cars[1].pdf (visited on).

[28] J. M. Anderson, N. Kalra, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, *Autonomous vehicle technology: A guide for policymakers*. Santa Monica CA: Rand Corporation, 2014. (visited on).

[29] Society of Automotive Engineers, *J3016B: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles - SAE International*, 2014. [Online]. Available: https://www.sae.org/standards/content/j3016_201806/ (visited on).

[30] U. S. DoT, *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation: Chapter 2*, 2017. [Online]. Available: https://ops.fhwa.dot.gov/congestion_report/chapter2.htm (visited on).

[31] B. Schneider, *The High Cost of Global Traffic Jams*, 2018. [Online]. Available: https://www.citylab.com/transportation/2018/02/traffics-mind-boggling-economic-toll/552488/ (visited on).

[32] INRIX, *AMERICANS WILL WASTE $2.8 TRILLION ON TRAFFIC BY 2030 IF GRIDLOCK PERSISTS*, 2014. [Online]. Available: http://inrix.com/press-releases/americans-will-waste-2-8-trillion-on-traffic-by-2030-if-gridlock-persists/ (visited on).

[33] Proceedings of the National Academy of Science, *100,000 Americans Die from Air Pollution, Study Finds*, 2018. [Online]. Available: https://www.usnews.com/news/national-news/articles/2019-04-08/100-000-americans-die-from-air-pollution-study-finds (visited on).

[34] Lancet, *Respiratory and cardiovascular responses to walking down a traffic-polluted road compared with walking in a traffic-free area in participants aged 60 years and older with chronic lung or heart disease and age-matched healthy controls: a randomised, crossover study*, 2017. [Online]. Available: https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(17)32643-0/fulltext?elscal=tlpr (visited on).

[35] Marron Institute of Urban Management, New York University School of Medicine, American Thoracic Society, «Trends in Excess Morbidity and Mortality Associated with Air Pollution above ATSRecommended Standards, 2008 to 2017», 2018. [Online]. Available: https://www.thoracic.org/about/newsroom/press-releases/conference/2019/health-of-the-air2.pdf (visited on).

[36] SFMTA, «SF Smart City Challenge_Final», 2018.

[37] Old Urbanist, *We Are the 25%: Looking at Street Area Percentages and Surface Parking*, 2011. [Online]. Available: https://oldurbanist.blogspot.com/2011/12/we-are-25-looking-at-street-area.html (visited on).

[38] RIHA, *RIHA Releases New Report: Quantified Parking - Comprehensive Parking Inventories for Five Major U.S. Cities | Mortgage Bankers Association*, 2018. [Online]. Available: https://www.mba.org/2018-press-releases/july/riha-releases-new-report-quantified-parking-comprehensive-parking-inventories-for-five-major-us-cities (visited on).

[39] Samuel J. Palmisano, «SJP_Smarter_Planet», 2008. [Online]. Available: https://www.ibm.com/ibm/cioleadershipexchange/us/en/pdfs/SJP_Smarter_Planet.pdf (visited on).

[40] C. Harrison, B. Eckman, R. Hamilton, P. Hartswick, J. Kalagnanam, J. Paraszczak, and P. Williams, «Foundations for Smarter Cities», *IBM Journal of Research and Development*, vol. 54, no. 4, pp. 1–16, 2010. DOI: 10.1147/JRD.2010.2048257. [Online]. Available: http://fumblog.um.ac.ir/gallery/902/Foundations%20for%20Smarter%20Cities.pdf (visited on).

[41] R. G. Hollands, «Will the real smart city please stand up?», *City*, vol. 12, no. 3, pp. 303–320, 2008. DOI: 10.1080/13604810802479126. [Online]. Available: http://labos.ulg.ac.be/smart-city/wp-content/uploads/sites/12/2017/03/Lecture-MODULE-3-2008-Will-the-real-smart-city-please-stand-up-Hollands.pdf (visited on).

[42] H. H. Sarbeswar Praharaj, *Cutting through the clutter of smart city definitions: A reading into the smart city perceptions in India*, 2019. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S1877916618302935?token=982FEBFDE501E46C7B3E7AEE5384EFC37BC4980B12B08755467795E1F551FC32910E8F0 (visited on).

[43] Andrea Caragliu, Chiara Del Bo, and Peter Nijkamp, «Smart cities in Europe», *3rd Central European Conference in Regional Science – CERS, 2009*, 2009. [Online]. Available: https://inta-aivn.org/images/cc/Urbanism/background%20documents/01_03_Nijkamp.pdf (visited on).

[44] CISCO and Dave Evans, «The Internet of Things - How the Next Evolution of the Internet Is Changing Everything», 2011. [Online]. Available: https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf (visited on).

[45] Luiz A. Bloem da Silveira Juniora, Eduardo Vasconcellosa, Liliana Vasconcellos Guedesa, Luis Fernando A. Guedesb, and Renato Machado Costa, «Technology roadmapping_ A methodological proposition to refine Delphi results | Elsevier Enhanced Reader», *Technological Forecasting & Social Change*, 2018. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S0040162516306734?token=282351F0FC58D7E39F2EC1A6BBA7B4D21149EC8988FADF (visited on).

[46] Hsi-Peng Lu, Chiao-Shan Chen, and Hueiju Yu b, «Technology roadmap for building a smart city: An exploring study on methodology», *Future Generation Computer Systems*, 2019. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S0167739X18304011?token=96072ED92CD1F974AC97BADBEE (visited on).

[47] atis, «Smart Cities Technology Roadmap», 2017. [Online]. Available: https://access.atis.org/apps/group_public/download.php/34053/ATIS-I-0000058.pdf (visited on).

[48] S. Shamsir, I. Mahbub, S. K. Islam, and A. Rahman, «Applications of sensing technology for smart cities», pp. 1150–1153, DOI: 10.1109/MWSCAS.2017.8053132.

[49] Kais Mekkia and Eddy Bajica, Frederic Chaxela, Fernand Meyerb, *A comparative study of LPWAN technologies for large-scale IoT deployment*, 2019. [Online]. Available: https://reader.elsevier.com/reader/sd/pii/S2405959517302953?token=91BD087B2B0F9DE6C62B7273D104FF525C37368AE2203FA6F423C (visited on).

[50] P. Deibert, «NGMN 5G White Paper», 2015. [Online]. Available: https://www.ngmn.org/fileadmin/ngmn/content/images/news/ngmn_news/NGMN_5G_White_Paper_V1_0.pdf (visited on).

[51] ITU, «Setting the Scene for 5G: Opportunities & Challenges», 2018. [Online]. Available: https://www.itu.int/en/ITU-D/Documents/ITU_5G_REPORT-2018.pdf (visited on).

[52] Rysavy Research, «2019-5G-Americas-Rysavy-Implications-of-a-Transformational-Technology-White-Paper», 2018.

[53] christy, «5G_Americas_White_Paper_on_5G_IOT_FINAL_7.16», 2019.

[54] The Government Summit, «2015-Smart Cities Report_Eng», 2015.

[55] Dubai Government ESS, *Smart Dubai 2021*, 2021. [Online]. Available: https://2021.smartdubai.ae/ (visited on).

[56] R45144, «Trends in Public Transportation Ridership: Implications for Federal Policy», 2018. [Online]. Available: https://fas.org/sgp/crs/misc/R45144.pdf (visited on).

[57] MaaSGlobal, *Whim - All your journeys with bus, tram, taxi, car, bike and more in 1 app.* 2019. [Online]. Available: https://maas.global/ (visited on).

[58] S. Hietanen, «PowerPoint-esitys», 2014. [Online]. Available: https://fsr.eui.eu/wp-content/uploads/150309-1-Hietanen-1.pdf (visited on).

[59] R. Utriainen and M. Pöllänen, «Review on mobility as a service in scientific publications», *Research in Transportation Business & Management*, vol. 27, pp. 15–23, 2018. DOI: 10.1016/j.rtbm.2018.10.005.

[60] Deloitte, «EN_Digital-Age-TRANSPORTATION_16.07.2014», 2014.

[61] Maria Kamargianni and Melinda Matyas, «The Business Ecosystem of Mobility-as-a-Service», 2017.

[62] P. Jittrapirom, V. Caiati, A.-M. Feneri, S. Ebrahimigharehbaghi, M. J. A. González, and J. Narayan, «Mobility as a Service: A Critical Review of Definitions, Assessments of Schemes, and Key Challenges», *Urban Planning*, vol. 2, no. 2, p. 13, 2017. DOI: 10.17645/up.v2i2.931.

[63] H. Ozaki, «Technical standardization of ITS and Asian initiatives for intelligent mobility», *IATSS Research*, vol. 42, no. 2, pp. 72–75, 2018. DOI: 10.1016/j.iatssr.2018.05.002.

[64] Clayton M. Christensen, Michael E. Raynor, and Rory McDonald, «2015-What Is Disruptive Innovation_», 2015.

[65] F. Sprei, «Disrupting mobility», *Energy Research & Social Science*, vol. 37, pp. 238–242, 2018. DOI: 10.1016/j.erss.2017.10.029.

[66] AlixPartners, *The AlixPartners Global Automotive Outlook 2019 | AlixPartners*, 2019. [Online]. Available: https://www.alixpartners.com/media-center/press-releases/alixpartners-global-automotive-industry-outlook-2019/ (visited on).

[67] Z. Wadud, D. MacKenzie, and P. Leiby, «Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles», *Transportation Research Part A: Policy and Practice*, vol. 86, pp. 1–18, 2016. DOI: 10.1016/j.tra.2015.12.001.

[68] RethinkX, «2017-Rethink-transportation-2020-2030», 2017.

[69] David A. Hensher, «Future bus transport contracts under a mobility as a service (MaaS) regime in the digital age: are they likely to change?», 2017. [Online]. Available: https://ses.library.usyd.edu.au/bitstream/2123/17497/1/Thredbo_15_Thredbo_15_Paper_2.pdf (visited on).

[70] A. Melis, M. Prandini, L. Sartori, and F. Callegati, «Public Transportation, IoT, Trust and Urban Habits», in *Internet Science*, ser. Lecture Notes in Computer Science, F. Bagnoli, A. Satsiou, I. Stavrakakis, P. Nesi, G. Pacini, Y. Welp, T. Tiropanis, and D. DiFranzo, Eds., vol. 9934, Cham: Springer International Publishing, 2016, pp. 318–325. DOI: 10.1007/978-3-319-45982-0{\textunderscore}27.

[71] Advancing public transport, «pUbliC TraNspOrT aT The hearT Of The iNTegraTeD UrbaN mObiliTy sOlUTiON20solution», 2016. [Online]. Available: http://www.uitp.org/sites/default/files/cck-focus-papers-files/Public%20transport%20at%20the%20heart%20of%20the%20integrated%20urban%20mobility%20solution.pdf (visited on).

[72] G. Smith, J. Sochor, and I. M. Karlsson, «Mobility as a Service: Development scenarios and implications for public transport», *Research in Transportation Economics*, vol. 69, pp. 592–599, 2018. DOI: 10.1016/j.retrec.2018.04.001.

[73] M. Zellner, D. Massey, Y. Shiftan, J. Levine, and M. J. Arquero, «Overcoming the Last-Mile Problem with Transportation and Land-Use Improvements: An Agent-Based Approach», *International Journal of Transportation*, vol. 4, no. 1, pp. 1–26, 2016. DOI: 10.14257/ijt.2016.4.1.01. [Online]. Available: https://pdfs.semanticscholar.org/de11/623f8250b8aa70ad535e4f4319a5ad244049.pdf (visited on).

[74] Populus, «The Micro-Mobility Revolution», 2018.

[75] T. Huddleston JR., *Uber and Alphabet just invested $335 million in Lime — here's why scooter start-ups are suddenly worth billions*, 2018. [Online]. Available: https://www.cnbc.com/2018/07/11/lime-bird-spin-why-scooter-start-ups-are-suddenly-worth-billions.html (visited on).

[76] NHTS, *Number of Vehicle Trips by Trip Distance*, 2009. [Online]. Available: https://nhts.ornl.gov/tables09/fatcat/2009/vt_TRPMILES.html (visited on).

[77] S. Smith and J. P. Schwieterman, «Evaluating the potential Mobility Benefits of Shared Dockless Scooter in Chicago», 2018.

[78] McKinsey&Company, «MICROMOBILITY'S 15,000-MILE CHECKUP», 2019.

[79] Deloitte, *Micromobility is the future of urban transportation | Deloitte Insights*, 2019. [Online]. Available: https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/micro-mobility-is-the-future-of-urban-transportation.html (visited on).

[80] Joël Hazan, Nikolaus Lang, and Hind El Abassi Chraibi, «Seeking Perpetual Motion with Mobility as a Service», 2019. [Online]. Available: http://image-src.bcg.com/Images/BCG-Seeking-Perpetual-Motion-with-Mobility-as-a-Service-Mar-2019_tcm9-215903.pdf (visited on).

[81] Goldman Sachs, «Rethinking Mobility: The 'pay as you go' car: Ride hailing just the start», 2017.

[82] Accenture, «Mobility as a Service | Accenture», 2018. [Online]. Available: https://www.accenture.com/_acnmedia/pdf-71/accenture-mobility-service.pdf (visited on).

[83] G. Goodall, «TCO:What's old is new», *Processor*, vol. 30, no. 12, 2008.

[84] D. Zeger and R. Filip, «Effectively Selecting Suppliers Using Total Cost of Ownership», 1999.

[85] L. M. Ellram, «A Framework for Total Cost of Ownership», *The International Journal of Logistics Management*, vol. 4, no. 2, pp. 49–60, 1993. DOI: 10.1108/09574099310804984.

[86] Z. Degraeve, E. Labro, and F. Roodhooft, «Total cost of ownership purchasing of a service: The case of airline selection at Alcatel Bell», *European Journal of Operational Research*, vol. 156, no. 1, pp. 23–40, 2004. DOI: 10.1016/j.ejor.2003.08.002.

[87] G. Wu, A. Inderbitzin, and C. Bening, «Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments», *Energy Policy*, vol. 80, pp. 196–214, 2015. DOI: 10.1016/j.enpol.2015.02.004.

[88] L. M. Ellram, «Total cost of ownership», *International Journal of Physical Distribution & Logistics Management*, vol. 25, no. 8, pp. 4–23, 1995. DOI: 10.1108/09600039510099928.

[89] L. Ellram, «Total Cost of Ownership: Elements and Implementation», *International Journal of Purchasing and Materials Management*, vol. 29, no. 3, pp. 2–11, 1993. DOI: 10.1111/j.1745-493X.1993.tb00013.x.

[90] U. S. EPA, «Peer Review for the Report, "How Consumers Value Fuel Economy: A Literature Review" (EPA-420-S-10-001) (April 2010)», 2010.

[91] S. Moon and D.-J. Lee, «An optimal electric vehicle investment model for consumers using total cost of ownership: A real option approach», *Applied Energy*, vol. 253, p. 113 494, 2019. DOI: 10.1016/j.apenergy.2019.113494.

[92] T. E. Lipman and M. A. Delucchi, «A retail and lifecycle cost analysis of hybrid electric vehicles», *Transportation Research Part D: Transport and Environment*, vol. 11, no. 2, pp. 115–132, 2006. DOI: 10.1016/j.trd.2005.10.002.

[93] S. Bubeck, J. Tomaschek, and U. Fahl, «Perspectives of electric mobility: Total cost of ownership of electric vehicles in Germany», *Transport Policy*, vol. 50, pp. 63–77, 2016. DOI: 10.1016/j.tranpol.2016.05.012.

[94] P. Z. Lévay, Y. Drossinos, and C. Thiel, «The effect of fiscal incentives on market penetration of electric vehicles: A pairwise comparison of total cost of ownership», *Energy Policy*, vol. 105, pp. 524–533, 2017. DOI: 10.1016/j.enpol.2017.02.054.

[95] J. Hagman, S. Ritzén, J. J. Stier, and Y. Susilo, «Total cost of ownership and its potential implications for battery electric vehicle diffusion», *Research in Transportation Business & Management*, vol. 18, pp. 11–17, 2016. DOI: 10.1016/j.rtbm.2016.01.003.

[96] L. K. Mitropoulos, P. D. Prevedouros, and P. Kopelias, «Total cost of ownership and externalities of conventional, hybrid and electric vehicle», *Transportation Research Procedia*, vol. 24, pp. 267–274, 2017. DOI: 10.1016/j.trpro.2017.05.117.

[97] B. M. Al-Alawi and T. H. Bradley, «Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles», *Applied Energy*, vol. 103, pp. 488–506, 2013. DOI: 10.1016/j.apenergy.2012.10.009.

[98] H. L. Breetz and D. Salon, «Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 U.S. cities», *Energy Policy*, vol. 120, pp. 238–249, 2018. DOI: 10.1016/j.enpol.2018.05.038.

[99] R. Danielis, M. Giansoldati, and L. Rotaris, «A probabilistic total cost of ownership model to evaluate the current and future prospects of electric cars uptake in Italy», *Energy Policy*, vol. 119, pp. 268–281, 2018. DOI: 10.1016/j.enpol.2018.04.024.

[100] C. Hou, H. Wang, and M. Ouyang, «Battery Sizing for Plug-in Hybrid Electric Vehicles in Beijing: A TCO Model Based Analysis», *Energies*, vol. 7, no. 8, pp. 5374–5399, 2014. DOI: 10.3390/en7085374.

[101] L. Kenneth, Philippe Lebeau, Cathy Macharis, and Joeri Van Mierlo, «How expensive are electric vehicles? A total cost of ownership analysis», 2013.

[102] M. Coffman, P. Bernstein, and S. Wee, «Integrating electric vehicles and residential solar PV», *Transport Policy*, vol. 53, pp. 30–38, 2017. DOI: 10.1016/j.tranpol.2016.08.008.

[103] Y. He, Q. Zhang, and Y. Pang, «The development pattern design of Chinese electric vehicles based on the analysis of the critical price of the life cycle cost», *Energy Policy*, vol. 109, pp. 382–388, 2017. DOI: 10.1016/j.enpol.2017.07.015.

[104] T. Gnann, P. Plötz, S. Funke, and M. Wietschel, «What is the market potential of plug-in electric vehicles as commercial passenger cars? A case study from Germany», *Transportation Research Part D: Transport and Environment*, vol. 37, pp. 171–187, 2015. DOI: 10.1016/j.trd.2015.04.015.

[105] P. Letmathe and M. Suares, «A consumer-oriented total cost of ownership model for different vehicle types in Germany», *Transportation Research Part D: Transport and Environment*, vol. 57, pp. 314–335, 2017. DOI: 10.1016/j.trd.2017.09.007.

[106] A. Le Duigou and A. Smatti, «On the comparison and the complementarity of batteries and fuel cells for electric driving», *International Journal of Hydrogen Energy*, vol. 39, no. 31, pp. 17 873–17 883, 2014. DOI: 10.1016/j.ijhydene.2014.08.077.

[107] E. A. Gilmore and L. B. Lave, «Comparing resale prices and total cost of ownership for gasoline, hybrid and diesel passenger cars and trucks», *Transport Policy*, vol. 27, pp. 200–208, 2013. DOI: 10.1016/j.tranpol.2012.12.007.

[108] Q. de Clerck, T. van Lier, M. Messagie, C. Macharis, J. van Mierlo, and L. Vanhaverbeke, «Total Cost for Society: A persona-based analysis of electric and conventional vehicles», *Transportation Research Part D: Transport and Environment*, vol. 64, pp. 90–110, 2018. DOI: 10.1016/j.trd.2018.02.017.

[109] Aymeric Rousseau, Martin Redelbach, Horst E. Friedrich, Francois Badin, Namdoo Kim, and Danilo Santini, «Comparison of Energy Consumption and Costs of Different Plug-in Electric Vehicles in European and American Context», 2015.

[110] S. Carley, N. Zirogiannis, S. Siddiki, D. Duncan, and J. D. Graham, «Overcoming the shortcomings of U.S. plug-in electric vehicle policies», *Renewable and Sustainable Energy Reviews*, vol. 113, p. 109 291, 2019. DOI: 10.1016/j.rser.2019.109291.

[111] A. van Velzen, J. A. Annema, G. van de Kaa, and B. van Wee, «Proposing a more comprehensive future total cost of ownership estimation framework for electric vehicles», *Energy Policy*, vol. 129, pp. 1034–1046, 2019. DOI: 10.1016/j.enpol.2019.02.071.

[112] Jennifer Kurtz, Sam Sprik, Genevieve Saur, and Shaun Onorato, «On-Road Fuel Cell Electric Vehicles Evaluation: Overview», 2019. [Online]. Available: https://www.nrel.gov/docs/fy19osti/73009.pdf (visited on).

[113] Consumer Report, *How much that new car will really cost*, 2015. [Online]. Available: https://www.consumerreports.org/cro/news/2012/08/how-much-that-new-car-will-really-cost/index.htm (visited on).

[114] European Commission, «REGULATION (EEC) No 4064/89 MERGER PROCEDURE», 1999. [Online]. Available: https://ec.europa.eu/competition/mergers/cases/decisions/m1406_en.pdf (visited on).

[115] Autoblog, *FIAT 500 Prices, Reviews and New Model Information*, 2019. [Online]. Available: https://www.autoblog.com/fiat/500/ (visited on).

[116] Tesla, *Model 3 | Tesla*, 2019. [Online]. Available: https://www.tesla.com/model3 (visited on).

[117] Green Car Report, *GM wins US grant to develop solid-state batteries*, 2019. [Online]. Available: https://www.greencarreports.com/news/1124702_gm-wins-us-grant-to-develop-solid-state-batteries (visited on).

[118] Digital Trends, *Toyota May Introduce Solid-state Batteries for Electric Cars By 2020 | Digital Trends*, 2019. [Online]. Available: https://www.digitaltrends.com/cars/toyota-may-introduce-solid-state-batteries-for-electric-cars-by-2020/ (visited on).

[119] Autoblog, *2019 Toyota Camry XLE V6 4dr Sedan Pictures*, 2019. [Online]. Available: https://www.autoblog.com/buy/2019-Toyota-Camry-XLE_V6__4dr_Sedan/photos/ (visited on).

[120] Matteo Leschiera, 2019.

[121] N. Lutsey, «Efficiency technology and cost assessment for U.S. 2025–2030 light-duty vehicles», 2017. [Online]. Available: https://theicct.org/sites/default/files/publications/US-LDV-tech-potential_ICCT_white-paper_22032017.pdf (visited on).

[122] U.S. EPA, Office of Transportation and Air Quality, Assessment and Standards Division, and prepared by RTI International and Transportation Research Institute - University of Michigan, «Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers (EPA-420-R-09-003)», 2009.

[123] P. A. Nelson, S. Ahmed, K. G. Gallagher, and D. W. Dees, *Modeling the Performance and Cost of Lithium-Ion Batteries for Electric-Drive Vehicles, Third Edition*, 2019. DOI: 10.2172/1503280.

[124] S. Plotkin, M. Singh, P. Patterson, J. Ward, F. Wood, N. Kydes, J. Holte, J. Moore, G. Miller, S. Das, and D. Greene, *Multi-Path Transportation Futures Study. Vehicle Characterization and Scenario Analyses: Main Text and Appendices A, B, C, D, and F*, 2009. DOI: 10.2172/1219274.

[125] I. Vema, «UBS-evidence-lab-electric-car-teardown», 2017.

[126] N. Lutsey, «Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030», *Energies*, vol. 10, no. 9, p. 1314, 2017. DOI: 10.3390/en10091314.

[127] American Automobile Association, «How much are you really paying to drive?», 2019.

[128] R. Stumpf, *Americans Cite Range Anxiety, Cost as Largest Barriers for New EV Purchases: Study*, 2019. [Online]. Available: https://www.thedrive.com/news/26637/americans-cite-range-anxiety-cost-as-largest-barriers-for-new-ev-purchases-study (visited on).

[129] Lamber F., *Tesla battery data shows path to over 500,000 miles on a single pack - Electrek*, 2016. [Online]. Available: https://electrek.co/2016/11/01/tesla-battery-degradation/ (visited on).

[130] Wikipedia, *Uber - Wikipedia*, Wikipedia, Ed., 2019. [Online]. Available: https://en.wikipedia.org/w/index.php?oldid=922146132 (visited on).

[131] Wikipedia, *Lyft - Wikipedia*, Wikipedia, Ed., 2019. [Online]. Available: https://en.wikipedia.org/w/index.php?oldid=920702625 (visited on).

[132] Engadget, *Waymo bids its self-driving bubble cars farewell*, 2019. [Online]. Available: https://www.engadget.com/2017/06/13/waymo-retires-self-driving-bubble-cars/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xl guce_referrer_sig=AQAAADYE7sPOGzoctB9b0KLiuhhFqziQxyhx2ANhQps3g1TpQX1_FfLCTl2lAxkCnDCg4mQ79S4kyrfCA1Rost-g7cWkz7MYG6mHtto_tDfTWjQu7jt0IIc5X8KVqEJ9C 8gncu55HW_ (visited on).

[133] Ashley Nunes and Kristen D. Hernandez, «Autnomous Vehicles and Public Health: High Cost or High Opportunity Cost?», 2019.

[134] M. Broussard, *The Dirty Truth Coming for Self-Driving Cars*, 2018. [Online]. Available: https://slate.com/technology/2018/05/who-will-clean-self-driving-cars.html (visited on).

[135] Car2Go, *car2go US*, 2019. [Online]. Available: https://www.car2go.com/US/en/ (visited on).

[136] ZipCar, *Car Sharing: An Alternative to Car Rental with Zipcar*, 2019. [Online]. Available: https://www.zipcar.com/ (visited on).

[137] ZipCar, *Avis Budget Group To Acquire Zipcar For $12.25 Per Share In Cash | Zipcar Press Center*, 2013. [Online]. Available: https://www.zipcar.com/press/releases/avis-budget-group-acquires-zipcar (visited on).

[138] Federal Highway Administration, *FOTW #1042, August 13, 2018: In 2017 Nearly 60% of All Vehicle Trips Were Less than Six Miles*, 2018. [Online]. Available: https://www.energy.gov/eere/vehicles/articles/fotw-1042-august-13-2018-2017-nearly-60-all-vehicle-trips-were-less-six-miles (visited on).

[139] V. Ho, *Stolen, burned, tossed in the lake: e-scooters face vandals' wrath*, 2018. [Online]. Available: https://www.theguardian.com/us-news/2018/dec/28/scooters-california-oakland-los-angeles-bird-lime (visited on).