Understanding how incentivizing Autonomous Vehicles to use TEXpress lanes may stimulate their diffusion in the Metroplex

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor of Business Administration by Julián Monsó Bustio

November 2021

Abstract

Public Private Partnerships (PPP) are becoming common in the US to develop multibillion infrastructure projects (e.g., highways). PPP developers take over the responsibility of designing, building, financing, operating, and maintaining (DBFOM) the asset for periods of time up to 99 years. In exchange, they are given the right to collect a toll fee from the drivers willing to use an infrastructure that offers better road safety and saves time. My company is one of the most prominent incumbents in the PPP market.

The innovations brought by the private partner are important in identifying the synergies between the different components of the project to increase the value of the asset. The requisite knowledge can only be provided by experienced and integrated multidisciplinary teams. However, the PPP market is maturing, and this knowledge is rapidly spreading across a wide number of newcomers, including financial investors (from pension plans to investment funds) attracted to investments that are long-term, low risk, and inflation protected.

This forces my company to innovate beyond our usual domains to maintain our competitive edge. The development of autonomous vehicles (AV) is widely seen by the industry as one of the key trends that shape the future of the automotive industry (KPMG, 2020). Although there is a general agreement that we will not see a massive number of AV in the short term, even gradual increases in automation will have profound impacts on the movement of people and goods (MIT, 2020). Such increases will be unevenly distributed across geographic areas, with the US offering one of the most prepared environments to support this transition (KPMG, 2020). PPP developers who are able to better understand the trajectory of this transition process and its consequences on the long-term value of the infrastructure may have an important competitive advantage.

The transition to AV will unfold in a sociotechnical system with multiple variables retrofitting each other, which adds to the unpredictability of the scenarios. Among the different transitions that the automotive industry has seen in the last century, the diffusion of Battery Electric Vehicles (BEV) is likely to be the closest transition to the deployment of AV. The convenience of incentivizing the diffusion of BEV has long been a controversial research subject. On the one hand, it is a point of contention whether the positive externalities created by BEV are significant enough to compensate for the cost of incentivizing them. On the other hand, the ease and convenience of establishing a feebate system has also been acknowledged, given the feasibility of encapsulating the local costs and benefits of such a schema in a

transparent and robust manner, so that AV can be incentivized and the Internal Combustion Engines (ICE) disincentivized by imposing a CO2 fee.

The current study interrogates the phenomenon of the diffusion of AV in the Dallas Fort Worth Metroplex and examines the possibility that a discounted access to TEXpress highway network for AVs may accelerate their penetration. Although the research explores adoption theories and constructs which mainly offer perspectives from the consumer's perspective, the organizational perspective is capital to the study.

Wisdom et al. (2014:480) refer to Frambach & Schillevaert to split the adoption of innovations in organizations into two stages: the organization's decision to pursue the innovation and the staff's acceptance and initiation of their individual processes of accepting the innovation. Shared understanding plays a pivotal role in solidifying the process, and thus the research explores the means of creating a consensus and actions an organization may take to influence the process.

Using a systematic approach based on a Mixed Mode Research (MMR) methodology, which combines quantitative (System Dynamics) and qualitative (Action Research and Multi-Level Perspective) methods, and a literature review, which places the transition to BEV as its core, this thesis provides exploratory evidences to support the hypothesis that incentivizing AV in the Metroplex is in the best interest of the public good, as the cost of such an incentive is less than the value of the positive externalities created. It also corroborates the notion that this incentive may increase the diffusion of AV, creating a virtuous circle which may drive the penetration of AV beyond the break-even point where it is self-sustainable.

Nevertheless, the study has also uncovered how tortuous, complex, and uncertain this transition will be, an observation that might cast a shadow over the above conclusions. Furthermore, the actions of the action research group and the subsequent inquiry process have proven the various perceptions that the different departments of my organization have about future actions and the consequences of this diffusion. This suggests that an internal organizational process that combines further research with education shall take precedence over approaching other stakeholders for support.

Acknowledgements

I would like to extend my deepest gratitude to my primary supervisor Professor Ron Fisher. His perseverance and wise guidance during the three years of this research, right from the early discussions about the topic and research questions, have been critical in ensuring a balance between academic rigor and practitioner perspective. Thanks as well to my secondary supervisor Jill Shepherd, who always provided keen and proper reviews to the different drafts, and to Felipe Haro without whose help the SD model would not have been possible. My gratitude to my superiors for their support (Nicolás Rubio and Belén Marcos) and to my practitioner peers (Travis Fustes, Alfonso Chicharro, Luis Berriochoa, and Jennifer Kim, among others), who willingly invested their time and energy in a discussion which I hope opened their minds to new challenges and quests for our organization and their professional careers. And finally, finally, thanks to my wife Cristina, for her patience during these last three years, and to my children, Julia, Pol, and Paula, for the many family movies I missed.

Although an extensive literature review was conducted with a significant number of papers and studies used as reference for the different models and data, it is fair to highlight some which have been the main sources of inspiration for the current project. Two PhD projects are particularly noteworthy when informing my research methodology. Holmström (2017), in exploring the intersections between SD and AR, demonstrated how both tools can be integrated to enhance the understanding of the system, which provided the prerequisites to use the results in practice. Mazur (2015), in showing how Multi-level Perspective can be used as a framework to better understand the socio-technical regime and the most likely transition pattern, helped in making sense of the different actions taken by the AR group. In addition, Nieuwenhuijsen et al. (2018) and Gnann et al. (2015) have been used as references when modeling the diffusion and utility of AV.

Acronyms

AADT	Average Annual Daily Traffic
ABM	Agent Based Modelling
ACE	Autonomous, Connected, and Electrification technologies
AFDC	Alternative Fuels Data Center
AR	Action Research
ARM	Advanced RISC Machine
AV	Autonomous Vehicle
AVS	Clean Air Vehicle Sticker
A&M	Texas A&M University
BEV	Battery Electric Vehicle
CAS	Complex Adaptative System
CBO	Congressional Budget Office
CLD	Causal Loop Diagram
CTR	Center for Transportation Research
CV	Connected Vehicle
C-V2X	Cellular Vehicle to Everything
DBA	Doctor Business Administration
DFW	Dallas Fort Worth
EBM	Equation Based Modelling
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ETSC	European Transport Safety Council

FCEV	Fuel Cell Vehicle
FR	Final Rule
GHG	Greenhouse Gas
GM	General Motors
HEV	Hybrid Electrical Vehicle
HOV	High Occupancy Vehicle
ICE	Internal Combustion Engine
ISRRPP	Interstate System Reconstruction and Rehabilitation Pilot Program
LBJ	Lyndon B Johnson Express
LDV	Light-Duty Vehicle
LS	Learning Set
ML	Managed Lane
MLP	Multi-Level Perspective
NCTCOG	North Central Texas Council of Governments
NHTSA	National Highway Traffic Safety Agency
NPV	Net Present Value
NRC	National Research Council
NTE	North Tarrant Express
NTTA	North Texas Tollway Agency
OD	Origin Destination
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PAR	Preceptory Action Research

PHEV	Plug-in Hybrid Electrical Vehicle
PM	Participatory Modelling
PPP	Public Private Partnership
R&D	Research & Development
SAE	Society of Autonomous Engineers
SAV	Shared Autonomous Vehicle
SD	System Dynamics
TCFC	Texas Connected Freight Corridor
TCO	Total Cost of Ownership
TERP	Texas Emissions Reduction Plan
TTC	Time to Collision
TTI	Texas Transportation Institute
TxDOT	Texas Department of Transportation
TxETRA	Texas Electric Transportation Resources Alliance
USDOE	US Department of Energy
USDOT	US Department of Transportation
VMT	Vehicle Mileage Travel
VSL	Value of Statistical Life
WtP	Willingness to Pay
WtC	Willingness to Consider
ZEV	Zero Emission Vehicle

Contents

List of Figures

List of Tables

1 Introduction

Public Private Partnerships (PPP) to develop large infrastructure projects is not a new, or even a recent, concept; it has been several centuries in the making. This long track record has resulted in multiple variants which shape the risk profile of each party. Essentially, they are the result of two criteria: i) the way in which the risk and the scope of the project (Design, Build, Finance, Operate, Maintain) is split between the public and the private partner, and ii) the source of revenue for the private partner which may be tolls from the user, therefore assuming demand (traffic) risk, or it may receive payment flows from the public partner, thus removing the risk of demand as those payments are (i) shadow toll, if payment is based on the usage of a customer that does not pay a toll to the concessionaire; and (ii) availability fee or annuity, if payment is based on the available capacity.

Our company, one of the largest PPP developers in the world, is targeting Managed Lanes (ML) traffic risk projects in the US. A ML (otherwise called an express lane) is a toll road in which several lanes of a corridor are tolled with a fee that depends on the density of vehicles using them to keep a minimum speed in these lanes. The fact that the remaining lanes are not tolled means that the revenue (and, therefore, the value of the asset) of the ML project is heavily dependent on the congestion of the non-tolled lanes (General Purpose Lanes).

Out of all the projects in the US, our projects in the Metroplex currently represent the largest proportion. The Metroplex is the largest inland metropolitan area in the US. It includes the cities of Dallas and Fort Worth and 19 counties that cover about 15,600 square miles with an estimated total population of 7.4 million in 2017 or more than 27 percent of the total population of Texas.

The three projects (LBJ, NTE 1&2, and NTE 35W) are an important part of an urban network (TEXpress), which provides an uncongested driving alternative in the Metroplex. The present research, with its focus on PPP, is grounded in the proposed innovation as it will take place in a network (TEXpress) which includes highways operated by a public agency (TxDOT) and others developed under a PPP schema between TxDOT and a consortium of private companies.

Any incentive given to autonomous vehicles (AV) in TEXpress will need to have the agreement of both the public and private stakeholders (even beyond those directly involved in the operation of the highways), and this research needs to identify the next steps toward aligning their views.

1.1 Workplace problem

In 1989, the California legislature passed AB680 which allowed Caltrans (California Department of Transportation) to execute agreements with private entities for the construction and operation of highways. In 1992, a partnership between Caltrans and a consortium of three private partners became the first PPP project in the US. Since then, PPP agreements have facilitated a myriad of highway projects in the US.

The benefits of PPP are multiple, but most of them stem from the ability of the private sponsor to maximize the value of the project by mastering an understanding of the multiple risks involved. In this regard, the competitive advantage of our organization as a PPP developer is supported by three pillars:

I. A proficiency of the multiple risks that these multibillion projects face and the proper measures to mitigate them (this allows for a reduction of the contingencies needed to build a project, thus reducing the cost).
II. Our capacity to maximize the demand of the project.
III. Our capability to perform the whole value chain. This allows us to maximize the value of the asset, as different alternatives to the reference design are evaluated and implemented by the same organization, which reduces costs and avoids cross liabilities between different partners.

Given the need for long-term financing, a project financing structure guaranteed by the expected cash-flow of the project is usually the preferred alternative. This structure has traditionally involved a combination of industrial sponsors that provide equity, lending institutions that provide loans, and some degree of state or federal credit assistance.

Nevertheless, the long track record of the industry has improved the ability of these different stakeholders to properly assess the risk – from the traffic and revenue engineering companies that forecast the expected demand to the design and construction companies that evaluate the risk associated with the construction, environment, or right of way.

This process has strongly influenced the attitudes of the lending institutions, incentivizing them to take a role as equity holders, even beyond asset recycling. The top manager of IFM, one of the leading Australian investment funds, has been recently quoted, “We are prepared for substantial investment in greenfield projects (before the income stream is proven), if the risk-and-reward returns are acceptable” (Chong, 2017). The cost of the money for these lenders is usually lower than ours (if they are large pension plans), and therefore, they are highly competitive.

In addition, the improved understanding of cities and states concerning the risk profile of these projects, combined with their access to the tax-exempt bond market, allows most of them to raise money inexpensively, increasing the total value of the project to limits unattainable by a PPP sponsor.

These changes in the market erode our competitive edge, increasing the pressure on our organization to keep a pace of permanent innovation in a variety of business domains including products, business model, or management strategies. In this regard, the development and diffusion of AV is an innovation expected to change our industry in a way unseen in the last century and is likely to spur a rapid process of change in these three domains.

Our business organization is set around small local teams that operate the projects. These teams rarely grow over a couple of hundred employees and follow a standardized organizational chart. Although they are supported by our corporate services, the agendas of the different equity holders sometimes limit the scope of services they may share.

AV may impact our organization structure significantly in numerous areas including operational processes (e.g., collecting toll fees or managing traffic), retention of the same business model by altering the capacity of the corridor (and therefore the appetite of the driver to pay a toll fee), or creation of opportunities for new sources of revenue. Furthermore, having a significant proportion of the vehicles on the roads connected through the services provided by their manufacturers will allow for a standardization of several processes which are currently being tailored for individual projects. It will produce huge economies of scale but, at the same time, will reduce the autonomy and local resources to be deployed for the individual projects.

Our group is also navigating a process of change in our business model which will divest an important part of our activities and geographical areas where we operate. This will allow us to concentrate on providing services that have been determined as ‘core’ by our top management. Providing infrastructure in the US through PPP is one of these core assets.

Taking both these facts into consideration, two areas of critical importance have been identified to ensure that the diffusion of AV will be the innovation driver that will ensure the competitiveness of our company in the marketplace: being able to forecast the rate of the aforementioned changes and means of influencing them in the local context of the Metroplex.

1.2 AV as a driver for innovation

Innovation, as a key component of competitiveness, has long been acknowledged as a vital ingredient to maintain our leadership and industrial relevance; hence, it is also the solution to our workplace problem. In this regard, the introduction of AV is widely considered as an innovation likely to spur a dramatic change not only in the transportation industry but in our society as well. Nevertheless, the diffusion of AV is likely to take several decades and be subjected to an uncertain process, as it is the result of multiple drivers whose evolution is very difficult to predict.

Although there is a general agreement that the introduction of AV would have a positive effect on our industry (by increasing the total vehicle miles driven) and on the society (by increasing the capacity and safety of the whole road network), a significant number of its benefits will emerge as positive externalities (e.g., environmental impacts or health and safety benefits) and, therefore, will not be considered by the consumer when evaluating its advantages. This creates a significant barrier to its diffusion, which suggests that, until the market is capable to support the diffusion by itself, a program of incentives to stimulate the demand will have to take a prime role to spur the growth of AV on our roads. Critical to this process is the net balance between the cost of the incentives and the value of these positive externalities, which will ultimately justify public policies.

The many technologies and their potential relevance during the transition process increase the uncertainty of its outcome. Battery Electric Vehicles (BEV)[1], Shared Autonomous Vehicles (SAV), and Connected Vehicles (CV) may have widely different roles. There seems to be a common understanding in choosing BEV powertrains as a preferred platform for AV in detriment of Internal Combustion Engines (ICE); therefore, the current policies that incentivize the diffusion of BEV may not be strange to the diffusion of AV and are likely to provide the groundwork for framing incentives to support the diffusion of AV. Fleets of SAV may coexist with privately owned AV, being driven autonomously in geofenced areas. The increasing use of SAV (seen before COVID-19), although limited, will increase the rate of abandoning of conventional vehicles, facilitating the introduction of CV technologies in vehicles. Due to the number of applications that make an intensive use of this technology, it will become a standard feature of AV and the cornerstone of those public policies targeted to align the

[1] The acronym BEV is used to refer to all zero emission vehicle (ZEV) powertrains including BEV, plug-in hybrids (PHEV), and Hydrogen fuell cell vehicles (FCEV).

private use of AV with the public good, especially when discouraging an improper use of AV in urban areas.

This process creates a complex system in which the multiple potential outcomes offered by the different technologies and new business models combine with the high degree of uncertainty when forecasting the reaction of the consumer to a change in which externalities are a significant player.

1.3 Aim of the research and research questions

The present research evaluates how a discounted access to TEXpress may increase the diffusion of AVs in the Metroplex. It also explores how building shared understanding through our organization can influence the process.

The research questions are as follows:

1. How will incentivizing the usage of TEXpress by AV facilitate its diffusion in the Metroplex?
2. What will be the extent of diffusion?
3. What will be the net balance for their public good?
4. What are the actionable implications for the organization resulting from the research?

1.4 Contextual perspective

The interplay between local and global markets in the automotive industry is unrivalled. Development roadmaps are often influenced by several global considerations (e.g., availability of new technologies, the evolution of the pricing to the consumer, or even the pressure on policymakers to reshape legal framework in a more suitable manner) and incentives which may overshadow the local consumer patterns. This adds a layer of complexity to this research because although this is meant to produce findings relevant in the local context of the Metroplex, some of the factors under consideration (those that depend on R&D investments or federal legal framework) will be discussed within the US perspective.

The research is cognizant of overcoming challenges to the production of actionable knowledge in an environment subject to a high-speed process of change and the imperfect knowledge of the drivers at play, which are unlikely to lead to precise outcomes. Therefore, the outputs of any simulation are likely to reflect this uncertainty. However, in this exploratory study, the simulation aims to draw high-level findings which may inform the researcher’s practice and enlighten further actions at an organizational and societal level concerning the consequences of deploying AV in an urban network.

1.5 Supporting literature

Multiple research streams can be isolated as relevant to my workplace problem. Not all of them were obvious from the beginning; some were not identified until after an initial systematic review was performed. Four research streams are relevant to my research: i) the use of research methodologies and frameworks to explore the diffusion of innovations, ii) the research on transition paths to AV, iii) the research on externalities and policies to incentivize BEV, and iv) the Metroplex as a local environment for the diffusion of AV.

There is a vibrant research stream focused on the diffusion of innovations in transportation, offering multiple branches with different paradigms and approaches. To provide a framework which may later be the basis of my research methodology, I initially conducted an exhaustive literature review with the intention to identify the most significant lines of inquiry used. In this way, I considered the concepts of sociotechnical systems and sustainable transitions, including the different qualitative analytical frameworks, which have been posited to research their dynamics and mechanisms such as multi-level perspective (MLP) and transition management. I also reviewed the diversity of quantitative models, including System Dynamics (SD) and Complex Adaptative Systems (CAS), to finalize the opportunities of mixing both paradigms by involving the different stakeholders in a collaborative inquiry process.

AV will not be deployed in isolation, the transition will take years with different powertrains coexisting, and while new business models will appear, others will disappear, reshape, or be reduced to niches. This results in different potential scenarios depending not only on the assumptions taken but also on local circumstances that will lead to different types of transitions. The transition scenario chosen for this research will be of critical importance for the credibility of my findings, as it will frame the actionable actions and hypothesis. A second research stream focuses on the components considered in the different roadmaps for AV diffusion proposed in the available literature.

Given the environmental pressure and the technological availability, BEV was the first “revolution” that aroused the interest of policymakers in establishing public policies to stimulate their demand, soon followed by share vehicles, albeit to a lesser extent. There is a rich research stream which offers empirical evidence about the results of such programs, and although the circumstances of both transitions (BEV and AV) are slightly different, it provides a rich source of data.

Finally, the available literature offers ample evidence of the importance of localizing the transition in its proper context. In this regard, a fourth research stream reviewed considers the environmental and road safety consequences for the Metroplex owing to an increased presence of AV on its roads.

1.6 Research methodology

Borshchev and Filippov (2004:1) define modeling as a "way to solve problems that occur in the real world. It is applied when prototyping or experimenting with the real system is expensive or impossible". These circumstances beautifully frame the research of my workplace problem, given how difficult it is for the relevant stakeholders to introduce change and innovations in a highly regulated environment, before being able to test and reflect on all the "what if" circumstances.

Although this puts quantitative modeling at the core of my research methodology, the diffusion process taking place in a complex environment coupled with the uncertainty and variability of the transportation environment necessitated a systematic perspective of analysis. Hence, an MMR methodology was adopted, where the purpose of the qualitative method is not to triangulate the findings but to help evaluate the results of its quantitative peer in a highly uncertain context. Initially, the different actors and the processes that connect them will be modeled using SD, which has a rich tradition of testing alternative management policies happening in complex systems that show nonlinear relationships between its components.

Coghlan and Brannick (2014:55) note that Action Research (AR) is predicated on two foundational principles. First, a system is better understood when one tries to change it and, second, involving the learners in their own learning produces better learning and more valid data. I have already referred to change as the driving force behind this research project, but modeling is of little use if it cannot be used to build social capital, credibility, and trust in order to foster the proposed changes among the variety of stakeholders who will have to be influenced. Thus, AR fits the goal of my research as it actively involves both the researcher and subjects as co-participants in the definition of the final values governing the modeling (and, therefore, its output). These values will be the result of a shared understanding among the stakeholders once a cycle of action planning, action taking (modeling), evaluation, and learning has been performed in the third and final phase of the research methodology.

Anderson and Thorpe (2004:659) advocate in favor of considering critical reflection when practicing AR. They refer to Reynolds concerning placing questioning assumptions at the center of critical reflection and note that "through the process of critically reflecting, managers become aware of a much wider environment in which they operate and begin to realize the social power relationships of the organization and their own networks". Both questioning the assumptions taken when modeling as well as realizing the wide environment in which the changes will unfold will be key components of the AR process, which suggest a critical approach.

Among the different qualitative schools of thought reviewed, experience with MLP proves its usefulness for understanding transitions and the complexity of both incremental and radical innovation (Whitmarsh, 2012:484), providing a frame of analysis and the possible transition pathways. AR uses this frame to reflect on the consequences of the actions taken. Section 2.3.2.3 shows MLP being used (e.g., Nykvist and Nilsson, 2015; Berkeley et al., 2017; Figenbaum, 2017) as a frame to analyze how the divergent attitudes of the local actors in Sweden and Norway towards BEV have resulted in wildly different penetration ratios in either countries.

Data collection methods are entirely based on secondary sources. The literature review shows that most of the data needed is currently available in open sources, either in the available literature or sourced by my company.

Summarizing, this research is based on an MMR methodology built on a mixture of MLP, SD, and AR research methods. The sociotechnical system of the Metroplex is conceptualized by means of MLP to inform the SD model, which is fed by secondary data available in the existing literature and calibrated with real data showing the diffusion of ICE and BEV in the Metroplex from 2010 till the present. The research process is conducted as an insider AR initiative, wherein SD participative modeling is used to evaluate and critically reflect on how the consequences of the actions proposed by the different stakeholders affect our organization. The methodology chosen acknowledges two weaknesses. One, the consequence of using secondary data; although in most of the cases it has been produced by recent research, owing to the rapid environmental changes, a longitudinal study may offer different results. The second weakness results from not involving the AR group until after the SD model has been produced (see section 3.4.6 for a further explanation), which reduces the potential for knowledge and inquiry.

1.7 Document structure

As discussed in the introduction (Chapter 1), and further detailed in Chapter 3, this research implements a methodology which mixes quantitative and qualitative research tools.

The study is specifically interested in constructs that are either identified as a driver of the AV diffusion (supply, demand, and public policies) or as a consequence (road safety and environment). The literature review presented in Chapter 2 characterizes these constructs based on academic literature, while Chapter 5 presents the quantitative model and the peer reviewed literature that supports the values adopted by the variables which operationalize these constructs.

The qualitative part of the process is presented in Chapter 3 (MLP analysis) and Chapter 6 (AR inquiry), while Chapter 7 delineates the findings, which precede a conclusion that summarizes the research.

1.8 Summary

Situated within an uncertain and rapidly changing environment, this research aims to produce both innovative and actionable knowledge.

The extensive literature review conducted underscores its innovative nature, since although most of the research about the diffusion of AV considers one or several of the key drivers (supply, demand, public policies, business models, and environment), research about the transition to AV within the context of a complex system is limited and, in most of the cases, is presented within the confines of the diffusion of BEV and the incentives that are at stake.

The research is actionable because the methodology has been crafted in such a way that the AR team may use the SD model as a sandbox to support self-reflective cycles of planning and acting over the assumptions made and critically reflect on the consequences of the change. This will not only ensure the actionability of the knowledge but also ensure that it is the result of a shared understanding.

2 Literature Review

This thesis aims to produce actionable knowledge about public policies that within the context of TEXpress may influence the choice preference of the users when adopting an AV, with the final goal of optimizing its penetration and dissemination in the Metroplex. The diffusion of new technologies in transportation has received considerable attention in the literature, resulting in a diversity of research strands that are gaining strength on a yearly basis. A comprehensive literature review has been undertaken that besides reviewing the qualitative and quantitative research methodologies used, gives precedence to those strands that offer insights about how the users perceive AV, how those public policies that may be used within the context of the DFW ML network have shaped user perception and the willingness to use an AV, and finally how these changes have affected the expected diffusion of AV.

As discussed, this thesis steams from the assumption that the pathway to an ubiquitous presence of AV in our roads, is intrinsically related to the diffusion of BEV. Not only due to the need to support a shared incentivized program, but also to the convenience to consider AV as an extension of the BEV diffusion. It is with this aim, that I will extend the AV literature review to include the deployment of BEV.

This literature review will follow the topology presented by Peng (2010:1) that defined the best stream as “programmatic and systematic, progressing from a theory/conceptual paper, to qualitative/case study research, and then to quantitative research”. In this way, I start reviewing the concepts of sociotechnical systems and sustainable transitions, including the different qualitative analytical frameworks which have been posited to research the dynamics and mechanisms behind the diffusion of innovations, to follow with the review of the diversity of quantitative models, to finalize with the opportunities to mix both paradigms, and to involve the different stakeholders in a collaborative inquiry process. This initial stage of the research quickly revealed the vast amount of research into these topics, something which suggested to focus on the appropriate research methods as soon as they were identified.

This chapter describes the findings of the literature review which sets the foundation for the different dimensions of the research process including ontology, epistemology, methodology and method. Nevertheless, literature and data are intertwined due to using secondary data, mainly from journals, as inputs to the SD model. This required to keep an attitude of inquiry during all the research process, extending the literature review beyond a one-off effort, with the end goal to provide the empirical data available in the public domain to feed the different sub models as they were built. The results of this continuous literature research will be cited as appropriate in the following chapters.

2.1 Pathways to the diffusion of Autonomous Vehicles

AV will not be deployed in isolation, the transition will take years during which different powertrains will coexist, and while new business models will appear, others will disappear, reshape, or be reduced to niches. This results in different potential scenarios depending not only on the assumptions taken, but also in local circumstances that will lead to different types of transitions. The transition scenario chosen to perform the research will be of critical importance for the credibility of my findings, as it will frame the actionable actions and hypothesis. This section will review the scenarios discussed in the available literature, and define a chosen scenario based on their critique. This scenario will be taken as a preliminary assumption of the research and will not be object of the research questions.

2.1.1 The Taxonomy of the Society of Automotive Engineers

AV diffusion scenarios have been researched by different authors in a rich research strand that anticipates all sorts of approaches, from a radical and revolutionary introduction of the AV, to a more evolutionary one. No matter which scenario and approach is favored, the AV taxonomy developed by the Society of Autonomous Engineers (SAE) in 2014 (J3016) is the most well know and accepted standard to “simplify communication and facilitate collaboration within technical and policy domains” as SAE notes. As it can be seen in the below picture, SAE taxonomy is built around 6 different levels from no automation to full autonomy (differentiated by the level of attention that is requested from the human driver, both physically and mentally), and is the one selected by the National Highway Traffic Safety Administration (NHTSA) when setting the policy framework in US, which offers a path forward for the safe deployment of automated vehicles. Central to the NHTSA’ Policy guidelines is the concept of the Operational Design Domain (ODD). This is a description of the specific conditions (in terms of interstate or local roadway, signaling, geographical area or environmental conditions) upon which an autonomous feature is expected to function safely. Among all the different levels of autonomy and ODDs in which they may operate, I predict that the commercial availability of level 4 vehicles able to operate in Managed Lanes as an ODD environment, will be a breakthrough in the deployment of AV.

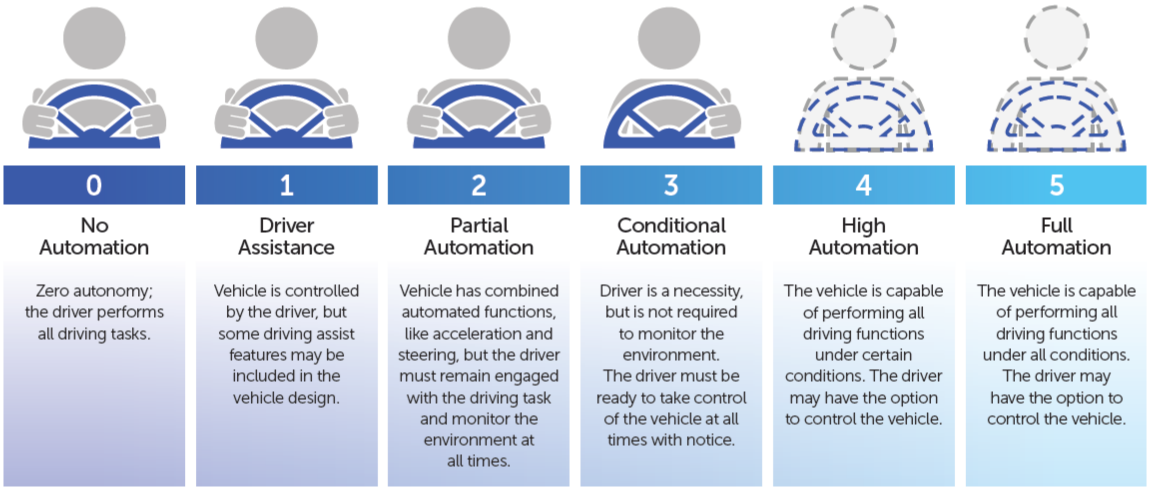


Figure 1: SAE Automation levels (Source: NHTSA 2020)

2.1.2 Three revolutions and the ensuing scenarios

The concept of three transportation "revolutions" 3Rs (vehicle automation, electrical and shared vehicles) was coined and championed by Sperling (2018) at the Institute of Transportation Studies at UC Davies in 2016, when the 3Rs initiative was launched. There is wide agreement in the current literature that two of these revolutions (electric and autonomous) are almost certain to happen (although the agreement in the timescales is limited), as they are heavily incentivized either by public policies (electric) or by industry competition (autonomous), while the last (shared vehicles) is more uncertain, as it is pulled by limited customer demand in concrete urban areas.

This circumstance (the uncertainty of the massive acceptance of shared vehicles) makes room for several scenarios being considered in the available literature. As it can be seen in the Table 1: Scenarios for AV diffusion (Source: Developed for this study) below, Arbib and Seba (2017) build upon the assumption that AV will coexist with privately owned BEV and ICE and be operated by fleet companies serving ride hail (RH) trips (e.g., Uber X or Lyft). The economies provided by this model will create a disruption of such a fast and extensive magnitude that by 2030, 95% of the US passenger miles travelled will be done by AV. On the other hand, Sperling (2018:3) presents two alternative scenarios (dream and nightmare) by 2040. One of them (dream) draws from the assumption that the range of mobility services provided by large fleets of autonomous serving ride sharing (RS) trips (e.g., Uber Pool or Lyft line) will be that efficient, that private ownership of autonomous cars will be almost nonexistent, something which will address the current congestion problems. The alternative scenario (nightmare) is the result of the third revolution (carpooling) being not successful enough as to eliminate AV ownership, leading to a significant increase in the number of miles traveled (and therefore congestion) because of a reduction of the cost per mile, empty travels, and the value of time. It seems clear that both the scenario presented by Arbib and Seba (2017) and the dream scenario proposed by Sperling (2018) stems from an approach where driver's rationality prevails over the habit, fear of new technologies or strangers or the love of driving, and the driver takes the more efficient alternative from an economic standpoint. Finally, Gruel and Stanford (2016) consider three different scenarios. The last one is equivalent to the dream scenario as proposed by Sperling (2018), while the other two acknowledge the existence of privately-owned AV, but while scenario 2 assumes major changes in travel behavior, scenario 1 consider they do not change.

Author	Scenario	ICE	ZEV	AV	AV (RH)	AV (RS)
Arbib and Seba (2017)	Base					
Sperling (2018) (Dream)	Dream					
Sperling (2018) (Nightmare)	Nightmare					
Gruel and Stanford (2016)	1					
Gruel and Stanford (2016)	2					
Gruel and Stanford (2016)	3					

Table 1: Scenarios for AV diffusion (Source: Developed for this study)

2.1.3 A critique of these scenarios

2.1.3.1 The fourth revolution: The connected vehicle

The above-described scenarios deserve several collective critiques, and chief among them is their complete disregard for the emerging V2X (Vehicle-to-Everything) technologies (and associated industry) which will allow vehicles to communicate with all entities within their perception range (other vehicles, infrastructure, and pedestrians), with the end goal to improve road safety and mobility. This is a fourth revolution, which has been going on for quite some time (since 1999) with limited success till now (besides 4G connections than many new cars do already equip for infotainment purposes, but which do not meet the latency requirements to support many road safety and mobility use case needs). In this respect, it is worth to note that there have been several high-profile tests, proof of concepts and pilots which have obscured its limited deployment. This seems to be the result of a lack of standardization of the different technologies competing for the market, and definition of the needed requirements by the different stakeholders.

This has not encouraged car manufacturers to act, further than issuing some media releases supporting the technology, preferring to let the current applications being served by the after-sale market. The fact that in 2017 the incoming US Administration shelved the Notice of Proposed Rulemaking (NPRM), by which NHTSA in charge of vehicle certification in US was intending to require all new light vehicles to be capable of Vehicle-to-Vehicle (“V2V”) communications from 2023, added more confusion and uncertainty to the process. This may change significantly with the upcoming deployment of 5G networks, which is expected to change this reality with a massive deployment in all sort of vehicles. In this regard, the very optimistic expectations about the deployment of small cells by mobile network operators (component that will support the deployment of AV will all sort of services and applications) that predict the number of small cells to rapidly increase from 86,000 this year to over 800,000 by 2026, seems to provide credibility to this trend.

Being true that it may have a lesser impact that 3Rs, when combined with them may open a whole new set of possibilities and alternative scenarios, as it will connect the vehicle to a whole range of entities and will power a new range of new functions such as over the air (OTA) software updates. In this regard, Tesla has been a pioneer, and currently most of the upgrades to the Tesla car are done by OTA, although not sometimes without some controversy about its security, and the opacity of Tesla with regards to the type of data which they are obtaining from the car.

If the communication vehicle to vehicles is mainly powered by the need to increase road safety, the impressive array of considered applications required to communicate an on-board device with the infrastructure is a key factor when ensuring the penetration of this technology. Many of these applications (e.g., tolling) have been around for years being in the verge of expanding and standardizing its equipment, but many others are new developments which will increase the pressure to have V2X. Among these applications:

1. Tolling: Since the Dallas North Tollway introduced in 1989 the nation’s first use of electronic toll collection (ETC) on a highway, more than 50 million transponders had been issued by 36 tolling agencies in US as of 2015. This represented one of every 5 cars in US for a tolled network which was relatively a smart portion of the whole network. An eventual toll schema on interstates would boost this number dramatically. Currently, US States cannot add tolls to an interstate without the prior permission of the Federal Highway Administration. Section 1216(b) of TEA-21 authorized the Interstate System Reconstruction and Rehabilitation Pilot Program (ISRRPP)

which allowed up to three existing Interstate facilities to be tolled to fund the reconstruction of interstate facilities which cannot be maintained without recurring to tolls. Missouri, Virginia, and North Carolina did receive provisional conditional approval to toll Interstate 70, and Interstate 95 (this last, both in the States of NC and VA). While there is significant support to increase the number of available slots, this has not happened to date, but there is wide agreement that this solution will have to be considered to face the increasing need for maintenance resources in the interstate network. Until now, on board transponders used for electronic toll collection were sold as aftermarket components by the same public agencies operating the toll or by third parties, and therefore were not integrated into the CAN bus of the vehicle. Audi with the e-tron has been the first car manufacturer to provide a transponder able to support the tolling function, and to be commanded through the vehicle's on-board infotainment system of the vehicle (see below picture), something which may challenge other manufacturers, and create the necessary momentum to expand CV technology for all sort of purposes.

2. Road User Charging: The establishment of a road charging schema to replace the current gas tax program which is not able to keep the balance of the Highway Trust Fund in the coming future. In the figure below we can see that 2022 is the breakeven year where cash inflows and outlays balanced each other. After that, the balance is lost, and the accumulated deficit increases every year. This is the consequence (among others) of two factors. In one side an increasing penetration of BEV cars, and in the other an increasing efficiency of IEC vehicles.

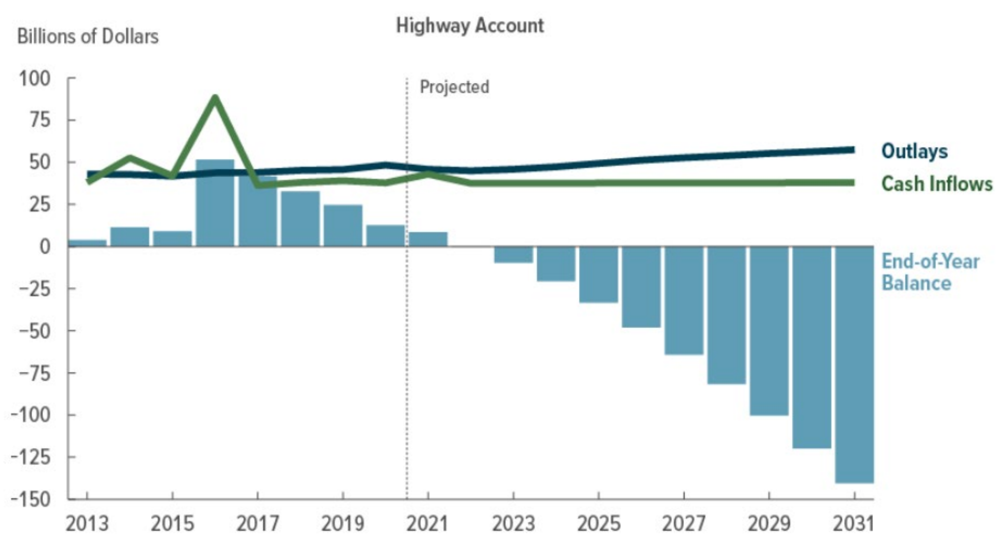


Figure 2: Projected shortfall of the Highway Trust Fund Account (Source: Congressional Budget Office)

Such road user charging scheme may tax vehicles in an equitable manner, based on the miles travelled, and no matter which powertrain they were using. This would facilitate the deployment of C-V2X to all vehicles and its operationalization (including a security credential management system which may ensure its cybernetic security), something which would facilitate public policies to incentive or disincentive user behavior to an unseen level of granularity. One of the programs at the forefront of this initiative is the ORe*GO* road usage charge program from the Oregon Department of Transportation. This program allows users to pay taxes by the mile instead of by the Gallon. They are similar programs being currently tested in Minnesota, California, and Washington, and although this was not a policy supported by the Obama administration is also rapidly gaining traction.

3. Truck tolling: The state of Rhode Island passed the RhodeWorks bill in February 2016 to rebuild Rhode Island's infrastructure by means of tolling specific types of tractor trailers in different places of the state. This decision, which lead to the first tolling point to be in operation early 2018, is mirroring other similar initiatives already popular in Europe, and is expected to be followed soon by other states in US.
4. Road Access Pricing: Congestion pricing in urban areas has been a success in many different cities across the world for many years. Singapore and Trondheim are well known examples of this strategy. In Stockholm, traffic fell 20 percent after congestion pricing was implemented in 2006 (it is noteworthy that the program to toll the access to central Stockholm was approved by referendum), while in London the number of vehicles entering the city center dropped by 44 percent. Up to now, congestion pricing has been debated for years in different cities of US (among them San Francisco, Seattle, Portland, and Los Angeles) but it was not until March 2019 that New York became the first city to embrace congestion pricing.

2.1.3.2 Ride Sharing

Mobility as a Service (MaaS) is currently offered in a myriad of versions. From alternatives that only require the user to change his travel behaviors to a limited extend (ride hail as offered by Uber or Lyft), to others that affect patterns more entrenched into our society, such as car ownership (car sharing as offered by Zipcar or Car2go) or the willingness to share the vehicle with strangers (ride sharing as offered by UberPOOL of Lyft Line). It can hardly be denied that this last option will have an uphill battle, given the tremendous barriers to change customer behavior (the generally underused HOV lanes are an example). Although ride sharing companies seem to be subsidizing the current services at an unsustainable level, ride sharing represents a mere 0.1% of miles driven in US, and Blablacar, the world's largest long-distance ride-sharing app that operates in 22 countries and has 60 million registered users, notes that the fewer public transportation hubs that the American cities have when compared to their European counterparts requires drivers to go out of their way to pick up and drop off passengers, adding a layer of inconvenience, something which explains why they are not planning to operate in US. This evidence seems to support the notion that although those alternatives that require the user to change his travel patterns to a limited extend are gaining traction, the notion of ride sharing to reduce the number of trips, and therefore compensating the increase in VMT created by AV is very uncertain, something which questions ride sharing as one of the core "revolutions". A different topic are the potential consequences of AV in car ownership, as we will see in section 5.1.1.

2.1.3.3 The pace of the transitions and the basis for the proposed scenarios

A final but relevant critique relates the pace of the US transition to BEV, which although is heavily subsidized, is showing an unexpected slowness (far beyond the expected consequences of the long product lifespan of motor vehicles, and the resulting slow fleet turnover). This situation may be alleviated (but hardly resolved) once BEV reach the cost breakeven point against ICE, something that Sperling (2018:43) predicts it will happen between 2022 and 2025. This suggest that the time frame of 2040 to have the three revolutions in full swing is probably unrealistic, and as a consequence a significant irruption of AV level 4 may happen while BEV are still not mainstream, especially if the reduction in cost of the AV components happens as predicted by General Motors (GM) which forecasts important reductions in the cost of the components that will equip the new generation of Chevrolet Volt and Cruise, in the range of 30% in the cost of the battery, and 99% in the cost of the Lidar sensors. Should this happen, and a significant diffusion of AV happens before the diffusion of BEV is massive, one of the assumptions of this research (public policy that incentivizes AV with BEV powertrain) would be strengthened.

The strand of research in the field of BEV and AV offers many identities between both transitions. i) Gaworn et al. (2018:3252) note that AV takes one step further the reduction in energy consumption claimed by BEV powertrains, as AV reduces the consumption of energy by a 14%, by increasing the efficiency when driving intersections, stop and go, and platooning in all sorts of situations. ii) Jenn et al. (2018:352) underline the need to increase customer awareness as a shared problem, as even in states with similar incentive programs, the per capita sales of BEV can differ significantly, a factor that is also confirmed by the BEV Task Force (2018) when they note that 75% of consumers know little or nothing at all about electric vehicles. iii) Phillips (2018:316) extends to AV the uncertainties already seen when researching the diffusion of BEV, noting the high number of stakeholders involved, and the possible outcomes which includes evaluating which powertrain (BEV or ICE) will be the preferred to power AV. With regards to the latter, Gawron et al. (2018:3254) have demonstrated the advantages of using a BEV platform, given the significant burden in terms of life cycle energy consumption and emissions due to the increased demands of power, weight, aerodynamics and data transmission through wireless networks. Nevertheless, several manufacturers (Ford amongst them) have shown their initial willingness to power AV by using an ICE powertrain (given their plans to offer mobility as a service having the car on the road round the clock) iv) Phillips (2018:316) notes as well that many of the benefits of AV would not be internalized by individual vehicle users (same as widely acknowledge within the BEV transition), something which would justify the governments to incentivize the use of AV by means of road pricing or parking fees. Nevertheless, if the contribution of BEV to common good can be objectively measured for every new BEV that hits the ground, and therefore the analysis cost benefit of the incentives clearly asserted by policymakers, road safety (which has been presented as the saint grail that justifies the diffusion of AV) not only needs a significant stock of AV in order to empirically probe its claims, but it will have to go through a prolonged transition period in which the coexistence with conventional vehicles will make it difficult to support its claims.

Unfortunately, and to crank the uncertainty of the transition to AV up one more notch, it needs to accommodate the coexistence of the different levels of automation as noted by SAE. This may result of large corporations owning fleets of vehicles operating at level 5 offering mobility as a service coexisting with private individuals making use of lower levels of automation such as level 4. As a conclusion, it appears that the transition to AV will be comparatively more complex that the transition to BEV, and its advantages more difficult to be quantified.

It would then seem a safe bet to conclude that at best, the diffusion of AV and BEV will face similar circumstances, in terms of need for awareness, long term cost-benefit approach, high barriers, tensions and uncertainty. Furthermore, in the current political climate, although NHTSA (2018) notes that “As our Nation and the world embrace technological advances in motor vehicle transportation through ADSs, safety must remain the top priority”, road safety does not seem to be that strong of an argument by itself to support a public policy that includes a robust incentive program to ensure the transition to AV. And not only that, BEV incentives have also been in place for a long time with limited success, something that is a legacy to the tremendous inertia of the automotive regime. It is difficult not to support the statement that the transition to AV would have a much smoother ride if considered within a more general roadmap that considers the current transition to BEV.

The convenience to adopt a set of policies that steer (through incentives and feebates) both transitions (to BEV and to AV) as part of a whole strategy to address mobility (rather than isolated processes) is stressed by the above critique which suggests framing this research in a midterm (to 2040) transition scenario, which although takes the ingredients of the above-described scenarios, these are combined in a different manner, and with different weights.

The base for all the proposed scenarios (see Table 2: Components of the proposed scenario (Source: Developed for this study)) is based on a transition grounded on the following assumptions (listed in order of importance):

i. AV are powered by an electric powertrain, and feature V2X capabilities.
ii. AV will be offered initially in all sorts of mobility modes, from private use (3), to ride hailing (4) and to ride sharing (5).
iii. Although there are fleets of robotaxis featuring RS and RH AV level 5 in geofenced sections of major urban areas, massification of AV will be predominantly driven by the initial operation of AV Level 4 in ODD areas (of which ML and TEXpress in the Metroplex are relevant actors).
iv. The individual travel behavior does not change, only AV incentivized users increase the use of TEXpress.

These scenarios are basically equivalent to the scenario 1 proposed by Gruel and Stanford (see Table 1: Scenarios for AV diffusion (Source: Developed for this study) with the addition of AV (RS) and AV (RS), and it corresponds to the one anticipated by Tesla in April 2019, although not in the timeframes proposed by the company.

Scenario Considered	1	2	3	4	5
	ICE	**ZEV**	**AV**	**AV (RH)**	**AV (RS)**

Table 2: Components of the proposed scenario (Source: Developed for this study)

In these scenarios, BEV and AV take central stage, with V2X partly replacing the criticality granted by several of the reviewed models to share vehicles. It is then important to note that all references to AV consider a vehicle which is autonomous, powered by a BEV powertrain and featuring V2X capabilities.

2.2 Externalities and incentives

2.2.1 Externalities

The adoption of AV will result in multiple first order consequences which will be felt both at a macro and a micro level. Most of them are externalities which can be defined as a cost (negative externality such as urban sprawl or an eventual increase in urban congestion resulted of the increase in VMT) or as a benefit (positive externality such as an increase in road safety or a decrease in CO_2 and GHG emissions) that an individual imposes on others when using a product or service. In this case, the price of purchasing or using the product does not reflect its true cost or benefit. Internalizing the externality means shifting the burden from a negative externality, such as pollution or traffic congestion to the individual owning the product, either through Pigouvian taxes, property rights, tolls, or government subsidies. The expression "tragedy of the commons", coined by biologist Garrett Hardin in 1968, to describe how shared environmental resources are overused and eventually depleted, is a classic tale of the catastrophic consequences of the failure to properly internalize the externalities.

In order to find the social optimum that ensures mobility for all citizens with the minimum cost, other costs need to be added to the TCO including i) air pollution during the whole life cycle of the vehicle, including both upstream during the production of the vehicle, electricity or gas from the well to the pump, and downstream in the operation of the vehicle, ii) congestion (to compensate for the public perception that public space has no cost), iii) noise pollution and finally iv) road safety.

A particular type of externality is the network externality. A product is characterized by network externalities (otherwise known as positive demand externalities) when its utility is a function of the installed base. This is the obvious case of communication goods such as the telephone or fax, but BEV to a certain extend show network externalities as well, when considering that the more users that drive a BEV, the lower the perceived risk of the new technology (see Greene et al., 2014), and the more the incentive to invest in charging stations or in increasing the offering, which will create a virtuous loop that will increase its diffusion (through bandwagon and penguin effects). Another obvious externality is the value of the connected vehicle when favoring cooperative driving, although below a certain threshold of penetration the number of connected vehicles will be that low that cooperative driving will be made useless.

2.2.2 Balance between the benefits and the cost to incentive

The net balance between the value of the positive externalities created, and the cost to incentive the usage of AV and BEV is what justifies a public incentive. NCHRP (2017:7) defines economic Instruments as "policy strategies that provide an explicit price signal by applying a tax, fee, or subsidy to effect a specific outcome" and identifies different types of policy levers that governments may utilize when internalizing externalities, either incentivizing those that are positive, or penalizing those that are negative. The need for a public policy program that makes a consistent and robust public usage of such tools to steer the diffusion of AV is twofold. In one side, and given the imbalance between private and public good, the need to align its positive social impacts with the factors that influence a private decision (a purchase). In this regard, Rabalais (2017) notes that the market properly fails to acknowledge many of the most important benefits of BEV, which are public goods consequence of an enhancement in the energy security and environmental stability. Adding salt to injury, Wesseling at el. (2014:196) note how BEV constitute competence-destroying innovations which discourage investment by incumbent manufacturers, as they depart from current longtime core technology (ICE). Both arguments would justify why in US (and by extension worldwide), Federal and state governments directly and indirectly subsidize the BEV industry to move towards a clean, renewable, and sustainable energy future. NCHRP (2017) has been instrumental in acknowledging the mismatches between societal consequences and factors that influence private decisions on AV and explore policy and planning actions (beyond the current incentives for BEV) that might better align these interests. These policy interventions should remain, until private benefits are able to sustain the transition by themselves. In the opposite side, the need to steer their private use accordingly to the value of the used public goods may call for some sort of road pricing schema in urban areas (feebates), to avoid congestion result of an overused of AV. Both arguments do not do without acknowledging that there is a growing debate within both the academic and practitioner's community as to whatever the final balance is positive or negative.

Among those that advocate for a positive balance, Fagnant and Kockelman (2015:180) posit that even when not considering all externalities (they exclude employment, pollution, or urban sprawl), the economic benefits of AV could be in the range of $27 billion, with 10% AV penetration ratio, and up to $450 billion with high penetration rates. Meanwhile Greene et al. (2014:45) offer a balance of external costs, benefits, and subsidies of the transition to BEV up to 2050, to conclude that its net present value (including current subsidies and externalities) is positive at more than a quarter of a trillion dollars ($294 billion). Sheldon and De Shazo (2017:15) posit that given that more than a fourth of the BEV sales in

California between 2010 and 2013 has been the result of the HOV incentive program in California, is not possible to estimate a balance of cost and benefits without considering the environmental benefits (researched by Holland et al., 2016) versus the congestion costs (researched by Bento et al., 2014). The available literature would appear to confirm that the positive externalities generated by BEV and AV are well above the cost of the current measures to incentivize BEV, and may be well above those that may be needed to incentivize AV.

Nevertheless, this not without controversy, as there is a rich stream of research which although does not completely question the convenience for public incentives to the diffusion of BEV and AV, suggests that they need to be carefully evaluated. Among them, the following research is noteworthy.

I. The cost of the Federal incentives to the diffusion of electric vehicles is set by the Congressional Budget Office (CBO) at $7.5 billion through 2019. This figure adds the $7,500 consumer tax credit, grants to battery car makers, and loans to auto companies. This represents that U.S. government will spend anywhere from $3 to $7 for each gallon of gasoline saved by consumers driving electric vehicles. Regardless of this sizable spending, CBO concludes that “tax credits will have little or no impact on the total gasoline use and greenhouse gas emissions of the nation’s vehicle fleet over the next several years”.

II. Bento et al. (2014) provide a complete analysis of the net welfare result of the Clean Air Vehicle (CAV) decal policy in California, which incentivizes the diffusion of BEV allowing them to be driven in the HOV lanes for free even when driving solo. Although there are relevant differences between this policy and the one researched in this thesis, this is the closest reference of which we have empirical data. Table 3: Net welfare effect of the AVs Policy for the I-10W (Source: Bento et al. 2014:41) summarizes the result and the cost-benefit of each component.

Concept	**Description**	**Value (year)**
Primary welfare gain	Reduced downstream emissions (ICE replaced by BEV)	$28,127
Cost-side congestion interaction effect	Increased congestion in the HOV lanes (new BEV users of the HOV lanes)	-$3,990,620
Rent effect	Reduced travel time (new BEV users of the HOV lanes)	$671,882
System-wide benefit congestion interaction effect	Potential reduction of congestion in the network (upper bounded)	$1,744,620
Emission interaction effect	Increased emissions in the GPL (induced demand)	-$7,240
Net welfare (all vehicles)		**-$1,553,231**
Net welfare without cost-side congestion and system wide congestion interaction (all vehicles)		**$692,769**

Table 3: Net welfare effect of the AVs Policy for the I-10W (Source: Bento et al. 2014:41)

Bento et al. (2014:14) find evidence of an increased congestion in HOV lanes (travel time increased by 2.2 minutes) and no changes in travel times in the GPL. They demonstrate as well that this increased congestion is uncoupled to an increase of the aggregate demand, so it can only be a consequence of the increase in BEV vehicles using the HOV lanes. Once they factor in all the other consequences, they conclude that the balance of net welfare that this policy offers is negative. A more detailed look to the data provided in Table 3: Net welfare effect of the AVs Policy for the I-10W (Source: Bento et al. 2014:41) shows that there are two main drivers which lead to the negative welfare result. In one side, the value of time associated to the increase of travel time in the HOV lane (by far the most important cost). In this regard, we must note that TEXpress lanes are currently operating well below their capacity, to the point in which an increase in the number of HOV users shall not create a negative externality by increasing the travel time. In the other, the system-wide benefit congestion interaction effect, which is a highly arguable concept.

III. Shewmake and Jarvis (2014:304) also demonstrate that the value of the reduction in air pollution in California result of allowing hybrid cars not meeting the minimum capacity requirements of HOV lanes, does not compensate the cost of the program.

IV. Another relevant example is proposed by Holland et al's (2016:3716) research, which although is not as holistic as the previous papers considered, it is noteworthy due to its consideration of the exported pollution consequence of the distributed nature of the electricity grid. In this manner, besides the native pollution, a car may induce emissions in a location far away (in fact this accounts for over 91% of the total pollution created). When considering the total population, the environmental damages per mile are higher for a BEV than for an ICE in almost half of the metropolitan statistical areas analyzed, reinforcing the notion that incentivizing the usage of BEV has a local component that needs to see beyond the improvement of the native pollution.

V. Michalek et al. (2011) conclude that the GHG and SO_2 emissions produced during the production of batteries for BEV and the needed electricity to power the vehicle during its whole lifecycle may overcome the tailpipe and upstream emissions of ICE (see Table 21: Total cost to build and operate ICE and BEV (Sources: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, (3) Holland et al. 2016)). As a result, the public interest would be better served subsidizing hybrid electrical vehicles (HEV) until these circumstances have improved significantly.

VI. Mitropoulos et al. (2017) produce an emissions inventory from the life cycle of ICE, BEV and HEV and their TCO, to conclude that although BEV presented the lowest cost of its externalities, the high retail value of the vehicle leads to the highest TCO which gave HEV the leading alternative (see Table 21: Total cost to build and operate ICE and BEV (Sources: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, (3) Holland et al. 2016)).

AV market penetration			
	10%	50%	90%
Lives saved*	1100	9600	21,700
Fewer crashes	211,000	1,880,000	4,220,000
Road safety economic cost savings ($ billion)*	5.5	48.8	109.7
Travel Time Savings (million hours)	756	1680	2772
Fuel saving (millions liters)	386	847	2740

*According to NTHSA, road fatalities in 2012 numbered more than 30,000, and the overall costs of road un-safety were about 300 billion $/year

Source: Eno Center for Transportation, 2013.

Table 4: Market penetration (Source: Alessandrini et al. 2015)

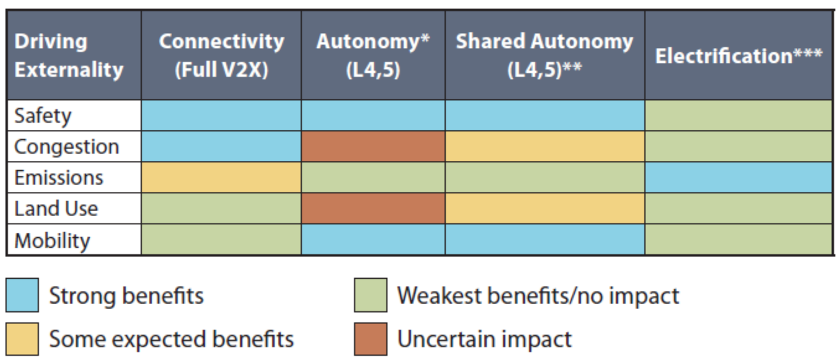


Table 5: Potential benefits of Connectivity and Automation (Source: NCHRP, 2017:3)

As an added effect to be considered, there is wide agreement in the available literature about the existence of feedback loops between the different drivers, and between the drivers and their consequences. This will result in positive loops reinforcing its effects (and thus creating a virtuous cycle should these consequences be beneficial), or negative weakening them.

This pictures a research stream which offers results highly dispersed and somewhat contradictory, showing the importance of localizing the model, since what it looks positive under one set of circumstances (cost of the incentives versus environmental benefits), may become negative under another. This could very well reflect the progressive maturity of the market, consequence of the tremendous amount of capital that both legacy stakeholders and newcomers are currently investing in the development of BEV. Nevertheless, Michalek et al. (2011) note some factors which may contribute to this dispersion. Among them, the type of vehicles evaluated, the pollutants considered, population demographics (see conclusions about BEV in Texas in Holland et al., 2016' research), the driving characteristics (free flow versus stop and go), or even the vehicle's life cycle considerations.

2.2.3 Incentivizing Battery Electric Vehicles in United States

The decision to implement an incentive needs to be supported by the evidence that the net present value (NPV) of the social good is above its cost. Greene et al. (2014) use the LAVE Trans model constructed by the National Research Council to conclude that "it may be possible for a transition to BEV to produce benefits that exceed the costs of a transition by an order of magnitude or more", but as costs must be paid upfront, the total net present value is negative for almost a decade, something that makes it a difficult sale to policy makers. To make things worse, Greene et al. (2014) remark the significant uncertainty of the process, and the barriers to the deployment (although they are small relative to the potential benefits, they are large in absolute terms) that fuel the skepticism that part of the US policymakers still have. The transition to BEV in Norway is a paradigmatic case of such inconsistency, given that although is the world's most successful BEV market (with a penetration over 50% of the new vehicles, when compared to slightly over 1% in US) Ryghaug and Toftaker (2014:147) note that "A common challenge is the lack of consistent and stable constitutional rules and national policies".

In US, BEV transition is incentivized through a myriad of incentives sponsored by different public agencies, to the point that Jenn et al. (2018) compiled a database of 198 incentives across 50 States. These incentives can be roughly divided into four groups: i) Federal incentives: The Federal government offers a tax break of up to $7,500 for the purchase of a BEV vehicle. As we have seen, the US CBO has reported the Federal incentives to BEV diffusion to be in the range of $7,5 billion from 2007 when the program was initiated to 2019 when is due to expire in the current shape, including tax breaks to the end user, and incentives both to produce batteries and to car manufacturers. ii) The BEV mandate issued by the government of California that has been pivotal in the early diffusion of BEV across US. This mandate, adopted subsequently by another 9 states, requires car manufacturers to sell low and zero emission vehicles in proportion to their total vehicle sales. iii) Most of the States offer other perks such as purchase, or value added tax exemption, direct point of sale rebates, HOV lane access, or infrastructure subsidies. particularly relevant to my workplace problem is the research of Jenn et al. (2018:356) when demonstrating that the two incentives that better correlate to an increase in the sales of BEV are the monetary incentives and the HOV lane access, and finally iv) rebates and incentives offered by electric utilities.

Nevertheless, the interest to invest for the common good in the long-term pales beside the current budget constraints of most of US's states, and the increasing pressure to keep control of the Federal deficit, something which has generated a debate to redraft the current incentive programs. To make things worse, Federal gas taxes, aren't keeping up with the needed maintenance on existing highways. Georgia not only eliminated already in 2015, the $5,000 tax credit it was offering but imposed a tax registration fee of $200 to new purchases of BEV. In parallel, the tax credit consumers are offered by the Federal government is currently under revision (with many policy makers questioning not only the fairness of a tax exemption limited to those that report a revenue high enough as to be able to make use of the exemption, but also by those that question the fairness to car manufacturers, as instead of rewarding the frontrunners, it rewards those that were late to the market (the exemption has a cap of 200,000 cars per manufacturer, so the newcomers will be banned to offer this exemption to the potential customers, at a time the latecomers still have the opportunity) and is uncertain the level of support it will have to be maintained for another 10 years. It is also worth to note that (although the AV mandate is a radical policy action) since it was first issued in 1990, four major amendments have been passed with hundreds of comments from the car manufacturers and their industry associations and lobby coalitions, as noted by Wesseling et al. (2014). But the current debate to limit the incentives to BEV is not only the result of budget constraints. In 2016, California met only 32% of the time the Federal benchmark that requires traffic flow in HOV lanes move at an average of 45mph. This resulted in the 2018 state legislature passing a bill that significantly limits the number of BEV vehicles that will have the privilege of being driven solo in HOV lanes. Drivers who earn above a certain amount will not be eligible for these decals, nor drivers who received their clean-air stickers before 2017, something which will penalize 220,000 early adopters.

The National Academy of Sciences is a private nonprofit society of scholars engaged in scientific and engineering research, which upon the authority of the charter granted to it by the Congress in 1863, has a mandate to advise the Federal government on scientific and technical matters. Its operating arm, the National Research Council (NRC) issued in 2013 the report "Transitions to Alternative Vehicles and Fuels". This report was seminal, as it was the first time that such a comprehensive research was conducted with regards to the transition to BEV. The report offers several technology and policy specific findings which are relevant to the present research. Among them (NRC 2013:6), the convenience to set up a feebate program incentivizing BEV and desensitizing ICE.

The above review of the development and status of the Federal and State incentives to the diffusion of BEV, reveals that although US is the world's second-largest carbon emitter, and BEV are widely recognized as critical to achieve the goals of reducing GHG emissions (although those are under discussion once US removed its commitment to the Paris agreement), in general the current public policies are uncertain and inconsistent, and a robust set of evidences will have to be provided to influence public policies which expand them to incentive the diffusion of AV.

2.2.4 Incentivizing Autonomous Vehicles in United States

Incentivizing the diffusion of AV by granting them free (or discounted) access to an HOV existing network (or eventually granting them the exclusive use of dedicated lanes) is subjected to an incipient research stream in the available literature. From pure speculative research to using empirical data from the programs that have been offering these incentives for years. Townsend (2014) elaborates alternative future scenarios that unfold in four different major metropolitan areas in US, and that picture a representation on different outcomes (from a virtuous growth to a collapse) that urban mobility may take in these areas. One of these scenarios (growth) takes place in the greater Atlanta and builds upon a consortium of public and private entities (headed by Google) being chartered with the operation of the then existing HOV network, with the main goal to improve mobility by having them transformed into a dedicated AV network that takes the name of G-Roads. Chen et al. (2016) introduces a model to calculate the total travel cost (AV plus ICE) to drive across a network whose links are progressively switched over to dedicated AV, once their penetration of AV reaches certain thresholds. The model is a combination of an equilibrium model (every user chose the route that minimizes his travel costs) and a diffusion model where the adoption of AV depends on the adoption and net benefit gained at the previous year. Chen et al. (2016) apply their model to the network of South Florida with a predefined Origin Destination (OD) demand to conclude that deploying AV progressively in the network may reduce the total cost of travel time from year 9 onwards.

This has limited significance in our case, as the differences between both metropolitan networks (TEXpress and South Florida) are significant. Chief among them is the fact that TEXpress is a tolled network (in opposition to the toll-free network considered by Chen et al. (2016) shared by public and private entities and heavily regulated through contracts that extend for 50 years. This is why although in both cases the incentive for ICE and BEV to switch over to AV is a reduction in travel time, in one case (South Florida) this considers a no cost alternative at the expense of AV (whose offer is reduced for any new link that is converted to AV), while in the case of TEXpress this would be achieved by offering heavy discounts to AV users, without recurrence to the BEV and ICE users which they could keep using the GP. In the case of Chen et al. (2016), the factor to consider is the reduction of total cost, while in my case the factor to consider will be what is the highest discount that can be offset by the network externalities that have not been considered in the Chen et al. (2016) model, and which are the consequences of such discount in the rate at which AV penetrate. As we noted in 1.4.1 "The balance between these positive externalities and the cost to incentive the usage of AV is what will justify public policies".

As a final side note when adding road safety into the equation, Blincoe et al. (2015:10) note that the wild dispersion of values of statistical life (VSL) found in the available literature (which range from a few million dollars to $30M), challenge the calculation of the total savings which may result of the increased road safety provided by AV.

2.3 Research Paradigms

2.3.1 The need for a holistic view

When characterizing the long-term diffusion of AV's technology, Nieuwenhuijsen et al. (2018:303) highlight three features: i) it's uncertain, complex, and dynamic nature, ii) the high degree of interrelation that the factors in the innovation system show, and finally iii) the fact that these factors are mostly endogenous and therefore change or adapt over time to keep the system stable. Five of these factors (supply, demand, public policies, business models and environment), some of which are endogenous and some exogenous, can be considered as core to the diffusion path, and hold a multiplicity of agents that play and retrofit each other increasing the complexity of the system.

The convenience to consider a systematic perspective to analyze diffusion process that happens in such complex environments enjoys a wide support within the research community. While Radzicki and Tauheed (2009:1044) suggest taking a holistic perspective to study and solve nonlinear systems, Abbas, and Bell (1994:373) underline the holistic nature of transportation problems, and Geels (2007:134) notes that "there is not a simple cause or driver in transitions" as diverse processes link-up and reinforce each other, something that does away with linear causality and requires a systematic analysis.

Although the research community seems to share the need to take a systematic approach, AV Literature does not offer too many references where the exploration of this non-lineal causality in the variables that drive the diffusion of AV considers several of the above factors. Nieuwenhuijsen et al. (2018) and Gruel and Stanford (2016) are part of this limited research. In the former, four different scenarios are presented where technology, customers' attitude, policy, economy, and environment are considered. In the latter, three speculative scenarios are considered where technology and customer behavior are considered. This thesis will contribute to the AV diffusion research strand by taking a systematic approach from a practitioner's perspective in which several of these factors will be considered.

Preserving this systematic approach, several schools of thought have influenced the research of transitions in complex systems. Three of them appear to have a predominant role when researching the diffusion of AV: i) sociotechnical systems, ii) complex adaptative systems and iii) system thinking. While sociotechnical systems embrace a qualitative paradigm, and complex adaptive systems take a quantitative approach, system thinking offers a variety of methodologies which embrace either a quantitative (e.g., system dynamics) or qualitative paradigm (e.g., soft system methodology). It is relevant to note the growing debate about the contribution of system thinking to the development of knowledge, given the little attention devoted to the creation of knowledge during the modeling process. The research methodology employed in this research bypasses this paradox building the knowledge because of the AR process.

2.3.2 Qualitative Paradigm

2.3.2.1 Sociotechnical systems and sustainable transitions

Sociotechnical systems include technical systems, operational processes and people who use and interact with the technical system, or as Ulli-Beer (2013:22) notes “interact with the subsystems of production diffusion and use of technology”. The concept of Sustainable transition builds on the sociotechnical system, and although we can see a diversity of definitions in the available literature (e.g. Lachman (2013:270) introduces it as a “fundamental change in structure, culture and practices” while Markard et al. (2012:956) and Köhler et al. (2017:3) expand this notion by referring to a “long term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption”) all of them converge in its fundamentals that include Multidimensionality and co-evolution, open-endedness, uncertainty, and finally Public Policy, which as will later see will play a critical role to incentivize the transition towards AV.

2.3.2.2 Analytical frameworks to conceptualize transitions

Moradi and Vagnoni (2018) build on the differences between transition and transformation (being transformation the result of a radical change that if resisted by the incumbent actors may result in a transition through a gradual change) to make the case for transition theory, as a method used to analyze past or present experiences or forecast future transition pathways. Transition theory has resulted in different qualitative analytical frameworks that address the characteristics of sustainable transitions as described above and have their origins in the study of innovation, and that as Ulli-Beer (2013:20) rightfully points out “have the aim to clarify the factors and processes that explain the rate, direction and patterns of (radical) innovation adoption, diffusion and use”. As it can be seen in Figure 3: Qualitative Analytical Frameworks (Source: Developed for this study), the most well know lines of inquiry are the multi-level perspective (MLP), transition management, strategic niche management and finally technological innovation systems.

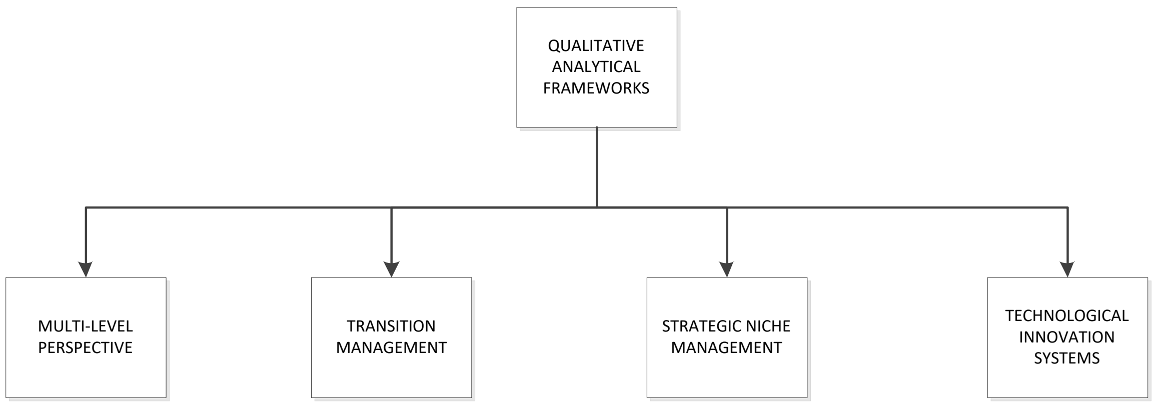


Figure 3: Qualitative Analytical Frameworks (Source: Developed for this study)

2.3.2.3 Multi-level perspective

Although these approaches may sometimes be found integrated (see Markard and Truffer, 2008), MLP has been widely seen as the framework of choice to analyze innovation processes in the transportation industry. The available literature offers many examples including Geels (2007), Geels et al. (2012), McDowall (2014), Van Bree et al. (2010), Berkeley et al. (2017), Nykvist and Nilsson (2015), Mazur (2015:51) and Moradi and Vagnoni (2018) to name but a few of the most representative. Moradi and Vagnoni (2018:235) justify this popularity because “it can describe, map and analyze the entire long-term process of change”.

That’s not to say that MLP does not have its detractors, as it has been criticized as neglecting place and space (Berkeley et al., 2017:323), offering a weak framework to operationalize the characterization of the landscape (Whitmarsh, 2012:485) or even being too complex. Regarding the latter, and although it may initially seem straightforward, Lachman (2013:271) notes that “such complexity may complicate the conception of computer models” as attention is split between the interactions between levels and between actors and events happening at the same level. On top of this, the use of MLP to research the diffusion of AV is certainly limited (e.g., Fraedrich et al., 2015), as most of the research available is devoted to the transition to BEV.

MLP provides a frame of analysis of socio technical systems, and the possible transition pathways (e.g., Van Bree et al., 2010) based on a typology of transition pathways build out of historical analysis of past trends in the transport sector. It recognizes that transitions are the result of a joint development between technology and society in processes that happen at three different levels: The middle level (meso-level) holds the socio-technical regime composed of a combination between the socio technical system, the actors, and the rules under which they operate. This is where the numerous "barriers" that impede the transition operate. The top level (macro-level) hosts the landscape, where those processes which are influenced by the regime stakeholders happen, and finally the niche level (micro-level), which is where these technologies and practices developed outside of the constrains of the regime actors take place.

The dynamic happening at the top and bottom layers determine the stabilization or destabilization of the regime. This happens through driving and restraining forces which force changes at the socio technical regime where incumbent companies and technologies are framed by their economic, technical and social context.

The niche-based model defines a bottom-up transformation which follows a single path, where innovation is born and nurtured in niches followed by a breakthrough and a final replacement of the current regime. This transition pattern represents a quite constrained way to characterize how transformation processes happen.

To help explain these processes in a more comprehensive way, Berkhout et al. (2003) and later Geels and Schoot (2007) introduced more complex typologies which considered variations in the timing of the interactions, and a multi-level nature. Geels and Schoot (2007) developed what arguably is the most well know MLP pathway typology. As it can be seen in Table 6: Geels and Shoot (2007) Pathway Topology (Source: Developed for this study)

Pathway	Landscape pressure	Niche	Regime
Reproduction	Non existent	Present but with limited impact	Stable, develops thorugh incremental innovation
Transformation	Moderate	Inmature	Develops through adjustments and reorientations
De-alignment and re-alignment	High and divergent	Multiple niche innovations	Replaced after a niche dominates
Technological substitution	High	Mature and ready	Replaced

Table 6: Geels and Shoot (2007) Pathway Topology (Source: Developed for this study)

The popularity of these early topologies does not mean that there is not a growing support for even more complex transition patterns, which are the result of a combination of different pathways as posited by Moradi and Vagnoni (2018), or the consequence of changes than happen slower in the landscape than in the regime or in the niche. This last pattern increases the pressure on the regime, something which may result in a re-framing which can open windows of opportunity, as Moradi and Vagnoni (2018) noted. This opens a parallelism with the current situation in the AV landscape where the changes in the landscape open windows of opportunities for niche companies such as Tesla or Waymo to speed up their efforts to test their vehicles, given the uncertainty of the market and the lack of public regulations.

Taking an empirical perspective, Nykvist and Nilsson (2015:33) and Figenbaum (2017:14) offer a straightforward example of how MLP can be used to make sense of transitions in the transportation world that had mixed fortunes (see Table 7: MLP analysis of the diffusion of BEV (Source: Figenbaum, 2017, Nykvist and Nilsson, 2015) below). Nykvist and Nilsson (2015:34) hypothesize how the barriers at the three levels combine to explain why although Sweden is a top innovation country and an environmental pioneer, Stockholm lags Norway in the BEV diffusion. Ambivalent landscape actors adverse to technology specific support measures give contradictory policy signals to the regime, that added to a weak niche activity reinforce the current regime. In contrast, Figenbaum (2017:29) researches the support to different hypothesis to explain why Norway is the country with the highest diffusion of BEV vehicles. The cases of Sweden and Norway show how a strong ICE regime combined with a weak landscape and regime explains the unsuccessful diffusion of BEV, while a weak regime combined with strong niches and landscape, and windows of opportunity lead to the opposite conclusion in Norway.

Norway		**Sweden**	
Status: High Diffussion BEV		**Status: Low Diffussion BEV**	
Hypothesis	**Support**	**Hypothesis**	**Support**
Strong Landscape	Strong and Weak	**Weak Landscape**	Strong
Weak ICE regime	Strong	**Strong ICE Regime**	Middle
Well functioning niches	Strong	**Weak niches**	Very strong
Windows of Opportunity	Strong		

Table 7: MLP analysis of the diffusion of BEV (Source: Figenbaum, 2017, Nykvist and Nilsson, 2015)

2.3.3 Quantitative Paradigm

There are many reasons which justify the use of a computer base quantitative model and simulation, including the need to improve the decision-making process, address problems, generating insights, favoring understanding of the factors that impact the design and operation of the system, and getting support and ownership across multiple stakeholders among others. With regards to this last issue, Akkermans and Bertrand (1997:953) emphasize how well established is the importance of good communication and high client ownership on strategic decision making by providing a sound literature review.

Quantitative modelling has been in the agenda of both academic researchers and professional practitioners for quite some time. The probit model, as a way to estimate the probability that an observation falls into one of two possible values, has been in use since the thirties when Chester Bliss came out with the concept. A few years later, in mid-1950's, at the time that David Cox published his logistic regression as an improvement to the original regression model, Professor Jay Forrester (1961) pioneered SD as a systematic approach to model system behaviors. Both discrete choice models and SD did not have a robust alternative approach until the nineties, when thanks to the advancements in computational processing power, agent-based modelling (ABM) to model complex adaptive systems became feasible and popular.

This wide range of quantitative methodologies can basically be split into two approaches based on their ability to take a systematic approach or not (Figure 4: Quantitative Research Methodologies (Source: Developed for this study)). Among the former, SD (top-down) or ABM (Bottom-up) are well known examples that champion this approach, while in the latter, Total Cost of Ownership (TCO), Discrete Choice Model or Bass are usual models. Worth noting as well is that while SD considers consumers on a group by group basis (with the obvious weakness that heterogeneity of individual purchasing decisions cannot be incorporated), ABM considers consumers as individuals, and therefore individual preferences (e.g. willingness to pay of every individual) and behaviors can be considered and simulated, with a caveat by Nieuwenhuijsen et al. (2018:301) that taking stated preferences done by consumers as a reference for the analysis of AV diffusion can be highly biased.

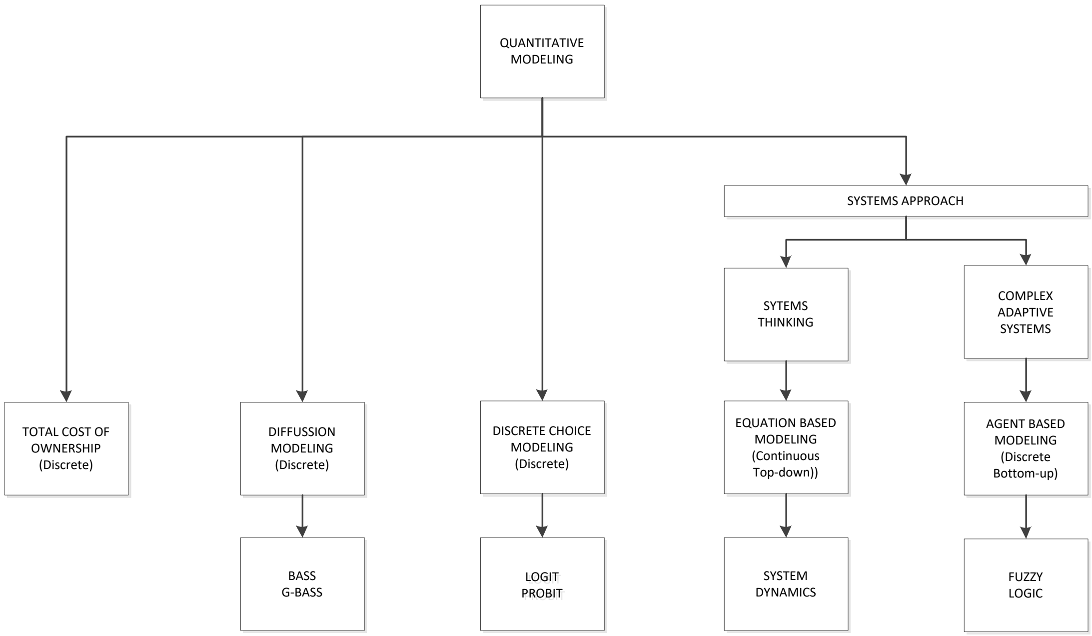


Figure 4: Quantitative Research Methodologies (Source: Developed for this study)

2.3.3.1 Discrete Choice Models

Discrete Choice Models use Stated Preference or Revealed Preference data to assess users' attitudes and behaviors towards AV. The two most well-known methods within this family are Logit and Probit. Logit model has been widely utilized to research technology adoption in the transportation domain (e.g., Bansal and Kockelman, 2018 and Siddiki et al., 2015) and works under the premise that the user will always make the choice that maximizes a utility function, assuming substantial rationality and complete information. In environments with high in-group variations in behavior, these two assumptions may originate a significate loss of prediction accuracy. Fuzzy logit (the base of ABM as we have seen) as an alternative to the logit model was introduced to address the dynamism of human behavior that is lost when it is characterized by a utility function that has a discrete value. If decision variables are clear and obvious, we only have a small amount of data, or the data sample can be easily divided into several sub-groups, logit maybe the option of choice. Nevertheless, if those circumstances are not met, Seetharaman et al. (2009) and Mao et al. (2015) were able to demonstrate (by formulating the same problem by the two logics) that fuzzy logic tends to give a more consistent prediction than the logit model.

2.3.3.2 Diffusion modeling

Thun et al. (2000:2) refer to Rogers to define diffusion as "the process by which an innovation is communicated through certain channels over time among the members of a social system". Such a definition encouraged me to dig further into this research stream as it aligns to my research topic. Diffusion models have been used widely to research the diffusion of AV (e.g., Lavasani and Jin, 2016, Cordill, 2012). Bass is one of the most well know diffusion models, and as a mixed-influence model works under the assumption that adopters of new technologies are either influenced by mass media (innovators) or by word of mouth of those that adopt the technology before (imitators). By using a limited set of parameters (innovation, imitation, and the total market potential) the model can forecast the cumulative sales of a new product which as usual takes an S-shape. Bass' model acknowledges several important weaknesses: i) Massiani and Gohs (2015) demonstrate that is very difficult to draw conclusions from the model when the market potential (M) is not well defined, given the important variability that the innovation coefficient has with this factor; ii) the imitation factor has a strong local component hindering the geographical transferability of the results to different markets. Nieuwenhuijsen et al. (2018:303) emphasize this weakness when they note the need to localize the research of innovation diffusion, given the sensitivity to regional differences; iii) The model, as initially defined, is not capable of considering other external influencer variables besides the innovation and imitation (the need to address this weaknesses led to the development of the Generalized Bass model where other factors that may influence the adoption behavior are embedded into these two extended variables); iv) Thun et al. (2000:2) note that the model does not offer any explanation about why diffusion happens (or not), or how it could be influenced by for example altering price structure; and v) a final and very relevant weaknesses of the model refers to its incapability to model networking effects such as those derived from the well know bandwagon and penguin effects. Should my research methodology include this model, this would be a significant drawback as it would not allow me to consider the externalities associated to the diffusion of connected vehicles.

2.3.3.3 Total Cost of Ownership (TCO)

TCO has been widely applied to research innovation diffusion in the automotive industry. The model calculates the total cost of the technology during all its life cycle (including depreciation, capital, and operating cost) and the potential customer is expected to make a rational decision based on different scenarios and the different cost efficiency calculations. Propfe et al. (2013) and Kihm and Trommer (2014) take a supply side perspective where the model is based on the TCO of the different powertrains to the diffusion of BEV in Germany. Massiani (2013) notes several potential weaknesses of this modelling including cost monism (the decision only considers an economic variable), excessive reliance on consumer's rationality and monolithic behavior (facing identical circumstances, two consumers would take the same decision).

2.3.3.4 Systems Thinking

In opposition to reductionism which describes a system out of the consideration of its constituent parts, thus ignoring the relationships between them, Systems thinking was developed in the twentieth century built on the premise of understanding the relations between seemingly isolated components of the system. Caulfield and Maj (2001:2795) underline its importance by labelling the transition from reductionism to system thinking as a real paradigm shift). Emergence (defined by Flood, 2000:1 as "an emergent property of a whole is said to arise where a phenomenon cannot be fully comprehended in terms only of constituent parts") and interrelatedness are its fundamental pillars. Based on these premises, system analysis facilitates the analysis of the complexity of a multidimensional system by means of conceptual models which are often represented by causal loop diagrams (CLD) that provide an overview of the system showing interconnections, feedbacks, cause and effect relationships and time delays between the different subsystems. These feedbacks create balancing loops that counterbalance them and provide one of the essential characteristics of system thinking which the equilibrium of the system is. Finally, this conceptual model structures are modeled and transferred into dynamic numerical models to understand the behavior of the system over time. To this end, several methodologies have been developed along the years. Among them, Caulfield, and Maj (2001:2793) propose System Dynamics as the one that paired with system thinking principles "boost the best tool set, they have the best intellectual credentials, and they are best suited to contemporary business and social situations"

2.3.3.4.1 System Dynamics (SD)

SD, also referred as Equation Based Modelling (EBM), is a methodology pioneered by Jay Forrester in the 1950s, and has a long tradition when being used to test the effects of different policies and assumptions in transportation (Shepperd et al., 2012, Haghani et al., 2002, Yu and Mu, 2016). Abbas and Bell (1994:385) presented an extensive review of different transport related topics researched by using SD, that probe how well-suited SD is to cater to the diverse requirements of analytics in transportation. This does not go without realizing that SD has been (and still is) the object of a continuous debate. Hayden (2006) criticizes SD for not being able to model real world systems that are open to their environment and therefore are in state of perpetual imbalance. A few years later, Radzicki and Tauheed (2009) responded to Professor Hayden and demonstrate how SD can be expanded to accommodate both openness and lack of equilibrium. As a result of these long-standing debates, while the proven and robust predictive powers that SD has shown in both engineering and non-engineering domains, it has had a limited impact on hard-core strategic decision making, as its nature (that favors the modelling of future outcomes in continuous times) is at odds with the current business reality that requires discrete time assumptions.

2.3.3.5 Complex Adaptive Systems (CAS)

A CAS can be explained by elaborating in the three words that formed its acronym. i) Complex, because it includes many autonomous working parts and components that interact to each other and to the environment. These connections show nonlinear properties such as positive and negative feedback and produce ripple effects through the system for every change. ii) Adaptive, because is constantly changing and adapting to changes in its environment (this key criterion is what distinguishes them for the Multi-Agent Systems that do not have this capability), and iii) a system because it operates within a wide range of scales. These characteristics produce four noteworthy properties: unpredictability, spread, modularity and redundancy (which having the last two combined ensure their resilience). Ding et al. (2018:1)' summarize nicely these characteristics, by saying that a CAS is a system "in which a perfect understanding of the individual parts does not automatically convey a perfect understanding of the whole system's behavior" something that highlights an important consequence of their complexity, in the sense that the agents tend to produce emergent behavior that cannot be whole explained by deconstructing the system into its constituent parts. Teose et al. (2011) label CAS as pervasive, as we all live interacting and being surrounded by them. Typical examples of a CAS include cities, governments, industries, power grids or traffic flows.

To formally model the adaptive capacity of Socio-Technical Systems, approaches based on the CAS paradigm have been previously identified as a promising alternative (Blok et al., 2018). Oughton and Tyler (2013) when researching the properties of infrastructure as a CAS, compare a CAS with a system that shows a general behavior, and in doing that increase the granularity of the previous description as shown in Table 8: System showing a general behavior versus a CAS (Source: Oughton and Tyler, 2013:7).

General Systems Theory	Complex Adaptive Systems Theory		
Key Properties	***Key Properties***	***Property Category***	***Hierarchical Level***
Complicated	Complex	Emergent behaviour and self-organisation	System level
Aggregatable with functional decomposition	Emergent with limited functional decomposition		
Centralised control	Distributed control		
Determinate and Linear	Non-determinate and Non-linear	Instability and robustness	
Static	Perpetual Dynamics	Dynamics and evolution	Network level
Equilibrium	A Far-from-equilibrium State		
Closed	Open		
Reversible	Irreversible		
Rational, deductive behaviour	Adaptive, evolutionary behaviour	Adaptiveness	Agent level
Simplified assumptions and homogenous agents	Diversity among agents and more realistic assumptions	Agent diversity	

Table 8: System showing a general behavior versus a CAS (Source: Oughton and Tyler, 2013:7)

One of the properties that Oughton and Tyler (2013:8) emphasize in a CAS is its openness, not only consequence of interactions between the different agents, but also in between them and the surrounding environment (note the long-standing debate about SD as the proper tool to model systems which are open to the environment).

The issue to be questioned at this point is to what extend the socio-technical system framing the diffusion of AV can be characterized as a CAS, and what are the implications of such identify for the research process. To address the first question, we'll consider the key features of a CAS as presented in Table 8: System showing a general behavior versus a CAS (Source: Oughton and Tyler, 2013:7). At the agent level, adaptiveness and agent diversity is the result of the continuous flow of new technologies, business models and newcomers to the marketplace. At the network level, the factors that influence the demand for AV and BEV, and its continuous and growing influence support the belief that it would be naïve to assume that the socio technical environment in which the diffusion of AV will take place, will be in a state of optimal equilibrium anytime soon and therefore the current dynamics will possibly turn perpetual. Besides this, the openness of the system can hardly be arguable taking into consideration the variety of stakeholders that range from consumers, large corporations, and multiple public agencies of all sizes. Finally, when considering the system level, its classical distributed control is accentuated by the variety and impact of new actors and technologies, and the ensuing loss of influence of the incumbents.

2.3.3.5.1 Agent Based Modelling

Agent Based Modelling (ABM) has long been considered the method of choice to model CAS and the transportation system (with the option to use complex-network based models to a lesser extend) based on the stated preferences of individual users (Longo et al., 2017 when modelling the optimal umber and position of charging stations, Gnann et al., 2015 when modelling market diffusion of electrical vehicles, Liu et al., 2017 when simulating a network of AV in Austin, and Biondi et al., 2016 are examples). Fuzzy logic, the theoretical basis of ABM, addresses the shortfalls of the Logit model, especially in cases where there is incomplete information or irrational behavior. In ABM, entities in a CAS are represented by discrete agents that behave autonomously and interrelate to produce emergent outcomes at the population level that are not intuitive (from this the consideration of this model as bottom-up). Borshchev and Filippov (2004:8) note two important advantages of ABM over EBM which relates to the possibility to capture more complex dynamic events, even in absence of knowledge about the global interdependences, and how the different variables behave at the aggregate level, as the global behavior emerges from the individual behavior. On the opposite side, although ABM is expected to increase the accuracy of SD, ABM is much more data dependent and requires much more data processing resources.

2.3.4 Hybrid

The principle of "everything affects everything" and the uncertainty and variability of the transportation environment, seems to call for a hybrid approach capable of optimizing the capabilities provided by both paradigms. The usability of qualitative approaches to enhance the quantitative modelling and simulation of a transition has long been a topic of research in the available literature (Ulli-Beer et al., 2011, Mazur, 2015). Among other reasons, this addresses the need to introduce soft variables (e.g., consumer satisfaction or salesforce motivation) in the simulation whose quantitative evidence is difficult to discern and speculative at best. In such cases, a qualitative approach to the description of the system maybe a useful precursor to simulation to provide the necessary insight. As Coyle (2000:241) notes "A correctly drawn influence diagram is the basis for a quantitative model and is easily transformed into equations". Ulli-Beer et al. (2011:1) concur with this approach noting that "MLP defines what basic sub-systems and elements should be considered of a socio-technical system including actors and organizations with their decision rules (institutions) or both the production side and application domain".

Mustafee et al. (2017) underlines two advantages of significant importance brought forward by a hybrid approach. The first refers to the possibility to start modelling in a low data requiring environment by using SD, and once the modeler has a better understanding of the global behavior of the system, to use ABM to zoom-in in those parts that reveal more sensitive to the result. The second refers to the possibilities of using a hybrid approach to trade-off accuracy and performance. Mustafee et al. (2017) supports this last advantage by an empirical research where SD and ABM (with over 20,000 agents) models were built to address the same problem. While ABM provided a much accurate result, it took 1.5 hours to run compared to the few seconds that took SD. A hybrid approach was later introduced which was able to reduce the time to run to acceptable levels, at the time that the accuracy was kept at the level offered by a pure ABM approach. Turnheim et al. (2015:241) take this integration one step further, noting that "navigating transitions requires connecting the past, the present and the future through a sense of trajectory" and therefore a combination of sociotechnical transitions analysis (past) with participative modelling (present) and quantitative systems modelling (future) is a promising avenue for research. Although the offer of software packages able to combine different modelling methods is limited, the current availability of drag and drop software packages enhance the opportunities to run a research agenda based on a hybrid approach without the need to have an in deep knowledge of programming languages.

2.3.5 Participatory Modelling

Participatory Modelling (PM) integrates the views and representations of a complex system of stakeholders, with the end goal of enhancing the shared knowledge of the system and identify the impacts of solutions to a given problem (Voinov and Bousquet, 2010:1268).

Bale (2017) and Voinov and Bousquet (2010:1269) identify a diversity of methodologies which are grounded either in the quantitative (group model building, participatory simulation or shared vision planning based on system dynamics or companion modelling based on agent-based simulation) or in the qualitative paradigm (soft system methodology). These methodologies have been applied to a wide range of research topics, which include sustainable environmental management where the support of a wide range of constituents is critical (Eker et al, 2017 is only one of the more than 200 published papers accordingly to Voinov et al., 2016:196), transportation industry (Stave, 2010 illustrates the use of PM when modelling the eventual measures which can be taken to address traffic congestion) or Health (Zimmerman et al., 2016). Voinov et al. (2016:202) note that "Participation usually slows decision making, it has many costs, and it can be confrontational and disturb the smooth running of a project" something which undoubtedly increase the risk and unpredictability of the process. Why would then anyone want to sponsor stakeholder participation? There is a wide diversity of authors that agree that the exchange of knowledge between the different stakeholders is what builds trust and social capital and therefore becomes the most important asset that PM brings to the table.

2.4 Summary

In summary, the diverse research streams explored in the literature review underline the complexity of the socio technical scenario in which the transition to AV will develop, the amplitude of the internal and external factors which will have to be considered, and as a result the diversity of research methodologies which can be applied.

The wide range of qualitative and quantitative approaches identified, either isolated or merged within a mixed mode research, reveal the different ways of seeing complexity systems.

The value of the transition to BEV, and the role of public incentives to compensate its externalities, have shown their relevance when being used as a reference to figure out how the scenarios the transition to AV may face. In this context, particularly relevant has been the reviewed research devoted to highlight the importance of localizing the research given the significant differences in public good shown by the different metropolitan areas in US.

3 Research Methodology

3.1 Gap scholar practitioner

As Rein and Schon (1977) noted, problem setting is not a well-formed problem, and one of the most notorious challenges of the practitioner is converting a problematic situation into a well-formed problem. This challenge was part of a colloquium on professional education held at the Massachusetts Institute of Technology in 1972, in which one of the participants stated, “When it comes to design a ship, the question we have to ask is, which ship makes sense in terms of the problems in transportation”. This statement, made almost half a century ago, reveals not only the complexity of transportation challenges that require a systematic approach far beyond any discipline, but also the divergence between an academic approach that primes rigor and a practitioner’s interest that primes relevance (and, therefore, the local context) and actionable knowledge rather than a focus on discipline knowledge. This divergence is a dichotomy found in the gap between theory and practice, the general (and rigorous academic ambition) versus the particular, and the need of the practitioner to handle specific problems in specific situations. My research topic has not been oblivious to such complexity, and I had to reshape my research questions and methodology three different times to balance the academic requirements of the doctorate with the business constraints, interests, and problems of my practitioner’s environment.

3.2 Research approach

This study aims to create new practice-based knowledge by finding answers to the research questions presented in the preceding section, without preexisting hypotheses or theories to be confirmed. This precludes a deductive approach and suggests an inductive research based on the identified patterns and reflections on the results of the different actions taken within the research methodology adopted.

3.3 Research philosophy: complex versus wicked problems

All research is grounded in a set of underlying philosophical assumptions about what constitutes 'valid' research and which research methodologies, and methods are valid for building knowledge. Four main dimensions are involved in the process: Ontology (concerned about the nature of reality and truth), epistemology (concerned about the nature of knowledge), methodology (concerned with the research approach and the researcher’s position in the research), and method (concerned with data collection and analysis). The research paradigm builds upon the philosophical assumptions made by the researcher on these dimensions (their worldwide view), which deal with the nature and source of knowledge. There are three paradigms that support most of the research streams. Of them, positivism and interpretivism are two opposite viewpoints that place pragmatism on the continuum between both the ends.

Pragmatism gives priority to what works and, thus, sidesteps the choice associated with the war of paradigms. As Tashakkori and Teddlie (1998) noted, “Pragmatists adopt an ontology that accepts external reality to produce desired outcomes effectively, an epistemology that accommodates both objective and subjective perspectives, while using a mix of quantitative and qualitative data”.

There is a rich research stream that supports the notion of using pragmatism when dealing with uncertain and complex scenarios. While Lake (2014:5) illustrates how the pragmatic method is applicable to solving problems developing in uncertain contexts, Nzembayie (2017:85) tackles the problem from a different angle, suggesting that AR, with its iterative, immersive, and emergent form of inquiry, is the pragmatic design of choice to research entrepreneurial processes that present high uncertainty. Pragmatism is, hence, the core paradigm that informs the selection of the tools and methods I will use for data collection and analysis.

Rittel and Webber (1973) are credited to have introduced the concept of the wicked problem. Wicked problems (otherwise known as messy, in opposition to tame problems) are dynamically complex, ill structured, and badly problematized, with no clear root cause and multiple stakeholders separated from each other, sometimes with contradictory agendas that generate multiple disagreements and misunderstandings, which lead to highly uncertain outcomes. In their seminal paper, Rittel and Webber (1973:160) identify ten distinguishing properties of wicked problems, including the difficulty to problematize, not having a stopping rule, being unique, or not having a true or false solution.

Yearworth and White (2015) and Head and Alford (2015:712) built on this concept. The former anticipated an increasingly messy landscape for the engineering practice, which included projects in the transportation and AV arena, as they can be characterized by features of a messy problem in terms of uncertainty and stakeholder’s complexity. The latter noted that although “conclusive solutions to wicked problems are rare, it is possible to frame partial, provisional courses of action against wicked problems”. That is, a wicked problem that embraces many variables in a complex and uncertain environment may hardly be offered a conclusive solution, and in many cases only partial solutions are possible.

Studies by these authors seem to suggest that a wicked problem will always be complex but not the reverse. A more thorough study of our problem confirms this assumption, since although the complex system in which our research unfolds seems to call for embracing the tenets of wicked research as its guiding principles, a further look into the properties defined by Rittel and Webber reveals the unsuitability of the approach if our problem can be understood, and a conclusive solution be found.

3.4 Research methodology

This section details the research methodology in five subsections. The first subsection describes MMR as a research methodology, following which MLP, SD, and AR are reviewed as research methods, and the last subsection explains how these methods were mixed in the research.

3.4.1 Mixed Mode Research

Baum (2006:854) defines research methodology as "a strategy or plan of action that shapes our choice and use of methods, and links them to the desired outcomes". The rise of pragmatism as a research paradigm was closely connected with the development of MMR as a research methodology, which aims to combine qualitative and quantitative research methods in the most convenient manner to realize the aims of the research process. The use of MMR to bring methodological pluralism to the research process of complex problems has been argued by multiple authors (Baum et al., 2006:854). Although modeling as a quantitative research method is one of the fundamental pillars of my research methodology, the complex environment within which the diffusion process takes place, combined with the uncertainty and variability of the transportation environment, necessitates a systematic perspective of analysis, which serves as an argument in support of incorporating a qualitative component within the MMR methodology.

3.4.2 Multi-Level Perspective

The Learning Set (LS) uses the MLP analysis of the Metroplex socio-technical system when planning action during the qualitative AR cycle. Among the different qualitative schools of thought reviewed, MLP is widely seen as the method of choice to analyze innovation processes in the transportation industry, providing a frame of analysis and the possible transition pathways. As an example, MLP has been used in previous research (e.g., Nykvist and Nilsson, 2015; Berkeley et al., 2017; Figenbaum, 2017) as an analytical frame to analyze how the divergent attitudes that the local actors in Sweden and Norway took to the diffusion of BEV have resulted in wildly different penetration ratios in either countries.

3.4.3 System Dynamics

The different actors and the processes that relate them were modeled and simulated by using SD, which has a rich tradition as the appropriate method for testing alternative management policies happening in complex systems that show nonlinear relationships between these components. SD can circumvent the simulation problems associated with a static consideration of the different variables, facilitating the incorporation of different feedback loop structures embedded into sub models capable of handling a significant number of hard and soft variables, including physical, behavioral, socioeconomic, and policy variables that are considered as model components.

The model and the simulation were performed by using AnyLogic (AnyLogic 8.5.2 Personal Edition), which offers a multimethod simulation modeling framework including SD, discrete event, and agent-based. The three methods can be combined in multiple manners to simulate business systems of a wide range of complexity – from process flowcharts, state charts, and action charts to stock & flow diagrams. This multimethod capability may be of significant use should the thesis open avenues for further research, which would require an extension of the current SD analysis using discrete modeling or agent-based modeling.

The whole process follows the SD design introduced by Oyo et al. (2009:4). The table below shows the three cycles to be performed and the activities they include.

<table>
<tr><th colspan="2">Phase</th><th colspan="2">Activity</th><th>Result</th><th>Cycle</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Problem Diagnosis</td><td>1</td><td>Problem Definition</td><td rowspan="3">Research Questions</td><td rowspan="9">Problem Articulation</td></tr>
<tr><td>2</td><td>Literature Review</td></tr>
<tr><td>3</td><td>Gaining insight</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Action Planning</td><td>4</td><td>Action Planning (Research Methodology)</td><td rowspan="3">Conceptual Framework</td></tr>
<tr><td>5</td><td>Explore complexity & Problem boundary (MLP)</td></tr>
<tr><td>6</td><td>Identification of Key Stakeholders (MLP)</td></tr>
<tr><td rowspan="3">3</td><td rowspan="3">Dynamic Hypothesis</td><td>7</td><td>Engagement of Key Stakeholders</td><td>Model Boundary</td></tr>
<tr><td>8</td><td>Inspect theories regarding the problem</td><td>Reference Modes</td></tr>
<tr><td>9</td><td></td><td>Causal Loop Diagram</td></tr>
<tr><td rowspan="5">4</td><td rowspan="5">Model Formulation</td><td>10</td><td>Stocks and flows</td><td rowspan="5">Detailed Model Structure</td><td rowspan="5">Modeling Proficiency</td></tr>
<tr><td>11</td><td>Estimation of parameters</td></tr>
<tr><td>12</td><td>Initial conditions</td></tr>
<tr><td>13</td><td>Decision rule</td></tr>
<tr><td>14</td><td>Data Collection</td></tr>
<tr><td rowspan="6">5</td><td rowspan="6">Model Testing</td><td>15</td><td>Parameter verification</td><td rowspan="6">Model Confidence</td><td rowspan="9">Solution Refinement</td></tr>
<tr><td>16</td><td>Extreme conditions</td></tr>
<tr><td>17</td><td>Behavioral Sensitivity</td></tr>
<tr><td>18</td><td>Behavior Replication</td></tr>
<tr><td>19</td><td>Anomalous behavior</td></tr>
<tr><td>20</td><td>Behavioral boundary</td></tr>
<tr><td rowspan="3">6</td><td rowspan="3">Policy Formulation and Analysis</td><td>21</td><td>Alternative Policy analysis</td><td rowspan="3">Policy Implementation</td></tr>
<tr><td>22</td><td>Sensitivity of potential policies</td></tr>
<tr><td>23</td><td>Policy recommendations</td></tr>
</table>

Table 9: SD implementation design (Source: Adapted from Oyo et al. 2009)

3.4.4 Action Research

Greenwood and Levin (2007:3) define AR as a research process that involves collaborative problem analysis and problem solving in context. This encompasses three foundational principles: action, research, and participation. Coghlan and Brannick (2014:55) advocate two of these foundational principles: action, while noting that "we cannot say that we know something until we have tried to act in the light of any knowledge" (Coghlan and Pedler, 2006:129), and participation, while positing that involving the learners in their own learning produces better learning and more valid data.

I have already referred to change as the driving force behind this research project, but modeling (SD) is of little use if it cannot be used to build social capital, credibility, and trust, to encourage the proposed changes among the variety of stakeholders who will have to be influenced. In this regard, AR fits the goal of my research, as it actively involves both the researcher and subjects as co-participants in the definition of the final values governing the modeling (and, therefore, its output).

Since AR was conceived by Kurt Lewin (1946) as a research method, it has evolved through several generations, and today the term includes multiple modalities that abide by the same foundational principles presented above yet consider a diverse group of practices which can be mixed as circumstances and research topics demand. These different approaches identify themselves by either preceding the expression 'action research' by a word emphasizing what is critical for this approach (e.g., participative, critical, or pragmatic) or by succeeding the word 'action' by the desired criteria (learning, research, or science). The number of approaches has become so vast that even Grenwood and Levin (2007:9) needed to qualify their seminal introduction to AR by saying that "we have made a good-faith effort to become knowledgeable about many different approaches".

Besides AR, Action Learning (AL) developed by Reg Revans is significant. The simplest way to grasp their key differences is by defining AR using Reasons' first- (enquiring into my own practice), second- (researching with others), and third person (involving a community of practice too wide for face-to-face relation) inquiry and comparing them to Revan's systems alpha (researching the workplace problem in its own context), beta (performing cycles of trial and error), and gamma (self-awareness of the participants). Given Revans' disregard for the third-person practice, a parallelism can be seen between Reason's first- and second-person practice and Revan's systems beta and gamma.

With so many different approaches available, and the convenience to follow a praxis independent from the academic terminology, I consider it is time to follow Greenwood and Levin's (2007:9) suggestion and be pragmatic "while keeping the different kinds of AR practice and visions in sight". Therefore, I decided that beyond the three foundational principles of AR noted above, I would limit the academic perspective exposure of the group to the introduction of the three practices described in the following sections, with the understanding that they would provide them with a common approach to operate as a group while also guaranteeing the quality of the research.

3.4.4.1 Maintaining an attitude of inquiry

Marshall and Reason (2007:369) describe the notion and importance of an attitude of inquiry, which encompasses practicing curiosity, willingness to articulate and explore purposes, humility, participation, and radical empiricism. These are all components that facilitate a participative reflection and ensure the quality of the research. Radical empiricism is a natural de facto condition of our corporate environment, but I will have to nurture the remaining qualities during the workshops.

Anderson and Thorpe (2004:659) advocate in favor of considering critical reflection when practicing AR. In doing so, they refer to Reynolds who favors questioning assumptions as the center of critical reflection and notes that "through the process of critically reflecting, managers become aware of a much wider environment in which they operate and begin to realize the social power relationships of the organization and their own networks". Both questioning the assumptions taken when modeling and realizing the wide environment in which the changes will unfold are key components of a critical approach to an AR process. Chapter 6 offers a deeper discussion on the implications of an attitude of inquiry and critical reflection on the work of the learning set.

3.4.4.2 A spiral of cycles

AR is often described in terms of a spiral or a circular methodology, where cycles of planning, action, and reflection take place successively. Kemmis and McTaggart (2015:276) introduce this concept as a "mechanical sequence of steps" to immediately warn the reader that the process does not usually happen in such a neat manner, as the stages overlap and become obsolete quickly. Considering that AR is a social process of collaborative learning, and the diverse participants I plan to involve in the LS, the process will probably honor Kemmis and McTaggart's statement and result in a very fluid application of the spiral cycles.

The LS embraces this spiral of AR cycles, as displayed in the figure below, considering different steps, including a first dialogic step where the possible actions are discussed within the LS until an approach is shared by the group, acting by modeling the proposed actions, evaluating, and reflecting on the consequences, and learning from them with an attitude of inquiry. This results in a final set of values that form the basis for the simulation that produces the evidence needed to answer the research questions.

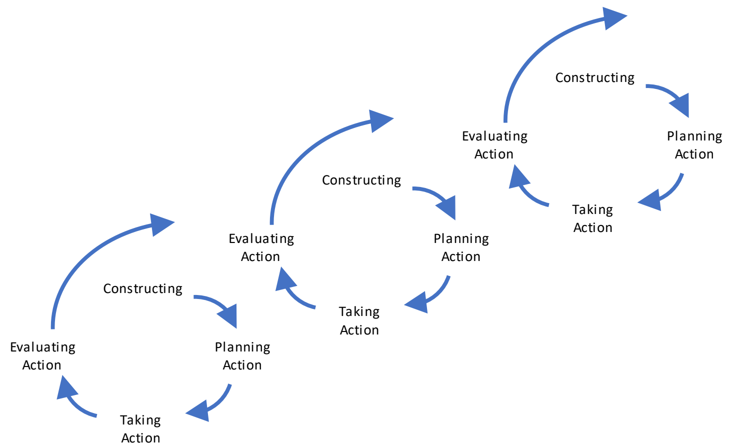


Figure 5: Spiral of Action Research cycles (Source: Coghlan and Brannick, 2014)

3.4.4.3 A double-loop reflection

Coghlan and Brannick (2014:12) identify two cycles in any AR research project. While Lewin's spiral of steps based on constructing, planning, taking actions, and evaluating the results is the core cycle, a reflection cycle takes a meta-learning approach and reflects about the processes and challenges behind the learning process. This notion parallels the seminal idea of first- and second-loop learning developed by Argyris and Schon (1978). In this theory, single-loop learning is seen as everyday problem solving, focusing on solving problems in the present and finding their underlying reasons, while double-loop learning examines the appropriateness of current learning behaviors.

For a practitioner, the journey from being a problem solver to a research practitioner capable of taking an inquiry approach that critically examines actions beyond a 'what works' attitude is not easy or quick and requires not only a shift in the mindset of the practitioner but also, to a certain extent, a change in the mindset of the organization they are working with. The consequences that the penetration of AV will have on our business and the ensuing organizational changes will likely accentuate the need for this change in mindset.

The capacity of any organization to embrace double learning into their culture is a direct measure of its capabilities to handle organizational learning and, therefore, manage this change. Therefore, beyond Lewin's spiral of steps (whose result is already embedded into the final values of the model); I consider that the actionable knowledge created by this study will greatly benefit from a double-loop reflection result of the findings of the three workshops.

3.4.5 Implementation of MMR

Ivankova et al. (2006) refer to Tashakkori and Teddlie to note that over forty different MMR implementation designs can be identified in the literature. They are the result of using a variety of quantitative and qualitative methods in either a sequential or concurrent manner. A review of MMR in transportation and construction research during the last few years seems to support this claim, as it offers an extraordinary variety of methods, tools, and designs, integrating SD in an MMR methodology to address different goals. From using qualitative methods to inform the conceptualization of SD (e.g., Mazur, 2015 using MLP; Kopainsky and Luna-Reyes, 2008 using theory building; or Coyle, 2000 utilizing influence diagrams) to using SD as a way to interpret qualitative findings (e.g., Rees et al., 2017 used SD to interpret the findings of a Delphi study) to mixing different quantitative methods during the implementation process of SD in a sort of quantitative-quantitative approach (Noto, 2017 combining SD and performance management; Ding et al., 2018 using SD and ABM; Zhang and Tay, 2017 combining SD with Data Mining; or Barabba et al., 2002 mixing SD with real options and diffusion models). Turnheim et al. (2015) take a different approach when advocating the use of different qualitative and quantitative methods (SD with socio-technical transition and initiative-based learning) to face the weaknesses of each approach when researching complex problems in a systematic view.

This diversity of options seems to suggest that the challenge is not only to choose which methods to use (MLP, SD, and AR in this case) but how to combine them to answer the research questions in as robust a manner as possible. In this regard, Ivankova et al. (2006) noted that a successful design needs to consider three features: priority, implementation, and integration. Priority refers to the method that is given emphasis, which is based on the interest of the researcher and the audience. In this study, and for the reasons discussed in the introduction to MMR in this section, SD as a quantitative methodology will be prioritized.

Figure *6*: Research Methodology (Source: Developed for this study) offers a visual flowchart of the research methodology and details how the different research tools were combined within MMR. As the figure shows, the MLP analysis is the foundation of both the SD model (when identifying stakeholders and variables) and the AR process (when proposing a transition path to be considered by the LS). The LS uses the SD model to act and reflect on the results. This leads to the following steps:

1. Step 1: MLP analysis of the Metroplex (Chapter 4).
2. Step 2: Problem articulation phase of the SD, leading to the causal loop diagram (Section 5.1). This is informed by the MLP analysis.

3. Step 3: Model proficiency phase of the SD (Section 5.2).
4. Step 4: Solution refinement phase of the SD (Section 5.3).
5. Step 5: Quantitative AR cycle (Section 6.2).
6. Step 6: Qualitative AR cycle. LS frames the results of the quantitative simulation within the MLP analysis and takes action as needed with the goal to understand how the different local stakeholders may embrace the proposed innovation (Section 6.3).

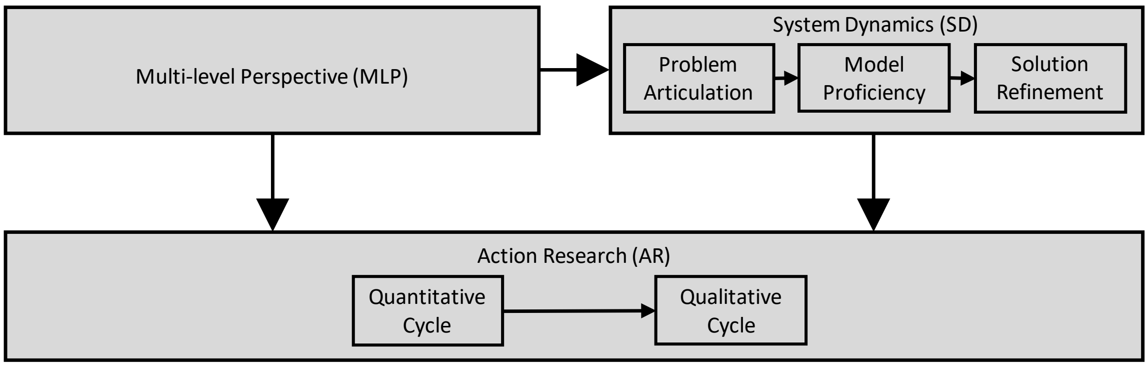


Figure 6: Research Methodology (Source: Developed for this study)

3.4.6 AR Methodology

As discussed in section 1.3, a fundamental aim of this research is to develop shared understanding through our organization about the potential of AV to address our workplace problem (need for innovation). This, combined with the intention to produce actionable knowledge that could enlighten the next steps, encourages me to carefully consider who to be invited to the LS and the research tools to be used (workshops, memos, and surveys).

As any AR R&D activity, the participation in the LS impacts the absorptive capacity of the team that needs to grapple with the uncertainty of the future. Although this advocates for increasing the size of the LS, I decided to limit the number of participants in the group in order to favor the participation of every member. Considering my intention to have participants from the different departments that will eventually have a direct implication in the project (innovation, operations, and technology), I invited five participants who met in three half-day long workshops conducted over a period of several months. Even though they were all deeply familiar with our business and the technologies considered, none of the participants was an expert in customer segmentation, fee structures, or marketing incentivization; hence, bias arising out of previous experiences could be avoided.

COVID-19 struck while the process was ongoing, and while it did not alter the working dynamics of the group, it forced the workshops to be remote and influenced the views of some of the participants, as described in Chapter 6.

As noted previously, one of the most significant risks of these projects is the eventuality that the group participants might lose interest in the project if concrete findings are not seen quickly enough. This resonated with me, and I carefully crafted the sequence and length of the process, including the contents of every workshop, to mitigate this risk. This allowed the LS not only to get the most out of the workshop during the time the group was assembled together but also to steer the group in a way that every individual could arrive at the next workshop with predefined thoughts, so as to maximize both the individual and the group learning process. Three workshops were conducted as follows:

- First workshop: Introduction to the research questions and methodology, assumptions made, dynamics considered, and the basics of the SD model.
- Second workshop: Initial results offered by the base case, evaluation of the assumptions, and planning of actions for the quantitative AR cycle.
- Third workshop: Review of the results offered by the simulation of the quantitative AR cycle, sensitivities to critical parameters, introduction to the socio-technical regime in the Metroplex, and actions proposed for the qualitative AR cycle. Discussions about the uncertainty of the research and the likely transition pathway.

Before the initial workshop, I (both in my role as internal researcher and as a modelist) produced and distributed an initial memo to all the participants wherein I introduced the goals of the research and the overall approach to the research methodology and tools. I also produced minutes which were distributed after every meeting and used by the participants to support further reflection between the workshops.

In order to bring a quantitative measure to the sought alignment, a survey was distributed at the end of the third workshop for the researcher to evaluate how aligned the participants were with the key topics discussed and the actions taken. The survey included a set of items on a one to five Likert-type scale ranging from “not at all” to “completely”. These items included topics which may add uncertainty to the conclusions of the research and the impact that they may represent.

3.4.6.1 Ethical considerations

Participants were made fully aware of the nature of their participation in the research prior to the first workshop. Although the process required them to fill a survey at the end of the process, the ethical obligations were met as the responses were not individualized and remained completely anonymous to the researcher. To ensue this, although the researcher distributed the survey by email to every one of the participants, they were asked to return the responses to a nominated third party who, in turn, forwarded the whole set to the researcher; thus the participants were not identifiable by the researcher. The participants were also asked to check a box on the survey indicating their consent.

Remarks and direct quotes included in the post-workshop minutes were also anonymous. All participant inputs and sensitivity requests were executed as much as possible during the same workshop, and no recording was made of the last remote workshop.

Concerning the secondary data sources used, the researcher gained organizational approval to collect data from the organization, although all data used was in the public domain, and as an employee, the researcher is under a "Cintra Confidentiality and Non-Disclosure and Invention Assignment Agreement", which does not allow the disclosure of confidential information beyond the organization.

3.4.6.2 Data collection methods

As previously discussed, a central tenet of this research is that it builds on the philosophical principles of pragmatism which primes what works and is meant to be more exploratory than conclusive.

Taking this into consideration, although primary data may reduce uncertainty, it would be extremely time and resource consuming; hence, after the literature review, I decided to feed both the qualitative analysis and the quantitative model with secondary data, given the maturity and variety of data available in the different research streams. There is only one exception to this approach, which is the TEXpress usage sub model, which will be fed with internal data from our own organization.

3.5 Problems and limitations

There are several threats to the ultimate success of this research. One of the most relevant threats relates to my role as an internal researcher. Roth (2007:41) describes some of the challenges to the internal researcher, including linking the internal action research process to the business strategy, pre-understanding, acting in a political organizational landscape, and the need to maintain a balance between opposing forces. While all of them are unquestionably important, a significant part of the success of this role lies in being able to guarantee the equality of influence between all participants in such a diverse group, so that all the members can feel that they are acting on equal footing.

Secondly, and as discussed previously, the research will be based in secondary sources. Although it is mostly sourced from peer reviewed papers, the literature review has shown the wide diversity of empirical data produced by the research streams. There are several possible reasons for such a diversity (which sometimes produces contradictory conclusions), but the dynamic context in which the development of AV unfolds (which may change even with a single accident) as well as the wild dispersion of assumptions which are made to conduct the research streams may serve as explanations.

Finally, Holmström (2017:12) refers to Jahangirian to describe some of the shortages that AR presents in a practitioner's environment. Although these problems have been assembled as a result of empirical experience in a clinical research, I can easily identify them in my practitioner's environment. Table *10*: Risks of the AR process (Source: Adapted from Holmström, 2017:12) below, shows these problems and the way I plan to mitigate them.

	Risks	Way to mitigate
1	Practitioner's workload	Three workshops once a month up to 3 hours each
2	Practitioners not knowledgeable about simulation and SD	Unless there is a specific requirement, the group will not be required to get into the intricacies of all cycles with the same level of detail. They will be exposed to a greater level of detail to those cycles where their participation is likely to provide more value (problem diagnosis, dynamic hypothesis, model testing, and policy formulation and analysis)
3	Project not producing tangible results fast enough, participant losing interest and dropping out	The workshops will be called once a first operational version of the model is available, and a minimum amount of data meaningful to them can be delivered in order to start acting immediately
5	Complex environment and high variability	Use stock that the group may easily recognize and be familiar with, and variables which allow ample variability when calibrating and fine tuning the model
6	Lack of easily accessible data	Based on the availability of secondary data, use as much empirical data as possible

Table 10: Risks of the AR process (Source: Adapted from Holmström, 2017:12)

3.6 Summary

Research questions constitute the cornerstone of any research process. Those that I have identified led me to consider an inductive approach within an exploratory design since this research is not meant to offer conclusive and definitive answers but a mere baseline for future action. In this regard, relevance takes precedence over a generalization of the findings. My personal worldview, including my assumptions about the world and the ways to understand it, places pragmatism as the paradigm driving my research methodology and, thus, suggests using MMR as a methodology and MLP, SD, and AR as the research tools. Furthermore, it is necessary to navigate the politics of a complex problem that unfolds in a context influenced by a myriad of stakeholders with different views and agendas, which suggests a scenario wherein a great diversity of threats may derail or condition the research process. To guarantee the quality of this process, it is critical that I, in my role as inside researcher, group facilitator, and modeler, mitigate and resolve these threats in a proper manner.

4 Multi-Level Perspective Framework

As discussed, the socio-technical system that frames the transition towards AV in the Metroplex will be analyzed using MLP. Such an analysis will be operationalized in three steps: i) Analysis of the socio-technical framework, ii) Identification of a likely future regime, and iii) Identification of the transition pathway.

4.1 Socio-technical framework

4.1.1 Landscape

Landscape dynamics results from the evolution of broad variables including changes in cultural (attitudes of the constituents towards climate change, road safety, or congestion), political (e.g., preservation of the status quo of local incumbent vehicle actors such as manufacturing plants and dealers versus newcomers), and societal perceptions or demography that put pressure on the regime to incentivize the change.

Texas is an ecosystem particularly prone to support the diffusion of vehicle innovations (Austin was the city were Google performed the world's first fully driverless journey on an open public road in 2015). As an example, Texas has one of the lowest average vehicle age in the US, which Autoalliance (2019:1) sets at 10.4 years – well below the 11.2 year average in the US. This favors a quick turnaround of the fleet which facilitates the introduction of new technologies. Nevertheless, the diffusion of innovations in a market highly regulated (from multiple angles such as technology, infrastructure, liabilities, human requirements, and insurance) as the automobile will undoubtedly be influenced by the attitudes and signs of the public agencies. In this case, there is an amalgam of Federal (NHTSA), state (TxDOT and TxDMV), and local (NCTCOG, NTTA) agencies operating nationally, statewide, and locally in the Metroplex. Although local and state agencies are supporting the development and deployment projects of AV happening in the niche (see below), a massive acceptation of this process is strongly dependent on the decisions taken at both the branches (executive and legislative) of the Federal government (see sections 2.2.3 and 2.2.4). Even the policymakers' support to the activities happening in niches, which may alter the regime, is moderated.

Although Texas ranks second within the states with the most BEV charging outlets, one example of this moderate support pertains to the restrictions to the direct sales of vehicles that come attached to the state $2,500 BEV rebate and which impede Tesla buyers from getting the rebate as long as Tesla does not sell through dealers.

The pressure that the landscape puts on the regime will be a combination of three factors: i) public policies to support the AV activities in the niche (supported by the "Texas is open for business" policy of the current administration), ii) activities to reduce the emission of greenhouse gases, and iii) endeavors to reduce the number of fatalities on our roads (and, therefore, incentivize BEV and AV directly or indirectly). A description of these factors follows below.

4.1.1.1 Policy-making

Although the US House of Representatives passed the Safely Ensuring Lives Future Deployment and Research in Vehicle Evolution Act (SELF DRIVE Act), the American Vision for Safer Transportation Through Advancement of Revolutionary Technologies (AV START) stalled in the Senate before the mid-term elections that took place in early November 2018, and its fate is rather uncertain. Both are key pieces of legislation to establish a clear demarcation concerning the responsibilities of both Federal and state governments, sorting, among other things, the controversial Federal pre-emption, the arbitration between OEM and the consumer, and the homogenization of the safety requirements between states. As a result, AV continue being developed and tested in a pre-regulatory environment, making usage of the exception process to the NHTSA certification, which does not allow the deactivation of a component (e.g., wheel), which was necessary to achieve the certification of the car.

On the legislative side, Texas has been giving mixed signals. On the one hand, the current BEV incentives ($2,500 discount for all-electric, plug-in hybrid, and fuel-cell vehicles or $5,000 for compressed natural gas or liquefied petroleum gas), which were reinstated in 2018 after a three-year hiatus, were finalized by May 2019, and the Texas 2019 legislative session saw policymakers fill six bills either to directly raise registration fees for BEV or to direct government agencies to study transportation funding which may include that. On the other hand, the last legislative period (2017) showed a clear support to the development of AV by providing a clear and straightforward framework to test and deploy them. This included both the House (H.B. 1791) and the Senate (S.B. 2205) passing bills supporting the deployment of AV. The law, effective September 1, 2017 is one of the most AV permissive in the country and establishes that a person may operate an AV anywhere in the State, without the need to have a human in the AV while it is being operated, or even any particular tagging/labeling of AV, and with only a limited number of requirements (insurance, registration with the DMV, compliance with Federal law and Federal Motor Safety Standards, and a recording device). To show how vibrant the legislative agenda about AV is, Texas 86th Legislature (2019) had the SB 969 passed, which governs the operation of a personal delivery or mobile carrying device in a pedestrian area or on the side or shoulder of a highway, and two additional AV bills being filled – one to increase the liability of manufacturers in the event of a crash involving an AV and another to require AV to be equipped with a failure alert system. This mature legislation is likely the reason why the niche is filled with so many startups testing AVs in Texas (see below description of the niche).

4.1.1.2 Environment

As reported by the Boston University's Database of Road Transportation Emissions, CO_2 emissions in the Dallas Fort Worth region have risen by 133% since 1990. With this is mind, the city has shown its commitment to reverse this situation by meeting the international emissions reduction targets set by the Paris Agreement in 2016 in the absence of Federal action on climate change. Dallas defined ambitious targets of reducing GHG emissions by 43 percent by 2030 and 100 percent by 2050. To this end, Dallas elaborated the Comprehensive Environmental and Climate Action Plan (GECAP) which was approved by the Dallas City Council on May 27, 2020 and which sets the roadmap to this goal. Together with the 5-Year Strategic Mobility Plan (SMP) that is being developed by the city of Dallas, GECAP identifies the transportation and energy sectors accounting for 99% of the total emissions with the waste sector responsible for the remaining 1%. Light vehicles are a significant part of this inventory of greenhouse gas emissions, which suggests that incentivizing future AV (BEV powertrain-based vehicles) may become an important component in the GECAP toolbox to achieve its target.

One more issue to consider is that air pollution resulting from the production of electricity in Texas is relatively low, which may increase public appeal to incentivize the transition to BEV powertrains. Adding to this topic, Holland et al. (2016) produced a remarkable research on the effectiveness of (or lack of) the one-size-fits-all nature of the BEV subsidies, when the exported emissions (exported to other locations because of the distribution of the electrical grid) are added to the native emissions. They consider two relevant factors: the population density, which drives the mortality consequences of the pollution, and the environmental cleanness of the national electrical grid, which is composed of three interconnections with very different characteristics –Texas, with a relatively clean grid that produces electricity out of gas with minor coal participation; Eastern, where coal has a relevant role; and Western, in which coal has a very limited participation.

The figures below produced by the Alternative Fuels Data Center (AFDC) of the US Department of Energy (DOE) provide a breakdown of electric sources on a per state basis. When considering the participation of coal in the grid, Texas can be seen in the national average, between a very coal intensive Eastern and a green Western.

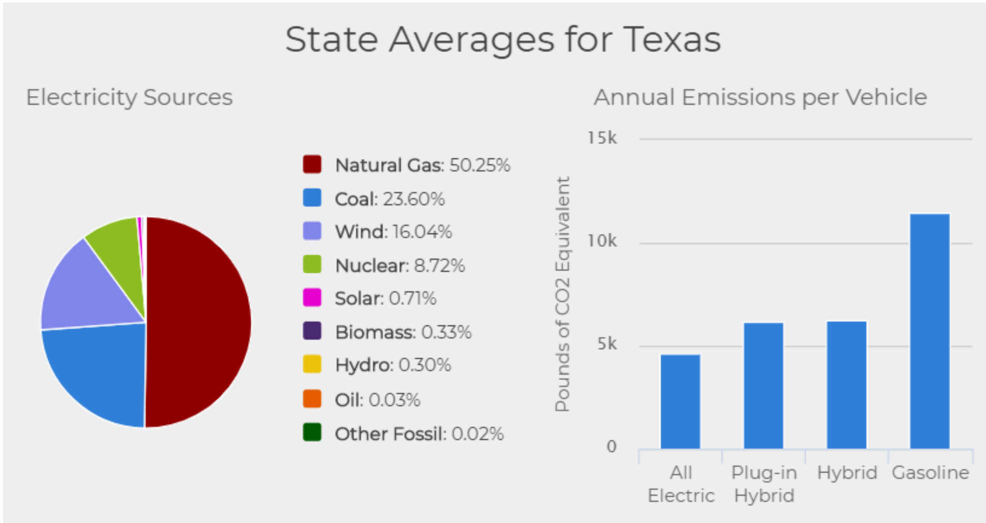


Figure 7: Texas electric grid by source (Source: AFDC, 2019)

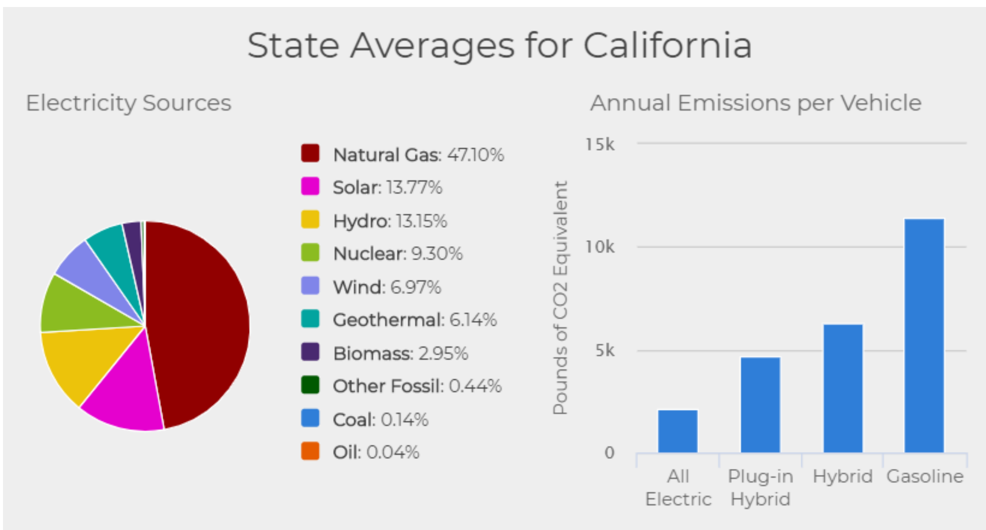


Figure 8: California electric grid by source (Source: AFDC, 2019)

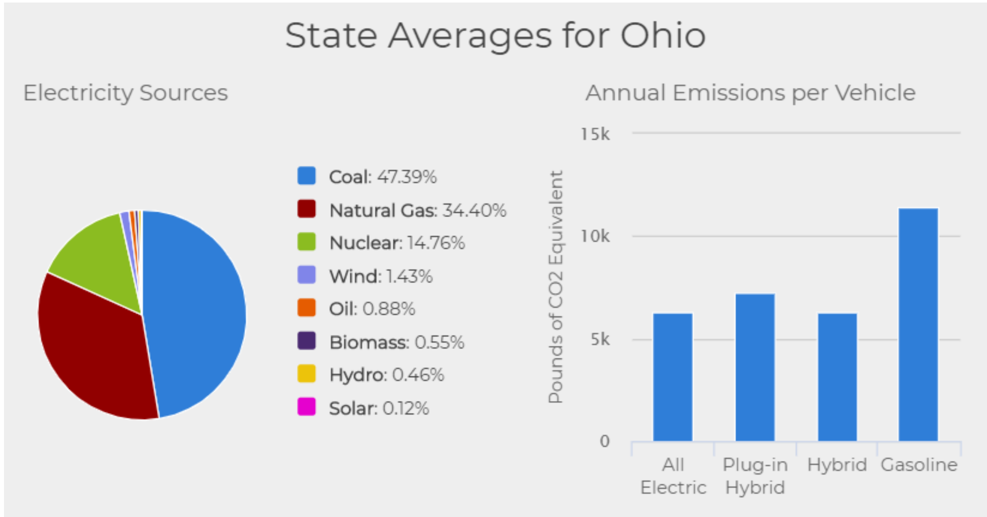


Figure 9: Ohio electric grid by source (Source AFDC, 2019)

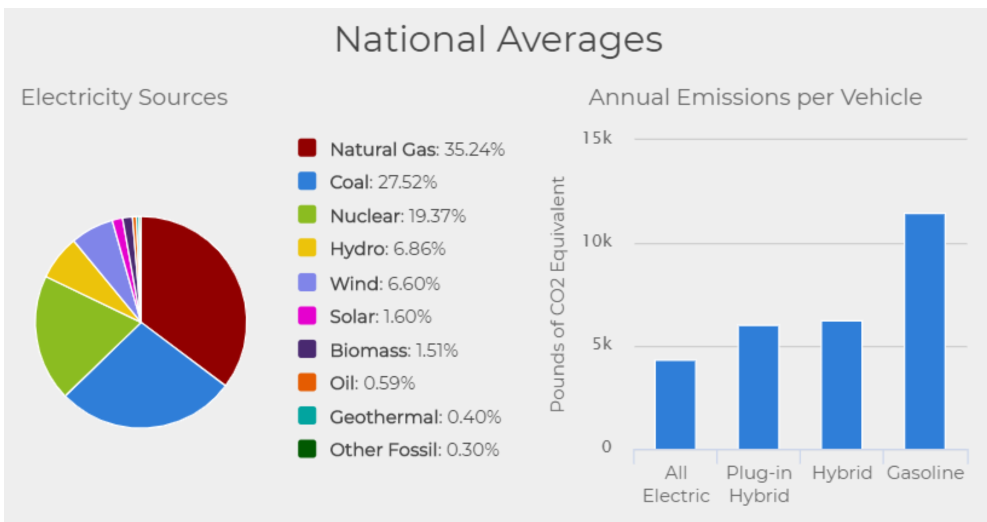


Figure 10: National electric grid by source (Source, AFDC 2019)

Holland et al. (2016:3717) conclude that “there are only 11 states in which the environmental benefits of HEV are positive, and Texas is the only high VMT state outside of the western interconnection in which this happens”. In fact, Texas has an environmental net benefit per mile of 0.34 cents (gasoline damages minus electric damages) which grows to 0.62 cents/mile in Dallas. The findings by Holland et al. clearly support Texas as one of the states where an eventual subsidy of electrical vehicles would provide the most benefit, even considering that the low density of Dallas (3,645 habitants/sqm against the 6,999 habitants/sqm of Los Angeles) limits the damages of ICE. The proposal by Holland et al. (2016) considers a worst-case scenario in which the upstream emissions of electricity are considered and not those associated to the production and distribution of gas.

4.1.1.3 Road safety

Texas had 3,720 fatalities in 2017, after several years of uninterrupted increase (see Figure 11: Fatalities in car accidents in Texas 2003 to 2018 (Source: NHTSA, 2018)). This was more than any other state in US, resulting in a ratio of 1,40 fatalities per 100 million vehicle miles, which compares to the national average of 1,19 (best state in the 0,63 range).

Acknowledging this reality as a crisis, the Texas Transportation Commission issued a Minute Order on May 30, 2019 instructing the TxDOT to work towards the goal of reducing the number of fatalities by half in 2035 and to zero in 2050. This confirms the need for Texas to champion the deployment of technologies that may reduce the number of road fatalities and encourage the TxDOT to incentivize the means to reach this goal.

Figure 11: Fatalities in car accidents in Texas 2003 to 2018 (Source: NHTSA, 2018)

The willingness of Texas' policymakers to support the development of AV, combined with the commitment of the state and its major cities (Dallas among them) in facing two significant challenges where BEV and AV may be important players (road fatalities and environment), may ignite landscape changes which will put gradual pressure on the regime.

4.1.2 Regime

Texas not only ranks 2nd in the number of registered vehicles and 7th nationally in automotive employment, with a 29% surge since 2010, but also serves as a natural link between the Mexican-based OEM and the rest of the US automotive industry. Consequently, it also presents a strong socio-technical regime populated by many different and very influential players. One the one hand, it has more than 1,300 franchised automobile dealers and on the other, an automaker ecosystem which, with over 1,700 facilities, have several OEMs (General Motors and Peterbilt in Dallas and Toyota in San Antonio; their flagships are to be joined shortly by the just-announced Tesla factory to be built in Austin with Toshiba and Caterpillar as its most significant representatives) and many Tier 1 suppliers. Many of these companies are Fortune 500 companies, and their policies in many cases are dependent on their mother companies located outside of the Metroplex, although GM has R&D facilities in Austin. Nevertheless, it is difficult to expect any proactivity from the car dealers (a strong stakeholder) until the consequences of the diffusion of AV are better known in terms of employment market consequences.

Ford has just announced that it will deploy its fleet of AV in Austin in 2022 with Lyft. This will make Austin the third city in the country where they will deploy, after Miami and Washington DC, which further reinforces the appeal of the state even for these OEMs that do not have local manufacturing facilities (Texas is the largest market for SUVs in the US, and Ford has the largest market share). This appeal was further increased when Tesla confirmed its intention to build a Gigafactory in Austin.

4.1.3 Niche

The Metroplex and Texas in general are pushing hard to draw alternative-transportation companies to help solve not only the congestion problems that result from a car-centric culture but all sorts of transportation challenges. The area was selected in 2017 as one of the first partner cities for Uber's flying taxi service, and Uber Elevate Google X chose Austin as its second city, after its hometown, to operate its AV fleet. They have current plans to operate ride hailing, food delivery, and urban air taxis.

Correspondingly, many initiatives are unfolding both within controlled environments at R&D facilities as well as on open roads within the legal framework we review in the landscape description. Among the former, those test tracks operated by private (e.g., Bridgestone, Continental, and Goodyear) and public entities such as South West Research Institute (SwRI operates a world-class office of automotive engineering with a vast accredited experience in AV) and Texas A&M are worth mentioning. Besides this, there are electronic companies (e.g., Texas Instruments and Freescale) with a long track record of providing technology to the automotive sector.

The Center for Transportation Research (CTR) at UT Austin, the Texas Transportation Institute (TTI) at A&M, and SwRI joined forces in 2016 as a network of public agencies and leading research institutions advancing mobility in Texas. In 2017, this led the US Department of Transportation (USDOT) to designate the partnership as one of the 10 proving ground pilot sites (see Figure 12: USDOT AV proving grounds (Source: USDOT, 2017)) to encourage testing and information sharing about automated vehicle technologies.

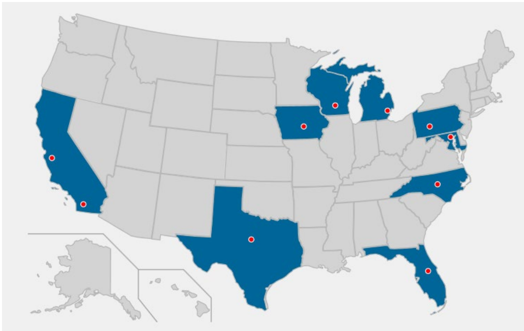


Figure 12: USDOT AV proving grounds (Source: USDOT, 2017)

Parallel to these research activities, city councils are currently sponsoring a flurry of activities related to AV. Some of these innovative projects as reported by TxDOT (2019) are as follows:

Statewide

a. Texas Connected Freight Corridor (TCFC): In a collaboration effort with public and private stakeholders, the TCFC project is deploying connected vehicle technology on more than 1,000 commercial vehicles to improve traveler information and asset condition management.

Arlington

b. EasyMile AV Deployment: Two EasyMile EZ10 autonomous shuttles were deployed in an off-street environment in Arlington's Entertainment District during a one-year period ending in August 2018. Arlington is using lessons learned from this deployment at over 110 events to prepare phase two of the project.
c. Drive.ai AV Deployment: For one year beginning in October 2018, several of Drive.ai's autonomous vehicles have been deployed in the Entertainment District of Arlington for an on-street, mixed traffic pilot program.

d. Autonomous Delivery Devices: Arlington approved a resolution to allow private companies to test and deploy robotic delivery devices in a real-world setting. Marble is the first company to begin mapping Arlington's sidewalks as routes for its autonomous robots.

Austin

e. AV Road Rules: Austin is currently deploying a platform called INRIV AV Road Rules that enables cities and road authorities to assign, validate, and manage traffic rules and restrictions for AV operating on public roads.
f. Autonomous Delivery Devices: In 2017, the Austin City Council approved a resolution that authorized a request for information (RFI) on autonomous personal delivery devices as well as the creation of a pilot program for these battery-powered delivery robots.
g. Connected Corridors: Austin has deployed DSRC technology at five intersections in the downtown and East Austin area to create connected corridors, with plans to deploy at two more intersections.

Frisco

h. AV Deployment: In 2018, Drive.ai launched an on-demand self-driving transportation service in the city of Frisco with rides offered to over 10,000 people in a geofenced area. This service was discontinued in late March the year after.

Houston

i. AV Deployment: An autonomous shuttle will be piloted on the campus of Texas Southern University in 2019 and then expanded to all METRO stations.
j. Platooning: Houston METRO is continuing to explore truck platooning to enhance its high-capacity transit system.
k. Nuro has partnered with Kroger, so that their customers can shop online and have the goods delivered by an AV the same day. The service is currently available for six zip codes of the city.
l. Kodiak is already operating autonomous 18-wheelers to carry goods between Houston and Dallas, a trip of more than 400 miles roundtrip.

San Antonio

m. AV Request for Information (RFI): The city of San Antonio has recently closed an RFI for potential AV pilots to better understand AVs and their ability to improve connectivity and safety.

Although much of the pressure to extend the recharging network of BEV will be exercised by BEV vehicles (as they will ensure a massive presence much earlier than the AV are deployed), utilities will also be a critical component to optimize its deployment. In this process, the role of electric utilities will be significant. Oncor, the largest utility in Texas serving 10 million users in the Metroplex, is already analyzing how their power grid will have to be expanded to attend to the recharging of commercial fleets of trucks class 6 and 8 in their area and how the excess of production resulting from the wind powered generators may be used to recharge electric cars at nighttime.

4.2 Future regime

According to Electric Vehicles North Texas (EVNT), and partly thanks to the incentives described in section 2.2.3, as of January 2020 the Metroplex has almost 14,000 BEVs being driven on its road network, which is more than that of any other major metropolitan area in Texas (see Figure 13: North Texas BEV Registrations January 2020 (Source: EVNT, 2020)).

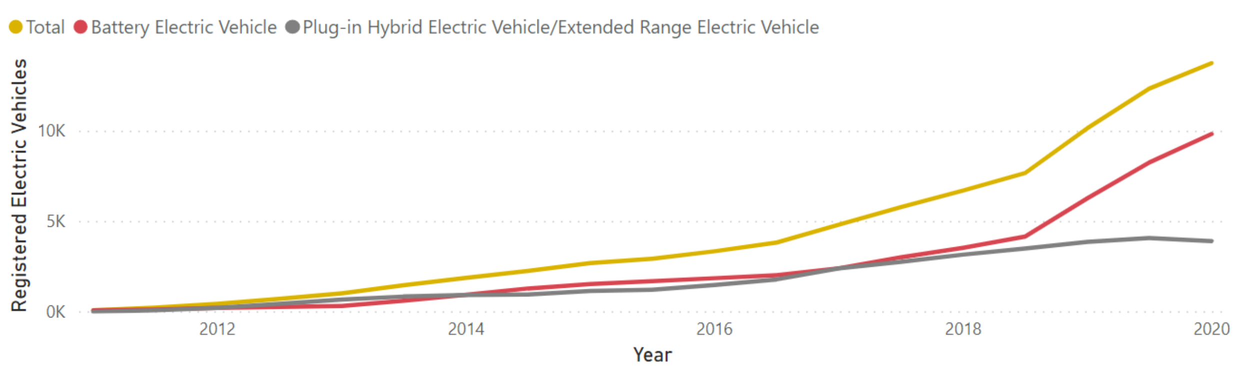


Figure 13: North Texas BEV Registrations January 2020 (Source: EVNT, 2020)

This number does not appear to be the result of any precise goal being set by the public authorities in charge of incentivizing its diffusion, such as the Texas Emissions Reduction Plan (TERP, 2020). Only the Texas Electric Transportation Resources Alliance (TxETRA, 2020), as a non-governmental organization, has set the ambitious goal of having 10 million electric vehicles and 75% of all trips to be electric propulsion by 2035. To what extent this is consistent with the goals which will be defined by GECAP is unknown.

However, Texas still must define an aspirational goal for the deployment of AV in the near future (and much less an incentive program). In October 2019, TxDOT celebrated the first meeting of the Connected and Autonomous Vehicle (AV) Task Force to become a central point for AV advancement, but the state appears to be in a very exploratory phase.

One may argue that although the commitment of local and state policymakers to face the challenges that may result in changing the dynamics of the landscape (and increase the pressure on the regime) seems to be substantiated, the extent to which this commitment influences a transition path that leads to the diffusion of AV in the Metroplex is unknown. For instance, one of the climate action plans (Houston) that is used by Dallas as a reference when building its own includes very few references to incentivize the diffusion of BEV to reduce the emission of GHG.

This situation makes it difficult to speculate about future outcomes, but it also implies that if the policymakers want to enact public policies to incentivize the diffusion of AV (like the one researched in this project), they will have to counterbalance the ambiguity of public agents by demonstrating that the net effect of an increasing diffusion of AV is in the public good.

4.3 Transition pathway

As Köhler et al. (2017:5) rightfully note "transitions are not linear processes, but entail multiple, interdependent developments". Texas and the Metroplex will not be any different. Both the landscape developments (a legal framework that incentivizes AV testing, environmental awareness, increasing congestion in the Metroplex, and a crisis of road safety that increases the number of fatalities by the day) and niche innovations (in particular through outsiders such as Waymo, Tesla, or Uber in the Metroplex) apply a moderate pressure over the regime that results in a limited destabilization, which is challenged by the regime actors by sponsoring their own niche players and their own AV initiatives (Ford and Volkswagen with Argo, or General Motors and Honda with Cruise).

The pressure over the regime is expected to grow significantly (Moradi and Vagnoni (2018:231) note that transportation is the only sector that has not yet achieved the sustainability objective), but this will take time as the technology matures and the legal regulations adapt. This paired with the relative immaturity of the niche to become a real alternative to the actors of the regime (which, as we have seen, offer a robust and stable ecosystem), would seem to suggest a transformation pathway in which the regime will adjust and reorient because of the pressure of the landscape and niche.

In his MLT analysis of the transition pathway from horse-drawn carriages to automobiles, Geels (2005) describes how an influx of changes in the society during the late 18th century destabilized the horse-based urban transportation regime to allow a niche-innovation (electric trams) to go mainstream, just to be replaced immediately after by the ICE automobile. Geels (2005:472) posits that this transition included a de-alignment and re-alignment of the regime followed by two technological substitutions. While I am not suggesting a complete parallelism between both transitions, the transition described by Geels shows how, in the presence of incentives (from landscape and niche) extended long enough, two technological substitutions may be chained within a single transition. Given that the factors that contribute to the landscape and niche pressure and destabilize the regimen do not seem to have an end in sight, a transition path akin to the transition from horse-drawn carriages to automobiles, in which the different "revolutions" discussed in the preceding chapter will intermingle to alter the regime, seems feasible.

When figuring out who will make cars in the future, KPMG (2012:32) refers to Burns to predict that "incumbent players rarely do well when industries disrupt". This may or may not be the case in the current transition, but a considerable amount of activity happening in niche is the result of deep-pocketed initiatives sponsored by incumbent actors. This would lead regime actors to not only innovate through 'learning by doing' (improving and developing the advanced driving assistance systems in the fleets) but also through 'learning by searching', i.e., through radical innovations in their sponsored niche initiatives. Both arms will have to be modeled to properly forecast the diffusion of AV.

Table 11: AV Socio-Technical Framework in Texas (Source: Developed for this study) summarizes the status of the three MLP analytical levels of the transition to AV in Texas.

MLP Analytical levels	
Landscape pressure	Moderate
Regime	Strong
Niche	Inmature

Table 11: AV Socio-Technical Framework in Texas (Source: Developed for this study)

5 System Dynamics Model

As discussed in section 3.4.3, the model was build following the process presented in Table 9: SD implementation design (Source: Adapted from Oyo et al. 2009). Each of the three cycles is described in one section. A first section identifies the drivers that determine the problem and how they retrofit each other in the causal loop diagram. The general construction of the model and the different sub models, the values used for the parameters in the simulation, and the rationale behind the more significant ones[2] are described in the second section. Finally, the third and last section details the verification of the values chosen for the different parameters, and the sensitivities which were run in order to measure the sensitivity of the model to potential policies.

5.1 Problem articulation cycle

The preceding chapters have addressed most of the topics included by Oyo et al (2009:8) in this first cycle. Chapter 1 describes completely the problem and introduces the RQ, Literature Review is addressed in chapter two, the research methodology in chapter three and finally the stakeholders and the local sociotechnical environment is included in chapter four. Building on this previous work, this section set the boundaries and the principles to structure the quantitative model.

5.1.1 Conceptual Framework

Underwood (2014:40) identifies seven barriers to the diffusion of AV (legal, regulations, cost, technology, infrastructure, and social and consumer acceptance). To simplify their modelling (see Figure 14: Conceptual Framework for the Model (Source: Developed for this study)), I have bundled them into four buckets (supply, demand, public policies and business models). Supply includes the availability and evolution of those components that enable AV (in the broadest sense which includes infrastructure as well) considering the attitudes, policies and strategies of those private companies that manufacture them (e.g. the activities conducted by the OEM manufacturers to counter the BEV mandate in California in the nineties). This driver also considers the circumstances, pricing and added value that these new technologies offer to the end user. The second driver, demand, encompasses user perception, and those cognitive components that condition its perception and willingness to use an AV, including the user's intention to own a AV. The third driver, public policies, tackles all these measures taken by governments and public agencies that influence the adoption of AV, and that have the aim to align the private interest

[2] Worth to note here that this section only details the final values of the parameters, and not those offered initlally to the AR group, and it was determined that the initial values were irrelevant to the objective of the research.

of the different stakeholders to the common good. And finally, the business models consider the new business models associated to the development of AV and to the new paradigm of mobility as a service (e.g. ride sharing and ride hailing). A weakness to note in the diverse research strands reviewed, is the relative absence of literature that considers more than one of these components in concert.

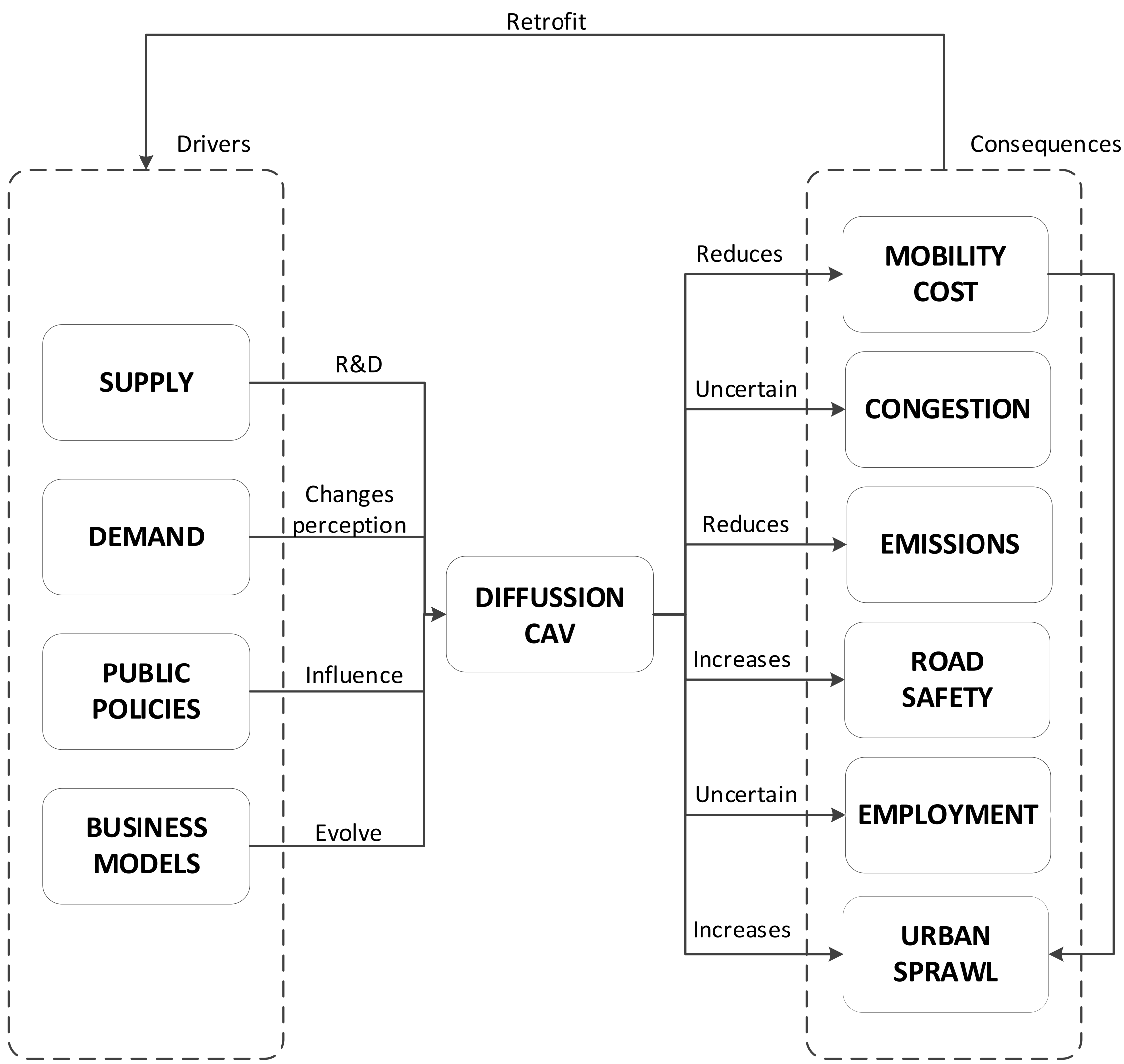


Figure 14: Conceptual Framework for the Model (Source: Developed for this study)

These drivers will fuel a process which may have dramatic consequences in our society. What follows does not pretend to be an exhaustive analysis of these consequences, but to offer a recollection of how the changes originated by their autonomous capabilities, BEV powertrains and V2X abilities will impact most of us, either as a private individual, members of corporations, or by affecting the public good, and therefore merit to be considered for modelling. Consequences of vehicle automation will range from large downtown parking lots suddenly available to be repurposed (as the vehicle will be send back home or kept on the road either running errands, serving other members of the family, or why not working for a shared service company), to attend underserved populations (elderly people or younger) able to travel for the first time (or again), to an eventual sprawl of the cities (comparable to the introduction of the car more than a century ago that suddenly was providing a way to commute longer distances) result of a value of time much lower. Sharing of AV by different members of a household may have dramatic effects in car ownership, although it is a model which may be severely questioned as a result of the new customer perceptions raised by the current pandemic. Schoettle and Sivak (2015b:8) show how the lack of trip overlap between most of the members of US households, may lead to reduce car ownership as much as 43%, something which will be compensated by an increase on vehicle usage, even when not considering the empty “return to home” miles.

From a corporative standpoint, these consequences result in a high degree of uncertainty in the demand for our services (and therefore the value of our assets). In one side, there is wide agreement that AV will increase the VMT, both because it is expected to reduce the total cost of ownership (and therefore the cost per mile) and also because of the increment of trips result of repositioning and empty trips, but in the other this increase in VMT may be compensated by the facility offered by AV to improve network efficiency (and therefore reduce congestion) as a result of a smoother drive. To what extend both consequences will balance off, or they will result in a final increase or decrease of congestion, is one of the hottest issues under debate right now.

Finally, although several high profile AV accidents (those involving Tesla and Uber have been objects of particular attention in the media) have increased the feeling that this transition maybe more painful than expected, probably the most highlighted benefit of V2X equipped AV is their contribution to increase the road safety of our highways which is a growing problem, as the last two years NHTSA has reported an annual increase of traffic fatalities of 14.4% in US roads after decades of declining numbers. *NHTSA* (2017:21) also reported 5.5 million police-reported crashes annually in the U.S., of which they estimate that V2V would have help to address 69 per cent of them (those in which more than one vehicle was involved), which would translate to approximately 13,329 fatalities and 2.1 million injuries.

Based on the above considerations, the model will consider three of these drivers (supply, demand, and public policies) making a simplification when modelling the relationship between supply and demand of AV. In this case, I will consider that the existing offer is able to meet the demand for AV no matter how significant this is and how quick it unfolds (or if there is a delay this is non-significant), and in this regard, I will only model the willingness of the driver to replace its vehicle for a AV, and not an eventual restriction (e.g. delay) which may occur as a result of a bounded offer.

With regards to the consequences, and although the diffusion of AV may change slightly the demand of ML as a result of its impact in mobility, employment and land use (and associated urban sprawl which will likely increase the demand for traffic), the causal loops between them are rather uncertain and difficult to predict within the context of this research. Although this is a simplification of my research, I consider them to be beyond the scope of this research.

5.1.2 Causal Loop Diagram

This cycle conceptualizes the model in terms of:

1. Components and reference behavior based in the current understanding of the model.
2. Dynamic hypothesis including feedback loops in terms of a causal loop diagram.

And sets the groundwork to shape its model structure in the next phase. Table 12: Model Boundary (Source: Developed for this study) defines the basic components that become part of the causal loop diagram, dividing them into exogenous (and therefore not directly affected by the system) and endogenous.

Construct	**Variable**		
	#	**Endogenous**	**Exogenous**
Supply	1	Technology Maturity	
	2	Price	
	3	Total Cost of Ownership (TCO)	
	4	Utility	
	5	Sales	
Demand	6		Willigness to Pay (WtP)
Public Policies	7		Toll Incentives
Road Safety	8	Fatalities	
Environment	9	Emissions	

Table 12: Model Boundary (Source: Developed for this study)

Figure *15*: Causal-loop Diagram (Source: Developed for this study) shows the logic structure of the different components of my model included in the table above. In the CLD we can see three reinforcing loops driven by an increase in sales (and therefore in the size of the fleet).

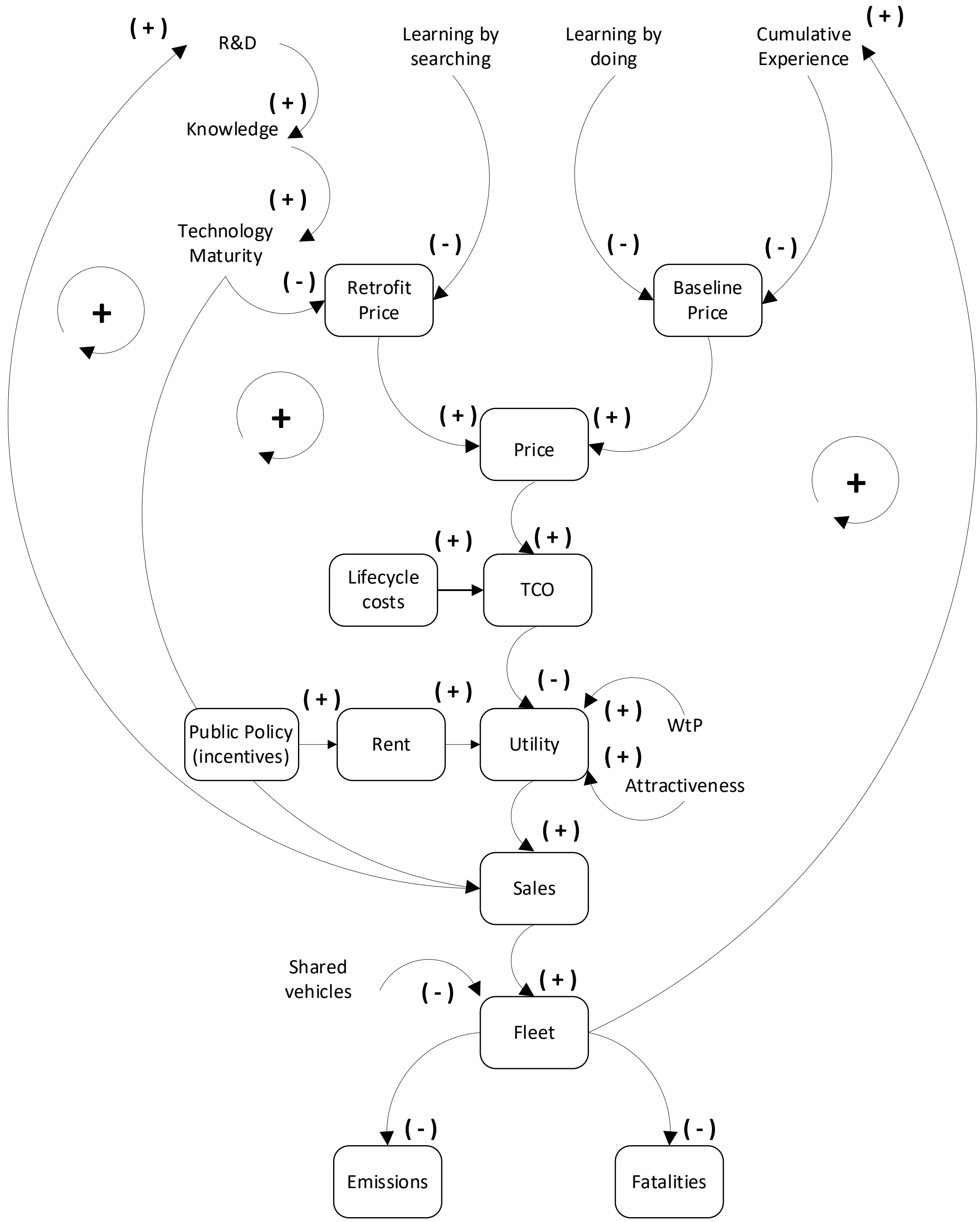


Figure 15: Causal-loop Diagram (Source: Developed for this study)

In the first loop (right hand side of the figure), an increment in the size of the fleet will increase the cumulative experience of the manufacturer, which paired with its learning by doing capabilities (see a more detailed explanation of this concept in section 5.2.2.1) will reduce the base price of the vehicle, thus increasing its utility and appeal to the customer, and finally looping in an increase in sales.

In parallel, an increase in sales will increase the R&D budget available, positively affecting the technology maturity of the platform, creating as a result two reinforcing loops. In one case by reducing the price of the vehicle (by increasing the learning by searching factor) and therefore its utility, and in a second case increasing its trust, because as Nieuwenhuijsen et al. (2018:310) rightfully note "when the maturity grows, people will gain more confidence in the reliability and performance of a vehicle and will be more likely to change their vehicle from i to j".

5.2 Model proficiency cycle

This section described the model by taking a top-down approach. The general construction of the model, sub models, and the logic behind them are described in the initial section. The second section introduces the stock and flow construction of each sub model, and finally a third section describes the values used for the different parameters, and the empirical research that supports those that are more critical to the simulation.

5.2.1 Model Construction

5.2.1.1 Fleets

The model splits the fleet of light duty vehicles (LDV) is into three sub fleets of interest (see below), each one of them which its own growing pattern. To simplify the model, I consider that all the vehicles of one fleet have the same level of automation. The three fleets and their level of automation are as follows:

- **ICE** (ICE powertrain with automation level L0).
- **BEV** (BEV powertrain with automation level L1).
- **AV** (BEV powertrain with automation level L4).

5.2.1.2 Sub models and Modules

The conceptual framework introduced in the preceding section has been modeled by building three sub models rooted in different theoretical backgrounds and empirical data. Initially, a sub model (price) predicts how the purchase price of the three alternatives will develop over time. From here, a second sub model (utility) forecasts the utility that the user will assign to each option, and finally the third of these sub models (choice) predicts the size of the fleet of each alternative, based on the purchase decision made by the user taking into consideration the utility earlier predicted. This third sub model will finally calculate the net welfare balancing the cost of the incentive with the road safety and environmental benefits of each vehicle. This requires parametrizing the price and utility sub models for each of the fleets (ICE, BEV, and AV), thus making a total of seven modules for the complete model.

Figure 16: General construction of the Model (Source: Developed for this study) shows how the different submodules retrofit each other for those variables which are shared (see links between the modules).

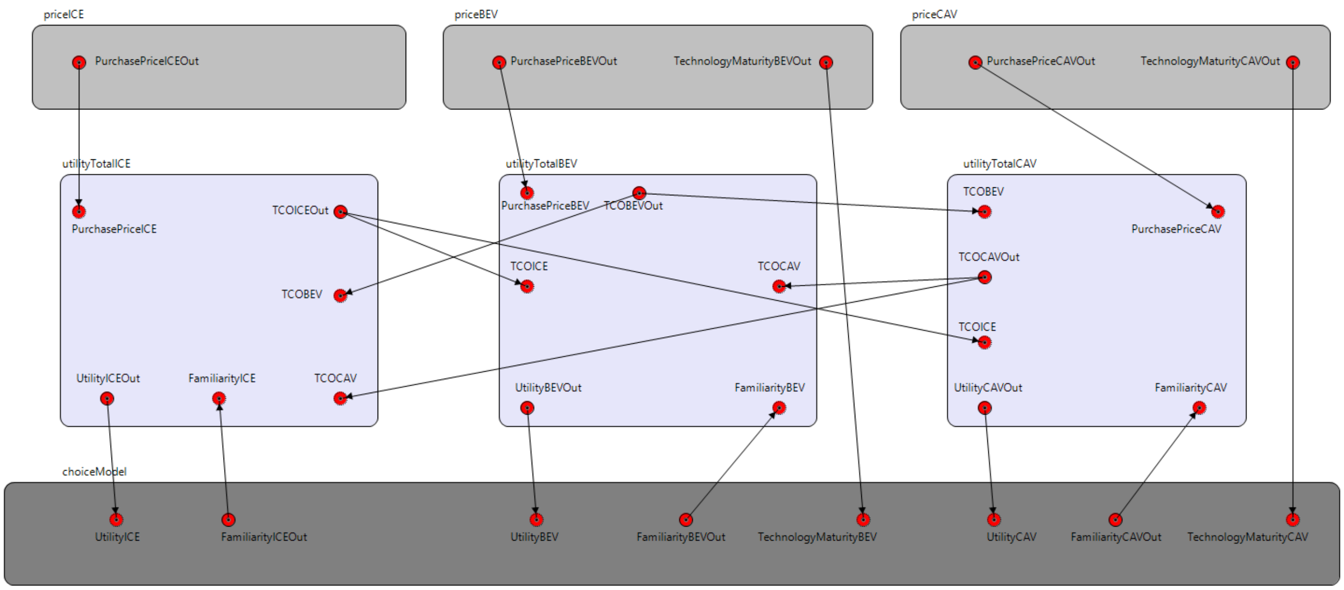


Figure 16: General construction of the Model (Source: Developed for this study)

5.2.1.3 *Externalities and internalities*

Section 2.2 presents the wide range of externalities and internalities produced during the Lifecyle of a vehicle, including its production and operation. Table *13*: Externalities and internalities considered in the model (Source: Developed for this study) offers a list of these components, showing those that have been selected to become part of the model based on i) their local relevance, and ii) the availability of empirical values in the research stream. The table also shows which sub model hosts the variable for these that have been selected to be modelled.

Component		Internality Externality	Upstream Downstream	Scope	Submodel
1	Tailpipe emission ICE-BEV	Externality	D	All miles	Choice Model
2	HOV Lane Congestion	Externality	D	ML	Utility
3	Congestion Relief	Externality	D	GPL	Utility
4	Emision induced	Externality	D	GPL	Utility
5	Vehicle production	Externality	U	All miles	Choice Model
6	Battery Production	Externality	U	All miles	Choice Model
7	Gas Production	Externality	U	All miles	Choice Model
8	Electricy Production	Externality	U	All miles	Choice Model
9	Supply Disruption	Oil Premium Cost	U	All miles	
10	Monopsony	Oil Premium Cost	U	All miles	
11	Military Spending	Oil Premium Cost	U	All miles	
12	Atractiveness of e-vehicle	Network Externality	D	N/A	Utility
13	Risk Adversion	Network Externality	D	N/A	Utility
14	Diversity of choices	Network Externality	D	N/A	
15	Cooperative Driving	Network Externality	D	All miles	
16	Noise Impacts	Externality	D	All miles	
17	Learning by doing	Externality	U	N/A	Price
18	Learning by searching	Externality	U	N/A	Price
19	Economies of scale	Externality	U	N/A	
20	Rent TEXpress AV	Internality	D	ML	Utility
21	Total Cost of Ownership	Internality	D	All miles	Utility
22	Refueling/Maintenance time	Internality	D	All miles	Choice Model
23	Road Safety	Externality	D	All mIles	Choice Model

Table 13: Externalities and internalities considered in the model (Source: Developed for this study)

The following components have been voluntarily excluded from the model:

1. Oil Premium Cost because these three externalities, as described by Michalek et al. (2011:16544), although representing a significant component of the total cost at a global level, they are not relevant in the practitioner environment in which the research is being conducted (components 9, 10 and 11 in Table 13: Externalities and internalities considered in the model (Source: Developed for this study).
2. Network externalities and economies of scale, because although Greene et al. (2014) models their impact in the diffusion of BEV in California, the available literature does not seem to offer enough empirical values that can be cross related to ensure their validity (components 14, 15 and 19 in Table 13: Externalities and internalities considered in the model (Source: Developed for this study).

3. Noise because the differences in noise level between ICE and BEV powertrains are assumed to be negligible, as the noise produced by the interaction between the tire and the road above 30 miles per hour in a Manage Lane dominates the noise produced by the engine (component 16 in Table 13: Externalities and internalities considered in the model (Source: Developed for this study).

5.2.2 Stock and Flow Sub models

5.2.2.1 Pricing sub model

The pricing sub model (see Appendix 2) models the evolution of the prices of the three fleets. The evolution of the purchase price is governed by i) the learning by doing (Greene et al., 2014:35 and Nieuwenhuijsen et al., 2018:308) result of the accumulation of experience and skillset, and ii) the learning by searching (Nieuwenhuijsen et al., 2018:308) consequence of massive R&D investments. Learning by doing has a direct effect on the base price (baseline) of the vehicle (ICE), while the technological evolution result of the knowledge created by the R&D activities conducted by the different stakeholders mediates between the learning by searching and the retrofit price which is the cost of upgrading to BEV or AV. The purchase price (see PurchasePrice variable in the SD models included in Appendix 2) will be the addition of the base and the retrofit prices.

Learning by doing is grounded in the economic theory that posits that the accumulation of practice, experience, and knowledge (through better use of the resources and the technology) drives productivity. More than the result of an investment or a research facility, learning by doing is the result of an innovative and inquisitive approach to the practitioner's day to day. In the opposite side, learning by searching is the learning that occurs during the research process, including the search outputs and learning outcome, and which often results in a cycle of virtuous development driven by competitive markets. In one end, it has the potential to have more path-breaking changes than learning by doing, but in the other is heavily influenced by the availability of R&D funds.

A technology is mature when it has been in use long enough that most of its initial faults and inherent problems have been fixed or mitigated by further development. A surge in the R&D budget will then boost the maturity of the technology, igniting two virtuous cycles as we have seen in Figure *15*: Causal-loop Diagram (Source: Developed for this study). Nieuwenhuijsen et al. (2018:307 and 310) merged the consequences of both cycles in a variable for every fleet which takes a value relative to the maturity of ICE, which is considered to be almost complete mature and therefore having a value of 0.9. This variable is used both in the price sub model and the user choice sub model.

5.2.2.2 Utility sub model

The utility of a product or service defines the aggregate level of satisfaction that a consumer receives through the consumption of this good or service. Being the variable that drives demand, it comes as no surprise that the role of utility in the diffusion of innovations has been the object of a vigorous research strand for quite some time. Nevertheless, in our case utility is of limited value if it considers only those components that directly and objectively add to the satisfaction of the user. When the innovation is so disruptive as AV, the choice made by the consumer may not be entirely based on the pure maximization of the utility, and other factors such as the lack of familiarity with the new technology or a perception of risk may influence the inertia of staying with what you know, even in cases where the utility of the innovation may objectively be higher.

Struben and Sterman (2008:1077) and Nieuwenhuijsen et al. (2018:305) are pioneers in complementing AV diffusion models with these concepts. The figure below shows the concepts that both authors use to introduce some degree of "soft" qualitative value into the calculation of the utility.

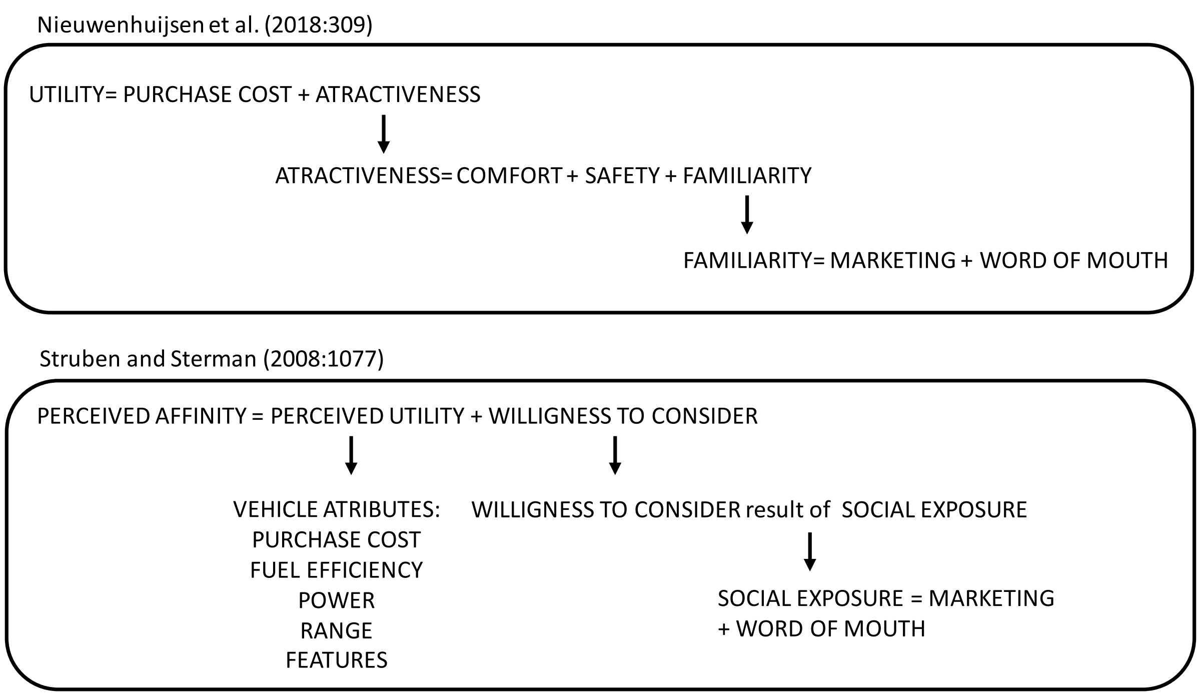


Figure 17: Utility (Source: Adapted from Neiuwenhuijsen et al. 2018, Struben and Sterman, 2008)

As we can see in Figure *17*: Utility (Source: Adapted from Neiuwenhuijsen et al. 2018, Struben and Sterman, 2008), although they have some differences in the terminology they use, both consider similar concepts with minor modifications. While Nieuwenhuijsen et al. (2018:308) introduce the attractiveness as a predictor of the openness of the consumer to switch brands and products to the new innovation, Struben and Sterman (2008:1077) consider that the decision to purchase a BEV or a AV depends on the perceived affinity of the customer (Shepherd at al., 2012 expanded this concept building on Struben and Sterman, 2008), which is the utility of the vehicle qualified by the user's willingness to consider (WtC) it as a real option. Struben and Sterman (2008:1077) define the WtC as "capturing the cognitive, emotional and social processes through which drivers gain enough information for a platform to enter into their consideration set" and increases because of the social exposure through the word of mouth (of both drivers and non-drivers of every powertrain) and the marketing (note the similarity to the foundation of Bass). They demonstrate how in the absence of a sustained marketing effort the WtC decays rapidly (before the sustainability point, in five years the WtC may decay from 50% to 5%). Both approaches beautifully merge the classical diffusion models based on social processes, with the discrete approaches based on the direct utility of the product for the consumer.

In my research I expand the proposal made by Nieuwenhuijsen et al. (2018:305) as follows:

$$Utility = TCO + Atractiveness$$

Where,

$$TCO = Purchase\ Cost + Operations\ Cost - \ Incentives - WtP$$

As it can be seen, my proposal replaces the purchasing price by the TCO. Besides the purchase cost, the TCO considers the cost to operate the vehicle, the rent obtained by the AV drivers when using TEXpress for free, which equals the value of the toll fee saved (see TEXpress sub model for more details), and the willingness to pay (WtP) more for an innovative product (see below).

To obtain a relative value of utility, both values (TCO and attractiveness) are weighted, and the TCO is normalized to the highest value of TCO.

$$Utility = \left(1 - \frac{TCO}{Max\ TCO}\right) * weight + \ Atractiveness * weight$$

The attractiveness is as follows (the familiarity is the relationship between the size of the fleet and the total fleet).

$$Attractiveness = Perception * weight + Familiarity * weight$$

Appendix 2 presents the stock and flow model which models the utility of each fleet accordingly to these principles. I expect this expanded version provides a more comprehensive view of the perception of the user about the utility of the different options he is presented with, when compared with the original approach taken by Nieuwenhuijsen et al. (2018:305).

5.2.2.3 Choice sub model

Choice models used in diffusion analysis are traditionally based on maximizing the utility of the different options the consumer may consider when acquiring a new product or replacing an existing one. Considering that the technology maturity is already been considered as the key driver when forecasting the evolution of the purchase price, this sub model continues relying on Nieuwenhuijsen et al. (2018:305) in order to guarantee the consistency of the whole model.

Research probes that customers take purchase decisions in a nested manner, so decisions between two options are taken in a sequence of nests which can be several levels deep. Following this though, the choice sub model considers that all the vehicle fleet was ICE until the first BEV were introduced in 2010. Starting at this date, the customer had to make a choice between both options (switching over to the new powertrain or not). Once AV are introduced in 2024, an ICE user is presented with two sets of decisions (keep the current ICE or switching over to a BEV or to an AV) and a BEV user with only one (switch over to an AV or not).

This logic is presented in the stock and flow diagram presented in Appendix 2, and is supported by the formula below based on Nieuwenhuijsen et al. (2018:310)

$$Cij = Vi * \left(\frac{1}{\alpha}\right) * TMj * \frac{Uj}{(Ui + Uj)}$$

Where:

1. C_{ij}: Change of vehicles between fleet i and fleet j.
2. V_i : Size of the current fleet
3. α: Average lifetime of a vehicle
4. TM_j : Technology Maturity of the future fleet
5. U: Relationship between the utilities of both fleets.

a) From this initial volume, the assumption has been made that the number of drivers who purchase a BEV or an AV the first time they purchase a car is negligible, and therefore the size of each fleet is given by the number of vehicles that switch from one fleet to the other (ICE to BEV, ICE to AV and BEV to AV) depending on the relative utilities of both fleets (see choice sub model for more details).

b) Each fleet has an exogenous yearly growth rate of 2% (which represents the natural growth of the market).

5.2.3 Estimation of Parameters

5.2.3.1 Price sub model

5.2.3.1.1 Internal R&D

As it can be seen in Table *14*: References for R&D budget (Source: Developed for this study), although the model has been designed to simulate the fleets of ICE, BEV and AV in the Metroplex, to estimate the evolution of the retrofit component of the vehicle price, the model stems from the value of all expected sales in the US market to find the internal budget available for R&D (references 1,2,4 in Table 14: References for R&D budget (Source: Developed for this study)). Similar proposition is made for the baseline component, with the slight difference that in this case being the cost of the base platform common to all powertrains, the model considers the added sales of all alternatives (references 6,7,8 in Table 14: References for R&D budget (Source: Developed for this study)). This results in the same evolution of the baseline price for all powertrains as we see in Figure 29: Evolution of the baseline price and purchase price (Source: Developed for this study).

Reference		Determines directly	Determines indirectly
1	US Sales ICE	Internal R&D ICE Budget	Retrofit Price ICE
2	US Sales BEV	Internal R&D BEV Budget	Retrofit Price BEV
3	US External Budget R&D BEV		
4	US Sales CAV	Internal R&D CAV Budget	Retrofit Price CAV
5	US External Budget R&D CAV		
6	US Sales ICE + BEV		Baseline Price ICE
7	US Sales ICE + BEV		Baseline Price BEV
8	US Sales ICE + BEV		Baseline Price CAV

Table 14: References for R&D budget (Source: Developed for this study)

Sizing the available R&D external budget for AV (References 3 and 5 in Table 14: References for R&D budget (Source: Developed for this study)) is a complex endeavor due to three main reasons. First, because the influx of newcomers without any previous track record in the automobile industry makes very difficult to predict their appetite to keep investing in the long run. It is also geographically challenging, because although we are researching the local consequences of the investment in R&D,

given the global scale in which most of the car manufacturers operate, the R&D is sized considering the revenue in a global scale. Finally, there is also a temporal component because the options we consider have very different levels of maturity, and therefore the traditional way to represent the maturity as a factor of the knowledge build by a R&D investment (as a percentage of the sales revenue) is misleading, as the current levels of investment are driven by expectations of future sales, and not by present revenues.

Kerry and Karsten (2017:5) compile the R&D investments in AV done by both incumbents and start-ups between 2014 and 2017. They come up with 171 deals with a total investment in the range of $78 billion ($19,5 billion per year) concluding that "the trend indicates that investment in 2018 should be substantially more than the $78 billion disclosed from 2014 to 2017, and continue upward for some period of time as the race to deploy self-driving moves on". This positive impression is nuanced by Pitchbook (2020:1) which although they identify 146 deals worth $10.3b made by venture capital in the AV market in 2018, they also find a significant downward trend in the first 6 months of 2019 with only 3,2 billion invested in 64 deals. This would seem to suggest that the incumbents will lead the continuous investment effort. Frost and Sullivan (2017) confirm this assumption when forecasting that the global key automakers will perform a yearly investment in autonomous, connected, and electrification (ACE) technologies of $34.5 billion up to 2025 which seems reasonable considering it amounts to a mere fourth of the global R&D investment done by automakers[3]. Grounded on these precedents, I make the assumption that the external budget available for R&D is as shown in Table 15: External R&D budget (Source: Developed for this study).

[3] Statista (2018) sizes the overall R&D expenditure of automakers in a 5.7% of their revenues. Using an average price per car sold worldwide of $31K, which seems a resonable average between Europe ($35,000), China ($30,000), Russia ($22,000) and US ($37,185), this results in a reference for the global R&D budget in 2018 of $ 134 billion (78.7 million cars sold globally * $31K * 5.7%).

Year	BEV ($M)	CAV ($M)
2010	5,000,000	0
2011	5,000,000	0
2012	5,000,000	0
2013	5,000,000	0
2014	5,000,000	100,000
2015	10,000,000	6,000,000
2016	10,000,000	14,000,000
2017	10,000,000	8,000,000
2018	15,000,000	5,000,000
2019	15,000,000	5,000,000
2020	15,000,000	5,000,000
2021	15,000,000	5,000,000
2022	15,000,000	5,000,000
2023	15,000,000	5,000,000
2024	15,000,000	5,000,000
2025	15,000,000	5,000,000
2026	15,000,000	5,000,000
2027	15,000,000	5,000,000
2028	15,000,000	5,000,000
2029	15,000,000	5,000,000
2030	15,000,000	5,000,000
2031	0	5,000,000
2032	0	5,000,000
2033	0	5,000,000
2034	0	5,000,000
2035	0	5,000,000
2036	0	5,000,000
2037	0	5,000,000
2038	0	5,000,000
2039	0	5,000,000
2040	0	5,000,000

5.2.3.1.3 Parameter values used in the pricing sub model

Table *34*: Values of the parametres in the price submodel (Source: Developed for this study) shows the values of all parameters used in this sub model.

5.2.3.2 Utility sub model

As the reader may remember, section 5.2.2.2 describes the two main components of the utility: TCO and attractiveness. This section introduces the rationale behind the most significative parameters of both components, OPEX, CAPEX, WtP and incentives for the TCO, and the perception of the user when it comes to the attractiveness (note that the second component of the attractiveness, the familiarity, is a percentage which reflects the participation of a fleet versus the total fleet of LDV).

5.2.3.2.1 OPEX and CAPEX

As shown in Figure *16*: General construction of the Model (Source: Developed for this study), the price component of the TCO comes from the price sub model. All other cost components of both OPEX and CAPEX are modeled out of Breetz and Salon's (2018) equations localized to the Metroplex. In their research, they highlight the importance of two factors to estimate properly the TCO. On the one hand, the depreciation (the Nissan Leaf loses value at a rate of 5% which once considered the tax credits means that it has no remaining value at the end of year 10). In the other the localization, given the heterogeneity of TCO result of differences in taxation, cost of fuel maintenance and insurance (the TCO of the Leaf city to city fluctuates up to 23%).

5.2.3.2.2 Willingness to Pay (WtP)

When researching the diffusion of innovations, Plotz et al. (2014:412) divide consumers into innovators, early adopters, early and late majority, and laggards. In such a topology, innovators and early adopters may be willing to pay more as a favoring aspect representing their appreciation for the new technology (see Gnann et al. 2015:97 for a list of authors who provide a detailed description and discussion of the WtP). Although the research stream that focus on the willingness to pay of the early adopters of BEV and AV is rather limited, there are evidences that empirically validate this attitude. The model considers values for the WtP for AV and BEV as shown in Table 16: Willingness to Pay (Source: Adapted from (1) Bansal and Kockelman (2017:54) (2) Hidrue et al. (2011:700) for configuration E, and (3) Plötz et al. (2014:412) below[4]. In this table, we can see that the percentage of innovators and early adopters that have a WtP over $7,500 is significant enough as to consider they will be most of the users during the forecasted period. This will be the value used in the simulation.

[4] Many of the available surveys offer a value of the WtP below what recent forecasts see as the price of L4 AV in 2030 (ARM's forecast sets the price in the range of $25,000 for the vehicle, and 15,000 for these components directly related to the automation function). The differences are significant, as Bansal and Kockelman (2018:646) find a WtP of $3,300. This would seem to suggest that in the short to mid run, to increase the penetration of L4 AV to a level which may be self-sustainable, incentives may be needed. Long term the situation may be different, as Bansal and Kockelman (2017:61) are forecasting that 87.2% of the fleet will be Level 4 in 2045, under the assumption that the cost of the technology is being reduced a 10% annually and the WtP increased by the same percentage. This forecast seems to be aligned to ARM (2018)'s prediction which expects an annual reduction of 17.5% in the cost of the AV technology between 2020 and 2030, although both forecasts offer a more optimistic picture than the findings of this study.

	$	<=0	<$1000	<$2000	<$3000	<$4000	<$5000	<$6000	<$7000	<$8000	<$9000	<$10000	<$11000	<$12000	<$13000	<$14000	<$15000	>$15000
CAV (1)	WtP	58.70%	2.40%	2.40%	2.40%	2.40%	2.40%	2.40%	1.29%	1.29%	1.29%	1.29%	1.29%	1.29%	1.29%	1.29%	0.78%	15.82%
	WtP (Acc)						70.70%			75.68%							84.18%	17.11%
BEV (2)	WtP	11.36%	4.55%	4.55%	4.55%	8.33%	8.33%	8.33%	8.33%	8.33%	8.33%	6.25%	6.25%	6.25%	6.25%	0.00%	0.00%	0.00%
	WtP (Acc)						41.67%			66.67%							100.00%	0.00%
BEV (3)	$	$500					$5,000			$7,500							$15,000	
	WtP	50%					48%			1.5%							0.5%	
	WtP (Acc)	50%					98.00%			99.50%							100.00%	

Table 16: Willingness to Pay (Source: Adapted from (1) Bansal and Kockelman (2017:54) (2) Hidrue et al. (2011:700) for configuration E, and (3) Plötz et al. (2014:412)

5.2.3.2.3 Incentives

5.2.3.2.3.1 BEV incentives

The following incentives are offered to purchase a BEV in Texas:

- The incentive of the State of Texas (not applicable to Tesla) to the purchase of BEV (up to $2,500) active from 2013 to 2015 and restated in 2018.
- The Federal tax rebate of up to $7,500 to purchase BEV vehicles (reduced since 2019 for Tesla and GM as they reach 200,000 cars sold).

The simulation considers that both incentives completely phase out once AV start to be available in 2024.

5.2.3.2.3.2 TEXpress incentives

The introduction of a public policy that incentives the diffusion of AV by offering the possibility to drive for free in the TEXpress network, may have multiple consequences. This section evaluates two of these consequences:

i. The rent effect appropriated by the AV users when internalizing the value of tolls, they save when using TEXpress. This value is included as one more component to the AV utility in the sub model. See TEXpressRent variable in Figure 37: Submodel Utility AV (Source: Developed for this study).
ii. Cost for the public finances as they will have to compensate TEXpress operators (this is considered in the choice model sub model but is explained here for consistency). See TotalPPCost in Figure 38: Choice Submodel (Source: Developed for this study).

5.2.3.2.4 User profile to be incentivized

To have a driving pattern as representative as possible of the whole TEXpress network, we have used the accumulated values of three of the projects with the most traffic in the network (LBJ, NTE and NTE35W). Table 17: Traffic at TEXpress (Source: Developed for this study) shows the values for 2019.

Comparing this table with Table 29: Ground truth for the fleet of the Metroplex (Source: Developed for this study), we see that close to 90% of all LDV vehicles registered in the counties of the Metroplex have used the TEXpress network at least once in 2019.

Number of Transactions	Amount Sent to TSP	AVG $ per Transaction	Distinct tags seen	AVG TRX per tag
117,023,546	$391,930,845	$3.35	3,696,960	32

Table 17: Traffic at TEXpress (Source: Developed for this study)

Table 18: User frequency at TEXpress (Source: Developed for this study) shows the frequency with which the tags have been seen in the network for a whole year.

Group 1		Group 2		Group 3		Group 4		Group 5		Group 6		Group 7	
Number of Tags 1-2 TRX	Trx done by Tags 1-2 TRX	Number of Tags 3-8 TRX	Trx done by Tags 3-8 TRX	Number of Tags 9-20 TRX	Trx done by Tags 9-20 TRX	Number of Tags 21-31 TRX	Trx done by Tags 21-31 TRX	Number of Tags 32-40 TRX	Trx done by Tags 32-40 TRX	Number of Tags 40-100 TRX	Trx done by Tags 40-100 TRX	Number of Tags >100 TRX	Trx done by Tags >100 TRX
1,172,163	1,727,852	1,187,539	5,731,945	592,101	7,859,223	205,792	5,227,189	99,739	3,559,878	249,438	3,560,846	190,309	64,560,832
31.7%	1.5%	32.1%	4.9%	16.0%	6.7%	5.6%	4.5%	2.7%	3.0%	6.7%	3.0%	5.1%	55.2%

Table 18: User frequency at TEXpress (Source: Developed for this study)

As we will discuss in the following chapter, the number of TEXpress users who will be incentivized to purchase an AV because of the TEXpress incentive are roughly 126,000 (assuming a 100% incentive). It is reasonable to assume that those users will mainly be found in these groups that currently make a higher usage of TEXpress. The rent and the cost are then calculated as follows:

1. The yearly rent created per tag ($597) with a 100% incentive is modelled out of the average number of transactions done per year by the tags of groups 6 and 7 (#178), multiplied by the average value of each one ($3.35).
2. The cost to create the rent ($106) is modelled as the average transactions done per year by all tags regardless of its frequency (#32), multiplied by the average value of each one ($3.35).

Table below summarizes the incentives considered

Year	ICE ($) Tax credit	BEV ($) Tax credit	CAV ($) rent per year		
			Base case	Low Incentive	High Incentive
2010	0	6,500	0	0	0
2011	0	6,500	0	0	0
2012	0	6,500	0	0	0
2013	0	8,500	0	0	0
2014	0	8,500	0	0	0
2015	0	8,500	0	0	0
2016	0	6,500	0	0	0
2017	0	6,500	0	0	0
2018	0	8,500	0	0	0
2019	0	5,000	0	0	0
2020	0	5,000	0	0	0
2021	0	5,000	0	0	0
2022	0	5,000	0	0	0
2023	0	5,000	0	0	0
2024	0	5,000	0	299	597
2025	0	0	0	299	597
2026	0	0	0	299	597
2027	0	0	0	299	597
2028	0	0	0	299	597
2029	0	0	0	299	597
2030	0	0	0	299	597
2031	0	0	0	299	597
2032	0	0	0	299	597
2033	0	0	0	299	597
2034	0	0	0	299	597
2035	0	0	0	299	597
2036	0	0	0	299	597
2037	0	0	0	299	597
2038	0	0	0	299	597
2039	0	0	0	299	597
2040	0	0	0	299	597

Table 19: Incentives considered[5] (Source: Developed for this study)

As a result of this incentive, An AV would be able to drive in the TEXpress network at a discounted price, either at peak or valley hours, regardless of how many times they use the managed lanes, or even if driven in manual or autonomous mode.

This would obviously admit several variants to be debated and reflected in AR. Instead of targeting the current users of TEXpress, one of the most obvious would target those users who are currently traveling on the GPLs of the TEXpress corridors, in which case the rent created should not be found in the toll avoided, but in the time saved. This may significantly alter the results.

[5] The average of the BEV Tax credit has been calculated considering the BEV State and Federal incentives described in section 5.2.3.2.3.1

It is assumed that AV users increase the frequency (+15%) with which they use TEXpress once the incentive is in place (see frequencies in Table 18: User frequency at TEXpress (Source: Developed for this study)). As we have seen, this topic is subject to an intense debate with arguments and findings on both sides. While Litman, 2020:17 presents a list of authors that support the idea of significant changes in VMT per AV, Zmud, 2017:2515's findings seem to suggest the contrary.

5.2.3.2.5 User perception (intention to purchase)

The evolution of the user perception about the different fleets during the simulated period, and as a result its intent to consider a particular option for its purchase has been modeled out of Carley et al. (2019:100) who performed one of the few available longitudinal studies of the willingness to purchase a BEV based on observations on 2011 and 2017. Based on this trend (and the warning discussed in section 2.3.3 about using the stated intention to purchase to predict the customer behavior), a projection of the user's perception has been made to 2040. The perception about AV takes as a reference Nieuwenhuijsen et al. (2018:324) with a relatively slow evolution during the twenties accelerating in the thirties capping it slightly above the BEV perception used for calibration, to reflect the fact that the user has become familiar with the new technology after these few years, and once the prices have reduced significantly.

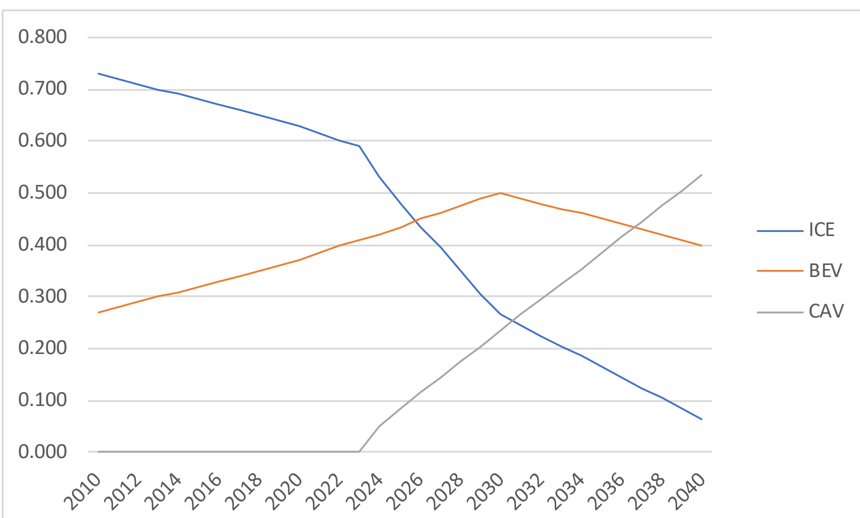


Figure 18: Expected evolution of the intention to purchase (Source: Developed for this study)

5.2.3.2.6 General parameter values used in the utility sub model

Besides the values above, Table 35: Values of the parameters in the utility submodel (Source: Developed for this study) offers a comprehensive view of the different parameters, variables, stocks and flows used in the utility sub model.

5.2.3.3 Choice sub model

As described in section 5.2.2.3, this sub model estimates the fleet of each powertrain in the Metroplex and calculates the net welfare based on the AV fleet, the cost of the incentive, and the benefits to road safety and environment. The following two sections present the rational to calculate these benefits.

5.2.3.3.1 Environment

5.2.3.3.1.1 BEV and ICE market: A fast moving target to regulate and forecast

One major component to be considered when architecting the model refers to the dynamics of a market (ICE and BEV development) that is developing rapidly. On the one hand, while Greene et al. (2014:40) use NHTSA and EPA estimates that forecast the cost of BEV batteries in the range of $160/KWh by 2025, GM already sees the cost of the battery cells in this range now. Even considering that the cost of the battery pack is roughly around 30% higher than the cost of the cell, this suggest a pricing in the range of $100 by mid-twenties, which reflects a significant cost reduction versus what it was forecasted just a few years ago.

On the other, it is important to bear in mind that ICE is under a significant pressure to reduce emissions. The Environmental Protection Agency (EPA) in charge of setting, reviewing, and updating the standards for environment, established the National Ambient Air Quality Standards to determine (among other things) the amount of air pollutants that every vehicle would be entitled to produce (not including GHG which are calculated as the addition of CO_2, N_2O and CH4 applying a ratio to equal CO2 emissions in the last two pollutants), and that the OEM should be able to gauge against. The latest standards (tier III) were signed into law Nov 3, 2014, and for the first time are aligned to the California LEV III standards. Within this standard, OEM are required to certify their vehicles into one of 7 bins that defines a limit for the emissions of NMOG+NOX, PM, CO and HCHO. The level in mg/ml of NMOG+NOX is what defines the bin (including both tailpipe and gas upstream), starting from 0 mg/ml (Bin 0) to 160 mg/ml at Bin 160). In addition to that, manufacturers are required to achieve an emission average for the whole fleet which reduces year by year over a period that goes from 2017 to 2025 (from 86mg/ml in 2017 to 30mg/ml in 2025). This results in an emission reduction of 66% by the whole ICE fleet in 2025, and underlines the importance of both requirements when comparing the environmental benefits of BEV against ICE.

5.2.3.3.1.2 Mitropoulos et al's findings as a foundation for the sub model

As it can be seen in the Table below, the environmental externalities caused by the automotive industry have been the object of ample research, although there are not that many studies that consider both

	Component	Environmental	Internality Externality	Upstream Downstream	Scope	Bento (2014)	Holland (2016)	Greene (2014)	Michalek (2011)	Mitropoulos (2017)	EPA	Blincoe (2015)
1	Tailpipe emission ICE-BEV	X	Externality	D	All miles							
2	HOV Lane Congestion		Externality	D	ML							
3	Congestion Relief		Externality	D	GPL							
4	Emision induced	X	Externality	D	GPL							
5	Vehicle production	X	Externality	U	All miles							
6	Battery Production	X	Externality	U	All miles							
7	Gas Production	X	Externality	U	All miles							
8	Electricy Production	X	Externality	U	All miles							
9	Supply Disruption		Oil Premium Cost	U	All miles							
10	Monopsony		Oil Premium Cost	U	All miles							
11	Military Spending		Oil Premium Cost	U	All miles							
12	Atractiveness of e-vehicle		Network Externality	D	N/A							
13	Risk Adversion		Network Externality	D	N/A							
14	Diversity of choices		Network Externality	D	N/A							
15	Cooperative Driving		Network Externality	D	All miles							
16	Noise Impacts	X	Externality	D	All miles							
17	Learning by doing		Externality	U	N/A							
18	Learning by searching		Externality	U	N/A							
19	Economies of scale		Externality	U	N/A							
20	Rent VoT BEV		Internality	D	ML							
21	Total Cost of Ownership		Internality	D	All miles							
22	Refueling/Maintenance time		Internality	D								
23	Road Safety		Externality	D	All MIles							

Table 20: Externalities and Internalities researched (Source: Developed for this study)

Two of the authors that consider upstream and downstream components in their research are Michalek et al. (2011) and Mitropulos et al. (2017) who model the total cost to operate a vehicle (ICE versus BEV) including the externalities produced both upstream and downstream. Although they have significant differences in their approach to calculate the net balance (while the former include in their calculation the cost to keep a steady supply of oil, Mitropoulos et al. (2017) include the cost of the time to maintain or recharge the vehicle), they both model a range of externalities comprehensive enough as to be compared. Table 21: Total cost to build and operate ICE and BEV (Sources: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, (3) Holland et al. 2016) presents a side by side comparison of costs of the environmental externalities and the TCO of both analyses.

		(1)	(2)	(3)	(1)	(2)	(3)
		$ (2010)	$ (2015)	$ (2014)	$ (2019)		
ICE	GHG (Greenhouse Gas)	2,025	1,899		2,361	2,038	
	Air Quality	1,492	2,619	2,288	1,740	2,810	2,457
	TCO	39,786	62,651		46,390	67,225	
	Total Cost	43,303	67,169		**50,491**	**72,072**	
BEV	GHG (Greenhouse Gas)	1,824	1,195		2,127	1,282	
	Air Quality	2,844	1,883	1,545	3,316	2,020	1,660
	TCO	62,364	58,797		72,716	63,089	
	Total Cost	67,032	61,875		**78,159**	**66,392**	
Difference on Air Quality					**-1,576**	**790**	**798**

Table 21: Total cost to build and operate ICE and BEV (Sources: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, (3) Holland et al. 2016)

Besides EPA Tier III mentioned in the section above, NHTSA finalized the Corporate average Fuel Economy standards under the Energy Policy and Conservation Act. In 2010, EPA and NHTSA issued a joint Final Rule (FR) to establish a national program consisting of new standards for light-duty vehicles that expand Tier III. The crossing between Michalek's data and the program confirm the strength of its conclusions, as Michalek's findings show a remarkable alignment to the requirements of the program in terms of the relationship between GHG upstream emissions of BEV versus ICE (a factor of 3 in FR, and 3.2 in Michalek) and the relationship between the total emissions (including both tailpipe and gas upstream) to tailpipe (a factor of 125% in FR, and 118% in Michalek). Furthermore, Table 22: Requirements for vehicle lifetime (Source: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, and (3) EPA) provides the vehicle lifecycle characteristics which align as well.

	(1)	(2)	(3)
Vehicle lifetime	12	11	15
Miles per year/lifecycle	14,000	11,300	
Total	117,000	119,780	150,000

Table 22: Requirements for vehicle lifetime (Source: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, and (3) EPA)

Having this in mind, a review of Table 21: Total cost to build and operate ICE and BEV (Sources: (1) Michalek et al. 2011, (2) Mitropoulos et al. 2017, (3) Holland et al. 2016), reveals some values worth to elaborate:

- A significant difference in ICE TCO between the data provided by the two authors ($46,390 offered by Michalek et al., 2011 versus $67,225 of Mitropoulos et al., 2017). This because Michalek et al. (2011) only consider the scheduled maintenance. Once Michalek et al's model is completed with the remaining costs (insurance, State fees and repairs) as described in Table 23: ICE lifetime operations' costs (Source: Kelley Blue Book, 2019, Michalek et al. 2011) Michalek et al. (2011) and Mitropoulos et al. (2017)' numbers align, even when we are not accounting the time devoted to maintenance and refueling which penalizes significantly BEV in the Mitropoulos model.

		1 year	5 years	12 years
KELLEY BLUE BOOK ($2019)	Insurance	956	4,780	11,472
	State Fees	240	1,200	2,880
	Maintenance	459	2,295	**5,508**
	Repairs	324	1,620	3,888
	Total	1,979	9,895	23,748
MICHALEK ($2019)	Maintenance			**5,107**

Table 23: ICE lifetime operations' costs (Source: Kelley Blue Book, 2019, Michalek et al. 2011)

- Similar but reverse is the case for the total cost of BEV. The reduction of 15% is clearly the consequence of the tremendous evolution of the BEV technology during the last few years helps as described in the precious section.
- Finally, the $790 calculated by Mitropulos et al. (2017) in concept of net environmental benefit, are in line with the $798 calculated by Holland et al. (2016).

The above sections support the assumption made by the author to use Mitropulos et al. (2017)' findings as a fair and objective calculation of the environmental upstream and downstream costs of ICE and BEV. Values used for the model are as presented in Table *24*: Total environmental cost during the lifetime of the vehicle (assumed to be 10.6 years) (Source: Developed for this study).

$ (2019)	ICE	BEV
CHG (Greenhouse Gas)	2,038	1,282
Air Quality	2,810	2,020
Total Cost	4,848	3,303

Table 24: Total environmental cost during the lifetime of the vehicle (assumed to be 10.6 years) (Source: Developed for this study)

5.2.3.3.2 Road Safety

5.2.3.3.2.1 The cost of road safety in US roads

In 2017, 37,133 persons were killed in US roads because of car crash accidents. Blincoe et al. (2015:11) provide a detailed analysis of the economic and social impact of these road crashes. Their research includes both police and non-police reported crashes, and for a whole variety of traffic configurations from highways to intersections in urban areas. They report an economic cost which includes workplace productivity (24%), household productivity (8%) medical (10%), congestion (12%), property damage (31%), insurance (8%), workplace (2%) and legal fees (5%), to a total cost of $242 billion ($2010) which equals the 1.6% of the U.S. Gross Domestic Product. If we add the social cost (loss of quality of life), the total adds to $836 billion ($2010). They provide a breakdown as well of how these expenses are funded: Private insurers (54%), Government (7%), Individuals (23%) and others (16%).

5.2.3.3.2.2 Impact of AV in road safety

Giuffrè et al. (2017:10) refer to Treat to note that in 93% of crashes, human error (e.g. driving too fast, misjudging the behavior of other drivers, alcohol impairment, distraction, or fatigue) was a contributing factor, and to Sabey and Taylor to confirm that human error was to blame either partially (95%) or completely (65%). These references match the findings of other authors including Singh as referred in Papadoulis et al. (2019:12), or Dingus et al. as referred in CPB (2018:5). Building on these empirical evidences, AV advocates posit that by eliminating human errors, the introduction of AV in our roads may reduce crash accidents in a percentage over 90% (e.g. Fagnant and Kockelman as referred in Papadoulis et al. 2019:13).

Taking a different perspective, the dramatic consequences that past technological innovations have had when improving the safety of our roads, may illustrate the potential of AV to contribute to the reduction of crashes. ETSC (2016:13) note that the introduction of ESC (Electronic Stability Control) reduced crashes by typically 20%, and AEB (Automatic Emergency Breaking) contributed to reduce the number of deaths by 7% on the EU25 scale. Papadoulis et al. (2019:13) use the consequences that the introduction of automation in railway and aviation had in the safety ratios of these transportation means, to posit that AV could reduce crash rates to 1% of the current figures.

Although this positive view is supported by a myriad of authors, there are others that take a more pessimistic approach, noting the potential failure of sensors, the interaction human-machine, unforeseen or unanticipated situations which cannot be sorted out by the AV, coding errors in a mission–critical code, or even the plethora of potential cyber-attacks in the wired and wireless connections of an AV.

The challenge is then how to objectively probe that AV are safe enough as to be allowed onto our roads. Two main approaches have been taken to estimate the impacts of AV in terms of road safety. One based on historical facts (safety by facts, where AV observed failures are compared to a known failure rate), and a second one supported by simulation (safety by simulation).

5.2.3.3.2.3 Safety by facts

AV crashes have been thoroughly researched, although none of these studies (known to the author) includes crashes that resulted in fatalities given the limited experience of AV in public roads. Only four fatalities have been reported at the time of writing this thesis when driving in an autonomous mode. Three of them were driver fatalities when riding in a Tesla (January and May 2016 and March 2018), and a fourth one a cyclist when it was hit by an Uber car in March of 2018). Favarò et al. (2017:9) present an analysis of all AV reported crashes in California from September 2014 to March 2017, to conclude that most of them were rear-end or fender-bender accidents in which the AV was not at fault (22 out of the 26), and which happened when a conventional vehicle hit the AV at a very low speed. Noteworthy among the findings is also the lineal correlation between the cumulative miles driven autonomously and the cumulative accidents, which indicates that AV have not yet reached a situation in 2017 in which the behavior of the car could be aligned to what a human would expect, and therefore these crashes be avoided. In doing an analysis of real-world AV crashes, Schoettle and Sivak (2015a:18) share the findings of Favarò et al. (2017:9), noting that given the limited amount of miles accumulated, the percentage of crashes of AV per mile driven was higher than conventional vehicles.

The above research suggests that should the problem be presented in terms of the estimated failure rate of AV, versus the known failure rate of conventional vehicles (the 1.03 fatalities per 100M miles driven, result of dividing the 3,133 billion miles driven into the 32,166 fatalities), none of this has statistical relevance as to probe the point. As Kalra and Paddock (2016:194) note, to probe a similar rate of fatalities than ICE and BEV with a 95% confidence level, they should have to run their AV for almost 300 million miles, which is obviously unachievable (Waymo, far ahead of the other competitors in miles driven has just past the mark of 10 million miles) and leads to the conclusion that the current fleet of AV being driven in our streets is far too small as to probe AV road safety.

5.2.3.3.2.4 Safety by simulation: Time to Collision (TTC) as a Proxy

Hars (2016:7) offers an interesting alternative when he can demonstrate that the correlation of the probability distribution of accidents with fatalities, and traffic conflicts. This allow Hars to conclude that a car that is much better at avoiding traffic conflicts resulting in non-fatal accidents, should also be better at avoiding fatal accidents, opening the door to use other variables (rather than miles driven) such as driven time, or intersections passed, as a proxy for fatalities when measuring road safety.

Traffic microsimulation software (such as TransModeler, PTV VISSIM or TSIS-CORSIM) has been widely used for years to improve our understanding of the impacts of AV in terms of traffic flow (e.g. Giuffrè et al., 2017 or FHWA have used microsimulation for traffic safety evaluation purposes). Papadoulis et al. (2019:14) pioneered its application to the research of the road safety consequences of operating both AV and ICE or BEV in a highway. For this purpose they used PTV VISSIM to simulate a three-lane motorway section (44km) of the M1 motorway between Leicester and Rugby in UK and input a real traffic dataset (minute by minute traffic flow, speed and headway distribution sensed in the highway) for every day of the labor week, and different levels of penetration of AV (0%, 25%, 50%, 75% and 100%).

Their end goal was to identify any eventual reduction in the percentage of traffic conflicts (understood as two vehicles in a collision course within a time window which by default was set to 1.5 sg[6]) that may be produced as a result of the increase in the number of AV. As it could be expected, the % of reduction in traffic conflicts was directly proportional to the volume of AV, but the results presented in Table 25: Traffic Conflicts vs AV penetration (Source: Papodoulis et al. 2019:19) also offer other valuable insights:

I. Even an AV penetration so small as 25% produced a significant reduction in the number of conflicts, in percentages close to 50% in certain cases.
II. A direct proportionality to the volume of traffic. Percentage of reduction higher on Friday (where the simulation yield 2,049 vehicles per hour and direction), than on Wednesday (where the result of the simulation was reduced to 1,545 cars hour and direction).
III. As it can be seen below, the reduction in the percentage of traffic conflicts ranges from 0% (null AV penetration) to more than 94% (100% AV penetration in a highly congested condition). As already admitted, there is not a direct relationship between traffic conflicts and crashes (not always one conflict ends up in a crash), but nevertheless this last value would appear to confirm the early referred predictions that expected the reduction in the number of fatalities (assuming traffic conflict as a rough proxy of fatalities) in a range above 90%.

[6] When testing different transition time conditions for vehicle occupants to regain control of an AV in emergency situation, Mok et al. (2015:2463) found that 5 seconds is the minimum time for vehicle occupants to safely regain control of an AV being driven in autonomous mode. Below this threshold, the participants in the test were not able to perform accurately as to safely regain control, and as a consequence the accident was likely. This provides an independent validation of the value of TTC used by Papadoulis et al. (2019:19) to identify a traffic conflict that may most likely would result in a traffic accident.

CAV Penetration	Total Conflict Reduction %				
	Monday	Tuesday	Wednesday	Thurdsday	Friday
0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
25.00%	42.71%	15.09%	12.19%	43.30%	46.81%
50.00%	72.06%	54.56%	50.96%	72.53%	80.34%
75.00%	91.56%	82.92%	82.19%	91.21%	91.04%
100.00%	94.29%	90.05%	91.78%	92.86%	94.32%

Table 25: Traffic Conflicts vs AV penetration (Source: Papodoulis et al. 2019:19)

5.2.3.3.2.5 Economic Impact of AV in the Metroplex

As discussed initially, the total cost of traffic accidents is split between the government, the individuals affected and the insurers. As the cost to private insurers reverts to the insurance premium, it is internalized by the consumer, and therefore the externalities produced do only include the 4% borne by the Federal government, and the 3% assumed by local and state governments as calculated by Blincoe et al. (2015:6).

The Metroplex is the largest inland metropolitan area in the US. It includes 19 counties which have the fatality rates and vehicles registered shown in the table below for the last year available (2017). Data as provided by TxDOT Fatal Crashes and Fatalities by County and Road Type.

County	Fatalities	Vehicles	
		Total	LDV
Collin	68	798,931	465,890
Cooke	10	57,879	33,752
Dallas	281	2,126,530	1,240,068
Denton	49	679,045	395,979
Ellis	33	180,077	105,010
Erath	10	41,921	24,446
Fannin	14	38,407	22,397
Grayson	22	134,047	78,168
Hood	11	70,127	40,894
Hunt	26	97,235	56,702
Johnson	21	176,846	103,126
Kaufman	31	124,765	72,756
Navarro	14	51,889	30,259
Palo Pinto	8	33,264	19,398
Parker	20	154,854	90,302
Rockwall	13	91,852	53,563
Somervell	9	12,022	7,011
Tarrant	180	1,703,773	993,541
Wise	21	88,539	51,631
Total	841	6,662,003	3,884,890

Table 26: 2017 fatality rates and registered vehicles in the Metroplex (Source: TxDOT, 2017)

Using the ratio of the latest figures of fatalities in US and in the Metroplex (2017) as a proxy to calculate the cost borne by the different governments (Federal, State and Local) in the crashes that occur in these 19 counties (see table below), the total value of the road safety externalities assumed by the different governments with responsibilities in the Metroplex comes to $493 million[7]

	2010	2017
Number of Fatalities US	32,999	37,133
Number of Fatalities Metroplex		841
Total cost in US ($ millions)	242,000	272,008
Total cost paid by Governments in US ($ millions)	19,360	21,761
Total cost paid by Government in Metroplex ($ millions)	438	493

Table 27: Cost borne by governments of crashes in the Metroplex (Source: Developed for this study)

[7] the social cost as calculated by Blincoe et al. (2015:11) will not be included in this calculation, to prime a conservative approach to the potential of AV to reduce the cost of externalities

Now to consider the consequences that the deployment of AV would have in this value, we consider the figure below which shows the 2017 Annual average Daily Traffic (AADT) in the Metroplex considering 24-hr two-way counts with truck and seasonal factors applied.). It includes TxDOT maintained roads (including frontage roads when present), county roads and city streets. As it could be expected, values over 100,000 AADT are seen in the permanent count stations of almost over all the major arterials in the area (I-35 E and I-35W, LBJ, I-30, with I-77 having the highest value over 270,000) with values between 15-20,000 seen almost everywhere.

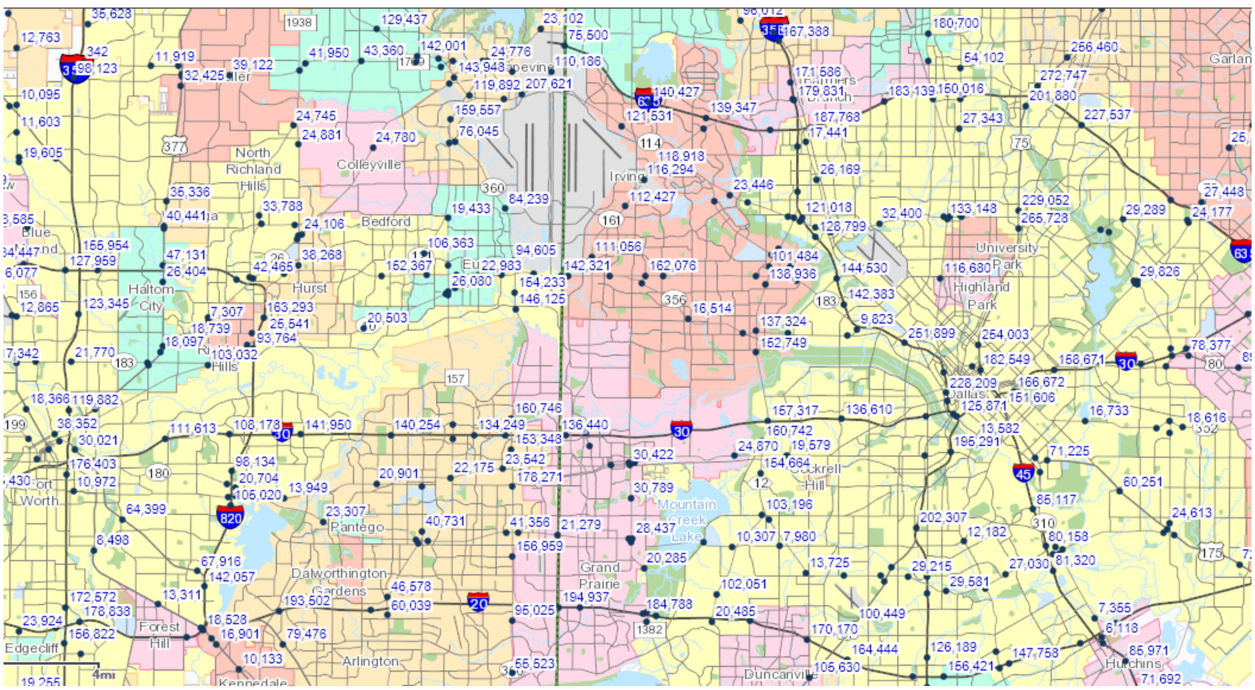


Figure 19: AADT of the traffic count stations in the Metroplex (Source: TxDOT, 2017)

In here, I make two important assumptions with regards to the validity of the results provided by Papadoulis et al. (2019:19):

I. Although the traffic conditions in most of this urban network (except for the main arterials) are not completely akin to the M1 Highway, average traffic volumes are in similar ranges of those modelled by Papadoulis for Friday (2,049 vehicles/hour), so this is the value used as a baseline for my analysis.

II. I consider the conflict reduction found by Papadoulis for the AV penetration between 0% and 25%, under the assumption that AV penetration hardly overcomes this value for the years considered, and I assume a lineal relationship between AV penetration and conflict reduction.

As it can be seen in Table *25*: Traffic Conflicts vs AV penetration (Source: Papodoulis et al. 2019:19), a 25% increase in the penetration of AV reduces the traffic conflicts by 46.81%, which equals a reduction of $231M in the cost to be borne by the government. This creates a positive externality of $9.23M for every 1% of increase in the penetration of AV (if both variables have a linear relationship).

For the sake of clarity and to facilitate the understanding of the reader, Figure *20*: Process followed in the safety sub model (Source: Developed for this study) represents the steps taken when figuring out the negative externalities avoided.

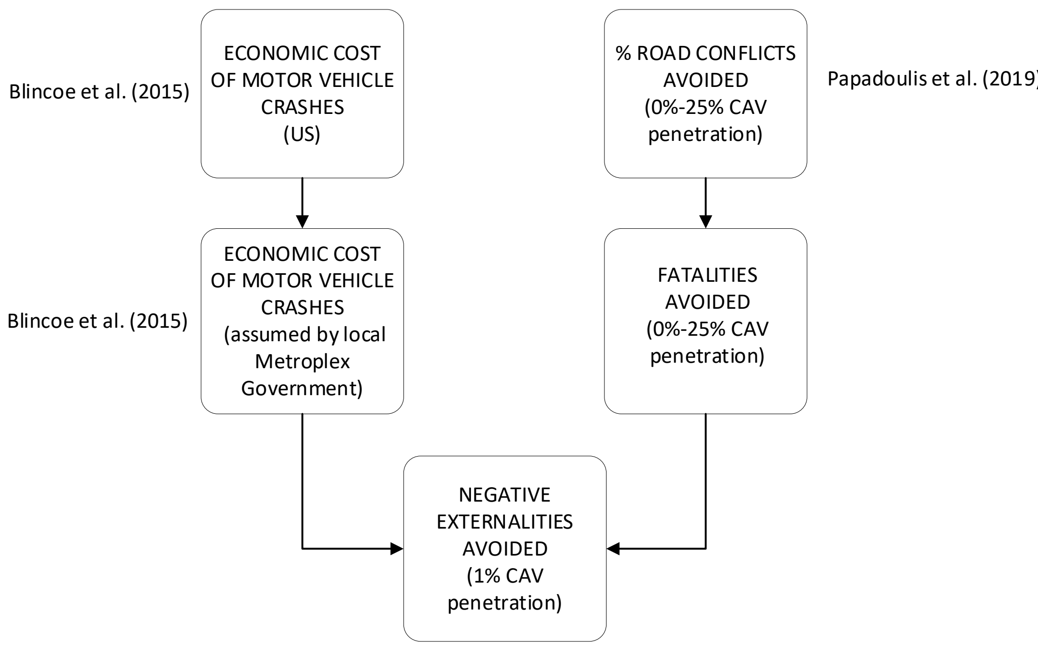


Figure 20: Process followed in the safety sub model (Source: Developed for this study)

5.2.3.3.2.6 General parameter values used in the choice sub model

Table *36*: Values of the parameters in the choice submodel (Source: Developed for this study) shows the values of the different parameters, variables, stocks, and flows used in the utility sub model.

5.3 Solution refinement cycle

5.3.1 Parameter verification

Confirming the validity of a model is split in two parts, verification, and validation. While verifying the model intends to ensure the correctness of its implementation, its validation aims to make certain that the model possesses a satisfactory range of accuracy consistent with the intended goal.

This last statement implies that although model verification processes and tools can be rather objective, its validation needs to follow a fit for purpose principle, aligned in this case to the exploratory nature of the research, which intends to identify trends more than providing an accurate replica of a system.

There are multiple tests to verify the correctness of the model from different perspectives (structure, behavior, or policies) including purpose, fitness, consistency, utility, and effectiveness). Anylogic provides several high-level tools embedded into the application to perform some of these tests, from checking the logic and syntactic rules of the program, to check snapshots compatibilities or the consistency of the system dynamic units. All these tests were passed by the current model prior to simulation.

The model is usually validated by comparing the results of the simulation with real or experimental data and performing sensitivity analysis. The simulation period (2010 to 2040) was chosen to facilitate the calibration of the model to the actual number of ICE and BEV vehicles sold from 2010 to 2020, and the EIA (2019) forecast thereafter. Figures 25 and 26 in section 5.3.3.3 and 5.3.3.4, offer a snapshot of the deviation (ICE and BEV vehicles sold before 2020, versus projected number). These figures show a deviation that is not material enough for the model not to meet its intended purpose.

The values of the parameters used for the base case are the result of the empirical research discussed in the literature review. The evolution of these values during the simulation period (2010 to 2040), has been estimated based on the calibration of the model to what is believed to be the Ground truth of the evolution of the fleet in the Metroplex during this period. Section 5.3.3 analyzes the sensitivity of the base case to different variations of these values, including the introduction of incentives in the Metroplex.

The model simulates the evolution of the fleet of all LDV registered in the 19 counties of the Metroplex, which comprises two metropolitan statistical areas (MSAs): the Sherman-Denison MSA, and the Dallas-Fort Worth-Arlington MSA including the counties shown in the table below.

County
Collin
Cooke
Dallas
Denton
Ellis
Erath
Fannin
Grayson
Hood
Hunt
Johnson
Kaufman
Navarro
Palo Pinto
Parker
Rockwall
Somervell
Tarrant
Wise

Table 28: Counties included in the Metroplex region (Source: Developed for this study)

Ground truth for this fleet is as shown in Table 29: Ground truth for the fleet of the Metroplex (Source: Developed for this study). This includes the actual number of registered vehicles (ICE and BEV) year by year to 2018 (BEV as shown in Figure 13: North Texas BEV Registrations January 2020 (Source: EVNT, 2020)) projected to 2040 in accordance with the US projections made by the US Energy Information Administration (EIA) as reported in EIA (2019).

	LDV	ICE	BEV
2010	3,104,406	3,104,302	104
2011	3,207,841	3,207,383	458
2012	3,322,123	3,321,093	1,030
2013	3,436,224	3,434,333	1,891
2014	3,555,713	3,553,005	2,708
2015	3,751,369	3,748,004	3,365
2016	3,784,733	3,779,891	4,842
2017	3,823,913	3,817,180	6,733
2018	3,884,890	3,874,708	10,182
2019	3,886,953	3,875,001	11,952
2020	3,889,324	3,875,294	14,030
2021	3,892,056	3,875,587	16,469
2022	3,895,213	3,875,880	19,332
2023	3,898,867	3,876,174	22,693
2024	3,903,105	3,876,467	26,638
2025	3,908,030	3,876,760	31,270
2026	3,913,759	3,877,053	36,706
2027	3,920,434	3,877,347	43,087
2028	3,928,218	3,877,640	50,578
2029	3,937,304	3,877,933	59,371
2030	3,947,919	3,878,226	69,692
2031	3,960,328	3,878,520	81,808
2032	3,974,844	3,878,813	96,031
2033	3,991,833	3,879,107	112,726
2034	4,011,723	3,879,400	132,323
2035	4,035,021	3,879,694	155,328
2036	4,062,319	3,879,987	182,332
2037	4,094,310	3,880,280	214,030
2038	4,131,813	3,880,574	251,239
2039	4,175,785	3,880,868	294,917
2040	4,227,350	3,881,161	346,189

Table 29: Ground truth for the fleet of the Metroplex (Source: Developed for this study)

The actual number of BEV vehicles sold in US beats EIA's forecast by 153% in 2018, and 40% in 2019, which shown how disruptive the introduction of Tesla model 3 in 2017 was, and how conservative this forecast may be. This would seem to suggest that in the long run the number of BEV vehicles sold in the Metroplex will significantly outperform the current EIA's prediction. Nevertheless, EIA's forecast (ICE and BEV) is used as a Ground truth given the consistency it offers to the current public policies.

Figures 21 and 22 show the differences between the results offered by the simulation and the Ground Truth for the base case, which have been considered small enough as not to condition the result of the research. The reduction of the participation of the ICE fleet which can be seen in the final years of the simulation with regards to the Ground truth (Figure 21: Comparison between GT and simulation (IEC) (Source: Developed for this study)) reflects the increase in sales of AV which is not considered in the EIA simulation.

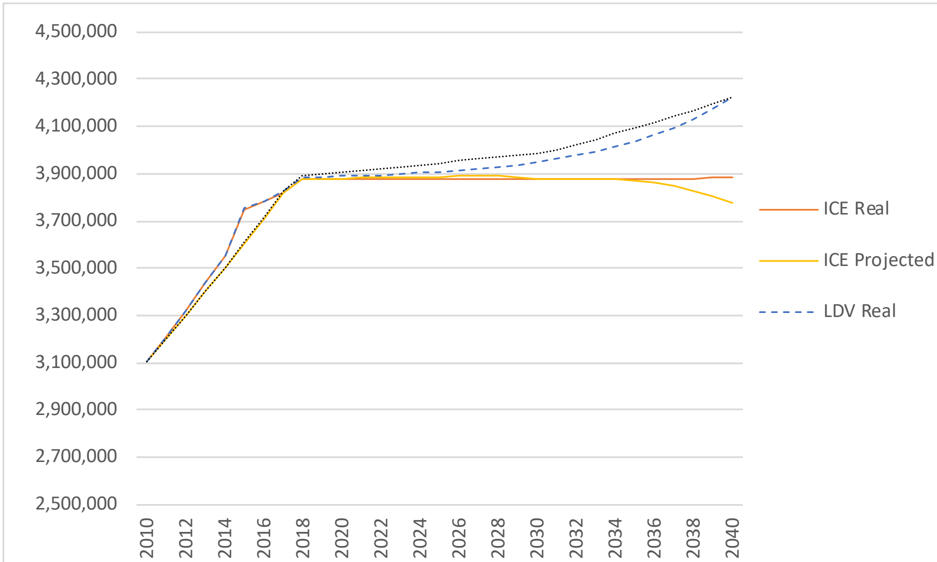


Figure 21: Comparison between GT and simulation (IEC) (Source: Developed for this study)

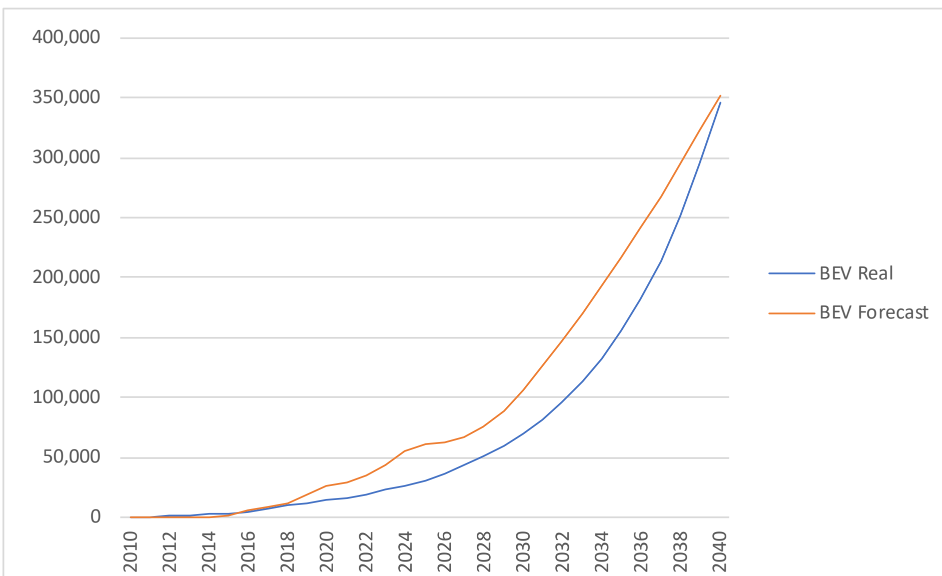


Figure 22: Comparison between GT and simulation (BEV) (Source: Developed for this study)

5.3.2 Model verification and validation

Although face validation is not intended to be the basis of a scientific assessment of the validity of the model, it provides relative trust and reassurance that the model results are plausible. Face validation was conducted by consensus of the learning set in the third and final workshop considering the results offered by the final simulation, and the prevailing views of the learning set members. In this regard, it was considered that the plausibility of the model behavior was ensure by considering that the evolution of several of the parameters was aligned to the expectations:

- BEV Purchase price: Section 7.1.1 summarizes different third-party forecasts which align to the predicted gap between IEC and BEV.
- AV Retrofit price: While McGee (2020) refers to Allix partners to forecast a retrofit price not to exceed $7,000 by 2025, Tesla plans to begin producing their Cybertruck in 2022 with a $8,000 full self-drive packaging. This is well below the $12,000 value forecasted by the model in 2040.
- AV penetration: The penetration forecasted by the simulation is well aligned to the expectations of Litman (2021:5).

When reflecting on this topic, the conclusion of the members of the LS was that the results revealed the conservative approach taken when making the assumptions, something which is appropriate given the intended audience of the research.

5.3.3 Sensitivities

User perception plays a crucial role when adopting new technologies. Penmetsa et al. (2019:12) provide evidence of the importance of the interactions of users with AV when increasing their perceptions of safety and ensuing approval ratios of the new technology (as presented in section 5.2.2.2, this provides the rational to consider the familiarity as a pillar of the attractiveness). Nevertheless, as discussed previously, these interactions will come with a risk during the transition period, and several different scenarios can be foreseen depending on how uneventful this process is.

To get a better understanding of the sensitivity of the model to these different outcomes, I have chosen a subset of parameters which can be affected positively or negatively by events which may happen during the transition. Different cases of the model have been run (low and high), altering the value of these parameters one at a time as shown in Table 30: Cases considered (Source: Developed for this study).

Variables AV	**Case**		
	Low	**Base**	**High**
External R and D	-10%	Table	+10%
Perception CAV	-10%	Table	+10%
WTP ($)	-10%	7,500	+10%
Incentive/Rent	50%	0%	100%

Table 30: Cases considered (Source: Developed for this study)

5.3.3.1 Changes in external R&D

As we have seen before, external investment in R&D is critical to reduce the cost of the retrofitting component of the sale price of the AV increasing its utility (and fleet). Nevertheless, there is a sweet spot beyond which even when the investment keeps flowing it does not significantly increase the fleet. The external R&D investment considered for the base case is rather close to this breakeven point. Figure 23: Sensitivity of AV Fleet to changes in R&D budget (Source: Developed for this study) clearly shows that the increase in 50% in R&D funds (high case) does not expand the diffusion of AV in a similar magnitude.

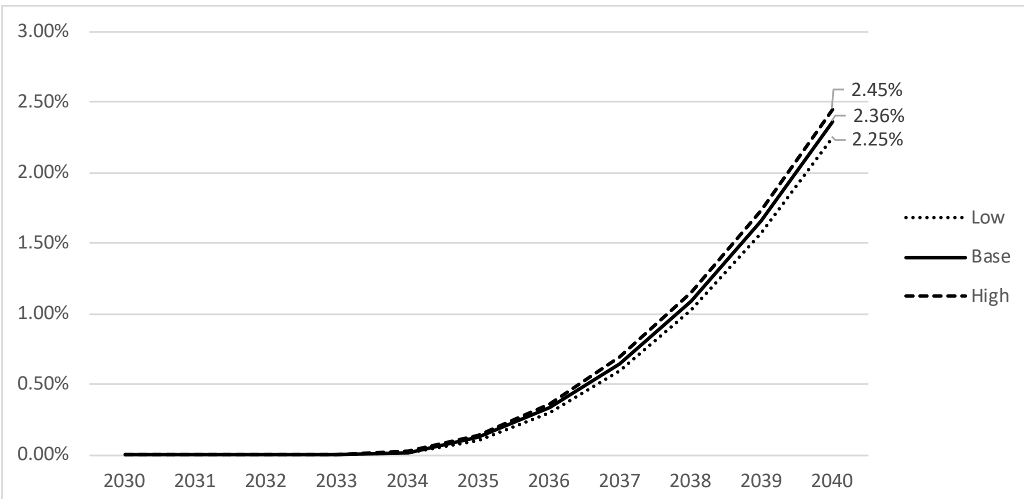


Figure 23: Sensitivity of AV Fleet to changes in R&D budget (Source: Developed for this study)

5.3.3.2 Changes in user perception

Figure 15: Causal-loop Diagram (Source: Developed for this study) identifies several reinforcing loops. As the fleet increases, the experience does as well, and this comes with an improvement in the perception of the user by means of word of mouth. Therefore, increasing the fleet does not only increase the utility (by decreasing the price) but also by increasing the perception. Figure 24: Sensitivity of AV fleet to changes in user perception (Source: Developed for this study) demonstrates that this last component (improve the user perception) has a more significant impact that a decrease in price in the early stages of AV diffusion.

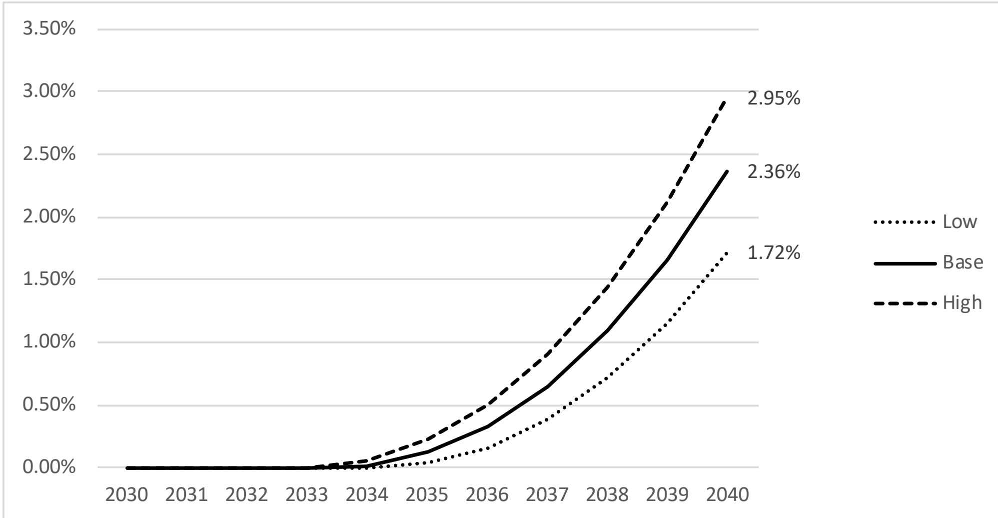


Figure 24: Sensitivity of AV fleet to changes in user perception (Source: Developed for this study)

5.3.3.3 Changes in the user willingness to pay

Table 16: Willingness to Pay (Source: Adapted from (1) Bansal and Kockelman (2017:54) (2) Hidrue et al. (2011:700) for configuration E, and (3) Plötz et al. (2014:412) shows how significant the changes in the WtP are depending on the group you are considering, with a significant number of users not willing to pay anything beyond the cost of a L0 vehicle.

Nevertheless, the number of innovators willing to pay $7.500 or more, is above the 5% that are predicted to be attracted by the TEXpress incentive. Should this number increase beyond the predictions, early adopters could be attracted early than anticipated and the average WtP would diminish with the consequences shown in Figure 25: Sensitivity of AV fleet to changes in user WtP (Source: Developed for this study).

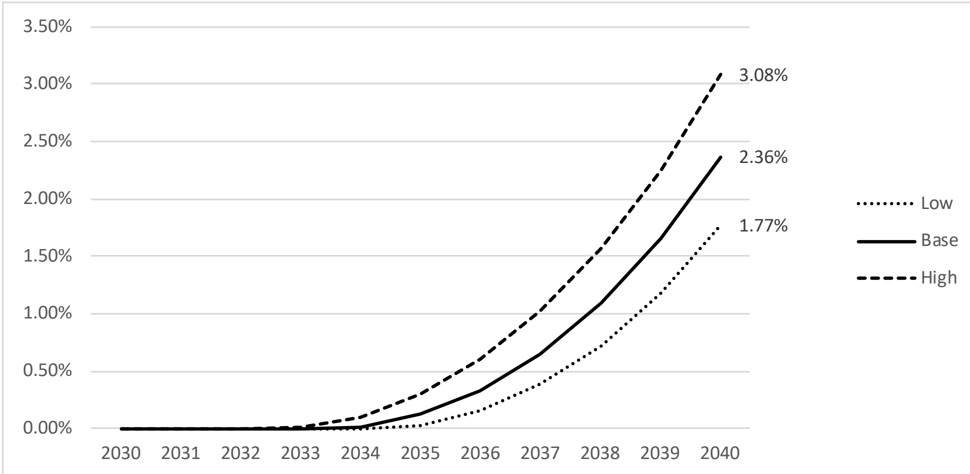


Figure 25: Sensitivity of AV fleet to changes in user WtP (Source: Developed for this study)

5.3.3.4 Changes in the TEXpress incentive

Figure 26: Sensitivity of AV fleet to changes of incentive (Source: Developed for this study) probes the positive effect of the incentive, as it increases the diffusion of AV in the Metroplex from 99K (no incentive in the base case) to 152K (low case) and to 226K should the incentive cover the toll fee in its entirety. Figure 27: Sensitivity of Net welfare to changes of incentive ($M) (Source: Developed for this study) shows how the market share of AV in the Metroplex changes with the different incentives.

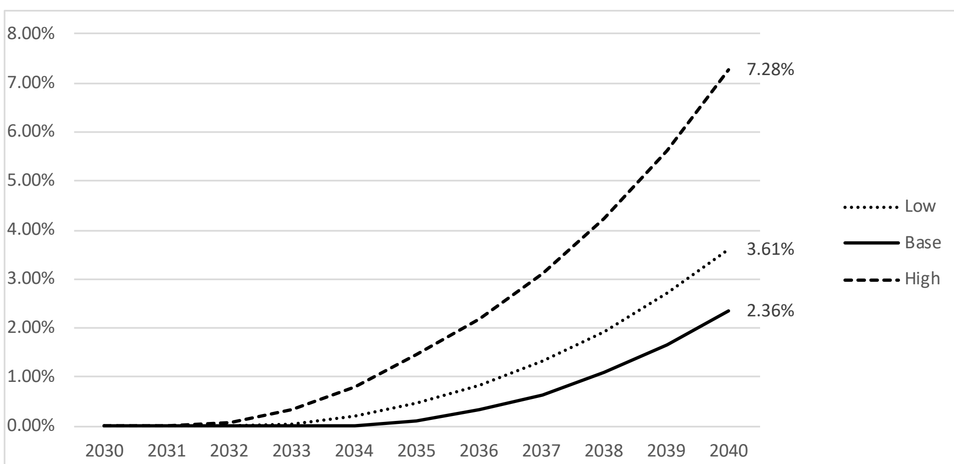


Figure 26: Sensitivity of AV fleet to changes of incentive (Source: Developed for this study)

Every simulated case result in a positive net welfare. If no incentive is provided, the road safety and environmental benefits of the non-incentivized AVs provides a positive welfare of $76M. If AV are incentivized, this net welfare increases to $120MK should 50% of the toll fee is incentivized (low case), and $172M should the complete fee is incentivized (high case). The latter represents an average net welfare of $761 for every incentivized AV for the whole simulated period.

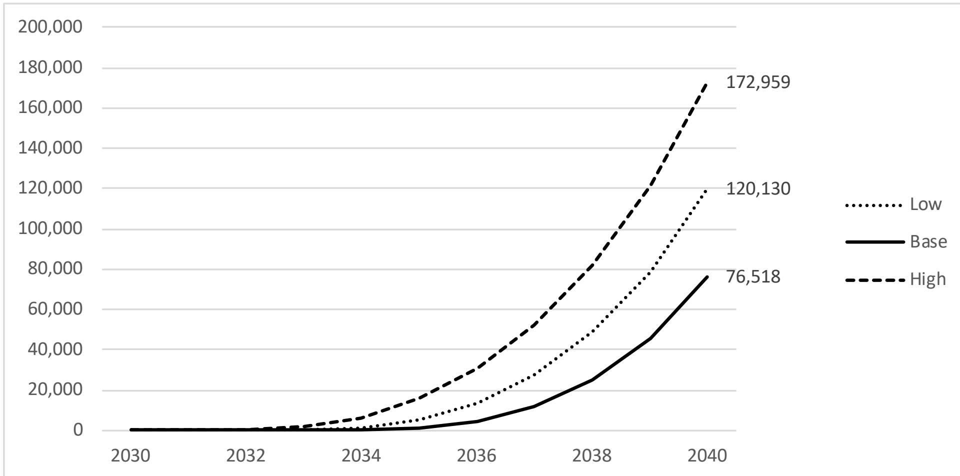


Figure 27: Sensitivity of Net welfare to changes of incentive ($M) (Source: Developed for this study)

6 Action Research Inquiry

Chapter 3 introduced the two AR cycles that are at the core of the research. Both act in the SD model but contribute to the interpretation of the modeling in a different manner. While the first takes a quantitative approach to identify potential actions to be considered, the second identifies and evaluates the actions from a qualitative standpoint, using the SD model in combination with the MLP analytical frame introduced in Chapter 4. This section describes this process in three parts. The first section reviews the challenges that the LS had to overcome, and the lessons learnt in this process, while the other two sections are devoted to the quantitative and the qualitative AR cycles respectively.

6.1 Challenges

Gaya and Reason (2009:250) note that "rushing too quickly into establishing an inquiry group is nearly always a mistake". The initial steps of the working group quickly revealed this first challenge. Getting the participants acquainted with the notion of collective inquiry and critical reflection is not a trivial task. Marshall and Reason (2007:1) assemble a list of qualities that define the terms "curiosity, willingness to articulate and explore purposes, humility, participation, and radical empiricism". These qualities have inadvertently been growing via my actions since I started the DBA, but unfortunately these are not traits that a practitioner used to working in a corporate hierarchical environment possesses by default. Introduction of ideas and scenarios to a group that is expected to question them with an attitude of inquiry requires altering the normal dynamics of the group. Gaya and Reason's (2009:250) reference to Richard Rorty that "the purpose of inquiry is to achieve agreement among human beings about what to do" seems to underscore this difficulty. The survey filled by the participants at the end of the third workshop reveals that the disparity of perceptions about the uncertainties surrounding the transition to AV and their consequences remained to a certain extent at the end of the two AR cycles.

Furthermore, contracting, which is understood as providing a sense of clear purpose, quickly showed its relevance when answering the questions posed by the LS members while walking them through the research questions and methodology. One of the questions concerned the extent to which the project solves the workplace problem (What do we gain by incentivizing AV?), while a second addressed the expectations of the AR group (Are you asking us to reflect on the actions which may be taken given the constraints of the project, or, given the uncertainties, do we reflect on the actions we think should be considered, no matter how aligned they are to the model, while disregarding the lack of evidences to support our views?). Other incentives (e.g., tax, insurance, or gamification based on experience; for example, Waze probes that the status-rank has a significant impact in human behavior) were discussed as an alternative to TEXpress. After some debate, the group agreed that we should question our beliefs considering the results of the empirical model but without leaving behind all the identified uncertainties that may question the model's forecast and the findings of the research.

A third challenge was the use of the academic terminology to frame the reflection process. Beyond introducing the cycles of action and reflection as a basis for AR, and given an audience of practitioners, does it provide any advantage elaborating on the differences between AR and AL, and why was one of them chosen? Should I briefly introduce them to the differences between Revan's philosophy of learning and Lewi's philosophy of inquiry? I decided to face this question with a pragmatic attitude and decided that they did not require any further introduction except to the AR fundamentals as presented in section 3.4.4. Finally, the asymmetrical knowledge between the members of the AR group and the internal researcher, combined with the hierarchical relationship of some of the members, increased the difficulty in presenting ideas without biasing the group inadvertently.

6.2 Quantitative AR Cycle

For the group to have a common understanding of the goals and the research methodology used in the study, the first workshop offered a summary of the model together with a description of the research tools. This workshop served multiple purposes and introduced the following topics:

1. Objectives of the research, research methodology and tools, and how SD is used to address complex multidimensional and messy problems. The time spent on describing SD fundamentals was quite limited and constrained to explain the functional concepts behind its main elements so that the group may understand how the complete model operates.
2. Causal Loop Diagram and model and sub model construction.
3. Literature review and data available (its robustness).
4. Base run parameter values.

I began the second meeting with a recap of the first workshop and the stated intention to follow a more hands-on pattern based on debating potential actions to be taken as part of the planning action. Results of the initial simulation were presented and debated together, including running sensitivities of the model regarding the different actions proposed by the participants. The end goal was to enhance the understanding of the participants about the consequences of actions and thoughts that may initially seem reasonable and the effects of these consequences on the business model of the company. To initiate subsequent discussion, a set of questions was presented to the participants as follows:

1. TEXpress sub model
    1.1. Which group of customers (GPL or frequent users of TEXpress, as described in section 5.2.3.2.4) is likely to be more appealed by the incentive?
    1.2. If the current GPL users are willing to use TEXpress for free, should the rent be limited to the time savings, or should we consider the full amount of the toll?
    1.3. If those appealed by the incentive are current users of TEXpress, should we consider lower frequency users than those using TEXpress more than 100 times a year?
    1.4. How likely is that the incentivized users maintain the same frequency patterns? Shall we increase their frequency, both when calculating the rent created and estimating the cost?
2. Utility sub model
    2.1. How likely is it that the BEV and AV customer perception (willingness to purchase) evolves as predicted in the model assumptions?
    2.2. How likely is it that one-off occurrences may alter this outcome (e.g., accidents with fatalities), hampering the customer's trust in the innovation?
    2.3. How about the weight of the TCO? Should we consider other values?
    2.4. Taking all these questions into consideration, shall we consider other incentives more effective or efficient in terms of cost-benefit, such as free recharging?
    2.5. What would their consequences be in terms of our business?
    2.6. Are there other actions which could be considered parallel to this incentive, such as dedicated lanes?
3. Choice sub model
    3.1. Do the options offered to the customer in the choice sub model make sense?

The results of the initial simulation and the ensuing discussions sparked by the proposed questions allowed the LS to identify a set of actions to be performed by me (as internal researcher and modeler). They included significant changes in the evolution of the user perception, the TEXpress frequency groups addressed by the incentive, and the calibration to updated ground truth data.

Once I ran the quantitative simulation, I launched the third workshop asking the LS to evaluate the consequences of the planned actions. Some of the members of the LS shared their concern that although several of the assumptions and values of the parameters changed significantly between the initial and the quantitative simulations, the result of the dependent variables did not change much. This would seem to suggest that we were not properly modeling all the levers that acted over the research variables. To address this concern, the group agreed that the qualitative cycle should include a sensitivity analysis to improve the understanding of the relationships between the dependent and the independent variables.

6.3 Qualitative AR Cycle

Coghlan and Brannick (2014:10) define the construction step of the AR cycle as dialogic, implying it is the result of an open dialogue between the members of the LS before planning the action. In order to facilitate this dialogue, I initially introduced the following three items: first, the MLP analysis of the socio-technical system in the Metroplex and the predicted transition path, as discussed in Chapter 4; second, my reflection about how the results of the quantitative simulation aligned with this predicted path; and, finally, a set of questions which may be tackled by the group. My reflection highlighted the following facts:

i. The quantitative simulation shows that the AV fleet does not start growing exponentially until 2030, and the volume of AV in the Metroplex will be limited until the 2040s. This favors the transition path introduced in section 4.3 where two technological substitutions (from ICE to BEV and AV) are chained within a single and continuous transition, which would allow the incumbents to adapt and play a key role in the transition and beyond. An incentive in TEXpress does not have consequences substantial enough as to change this trend (for example, boosting the AV penetration to a point where the incumbents do not have enough time to catch up).
ii. Furthermore, the MLP analysis offers solid indications that the appetite of the landscape to increase the pressure on the regime by incentivizing the deployment of AV is somewhat limited. As discussed in section 4.1.1, the landscape has currently tree main avenues to increase the pressure over the regime: i) supporting the niche by keeping a permissive legal framework that facilitates innovation, ii) favoring the environment and the reduction of CO_2 emissions through the GECAP program in Dallas, and iii) the marching orders that the TxDOT has to work towards the goal of reducing the number of fatalities by half in 2035.
iii. Although state and local authorities are showing a robust support to the initiatives developing in the niche, incentivizing AV to reduce CO_2 or improving road safety requires a previous acknowledgement of the importance of AV to achieve these goals. In this regard, although

GECAP and the SMP define vision and goals for environment and transportation in Dallas and identify electric fleets as one of the main action areas, they do not plan to offer incentives. Furthermore, the order issued by the TTC to TxDOT will eventually result in improvements within the Traffic Safety Division of TxDOT, which oversees the design and placement of signs, signals, pavement markings, and intelligent transportation systems. Although this division also develops traffic safety initiatives aimed at reducing fatalities from motor vehicle crashes, this will have a limited effect on the automotive regime as it is mainly regulated by the Department of Motor Vehicles which is a parallel agency of TxDOT.

iv. On top of this, the current budget constraints, which did certainly exist before COVID-19 (as noted in section 4.1.1.1 when reviewing the pressures to reduce the current BEV incentives and the lack of clear and measurable goals to ensure a massive penetration of BEV on our roads), have been exacerbated by the pandemic. As a result, it would not seem that incentivizing AV by itself will be a popular idea in the short run, until the concern about environment and road safety and the relationship between these concerns and AV is widely accepted.

v. Chaining two technological substitutions in a single transition path supports one of the main assumptions of this research that public policies may not favor an incentive to AV if it is seen as an isolated innovation, but they may be open to incentivizing its diffusion if it is seen as a factor that, while consolidating BEV, increases road safety.

The following questions were presented for further reflection and discussion:

1. Although the MLP analysis presents the Metroplex as the more dynamic Metropolitan zone in Texas in terms of BEV diffusion, is it a fair assumption to say that policymakers
   i. Perceive the magnitude of the crisis created by the road fatalities and GHG emissions?
   ii. Acknowledge AV as an effective way to improve this?

   Would they be willing to support an incentive to enhance the AV diffusion (even if this maybe be revenue neutral or even positive)?
2. If this is so, why does the current policy to incentivize BEV appear to be so ambiguous?
3. Will the apparent lack of statewide ambition in setting goals hamper the local efforts? Is there any way likely to increase the pressure of the landscape?
4. How about the social environment? Texas seems to be an environment prone to automotive innovation as a consequence of the quick turnaround time for the average vehicle, but could this be more the result of a high mileage than a willingness to embrace change and innovation?

5. How about the regime? Will the absence of local research activity hamper the support of the local OEM to the initiative?
6. Will the significant activity in the niche make any difference in the willingness of the landscape to fund the incentive?
7. The MLP analysis builds a transition pathway which suggests that both transitions (to BEV and to AV) may overlap in the absence of significant incentives, which may accelerate the transition to BEV that is already in progress. Would this influence the actions to be considered?
8. What are the consequences for our organization? Is the value of the toll the lever that would allow us to control the congestion in our Managed Lanes, or will the logic of the business change completely?

COVID-19 as a cause of significant uncertainty was one of the widely shared factors. Quoting two of the members of the LS, "I think post pandemic things like carsharing and travel behavior would be scored differently" and "Model structure and localization: fairly uncertain, particularly in the context of COVID-19, which may impact the structure of the different sub models in terms of time and weight".

The participants had different views about how public policies may influence the diffusion of AV in the Metroplex. This resulted in two opposite approaches concerning further actions by our organization. One alternative posited approaching public agencies that are eventually responsible for funding the incentive (noting that a 100% incentive more than doubles the AV penetration by 2040), while the second supported an internal process within the organization that may further evaluate the results of this research before approaching the external stakeholders. This last approach was supported by the MLP analysis, which shows a robust and stable socio-technical regime (unlikely to be influenced by the increase in the diffusion of AV produced by the discount, if other public policy actions are not taken simultaneously) as well as the uncertainty around the quantitative results of the model.

Taking into account that, on the one hand, the MLP analysis portrayed a socio-technical system that suggested the slim likelihood of policymakers being supportive of a higher discount for AV than that currently offered to HOV and, on the other hand, all results (refer to Figure *26*: Sensitivity of AV fleet to changes of incentive (Source: Developed for this study)) show that the penetration does not start increasing until after 2030, the LS suggested following the internal approach initially.

In this case, the following organizational actions were proposed:

- Conduct an internal educational process to align the different perceptions. The complex socio-technical environment and uncertainty of the multiple variables to be considered to make room for the multiple perceptions that need to be aligned.
- Influence the T&R modeling team to consider the findings of the model.
- Weight the organizational changes to obtain a concrete view of the service areas that would be impacted the most.

As discussed in section 3.4.6, which presents the action research methodology, a questionnaire was distributed at the end of the third workshop. The questionnaire was meant to gauge how the inquiry process influenced their perception about the key tenets of the research, both regarding their level of uncertainty and their impact on the transition process. The topics included were as follows:

- Private use of CAV L4
- CAV powered by electric powertrain
- External R&D investment
- Customer perception
- Policy framework
- Travel behavior
- Carsharing
- Metroplex as a stable socio-technical environment

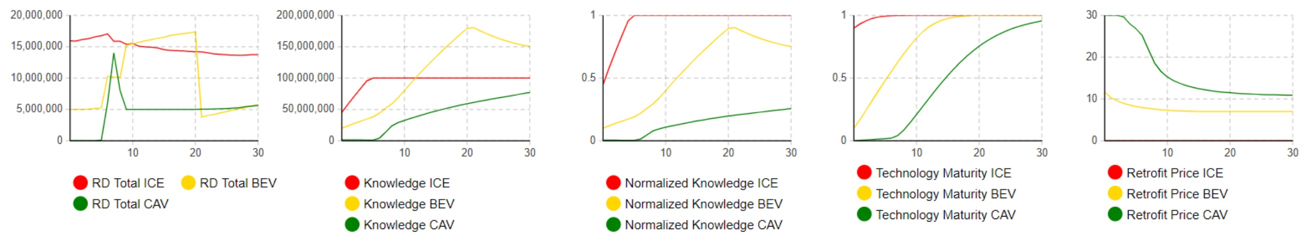
The survey data was analyzed by equally weighting each of the topics and the answers given by the participants. This revealed some persisting misalignments, even after the workshops supported a joint inquiry process. Although most of the members of the LS agreed that the uncertainty was significant and that this may have a significant impact on the results of the model, there were significant discrepancies in deciding which topics were more impactful. These differences were centered on the impact that the external R&D investment and the policy framework may have in the diffusion of AV. In these two cases, the answers range from 'slightly important' to 'very important'.

The appropriateness of AR as a tool for the participants to build knowledge and alignment beyond their expertise was evidenced by one of the participant's final statement, "Until the LS, I didn't realize how broad the idea is, it is very interesting to play futurist for a bit".

7 Discussion[8]

7.1 Quantitative results

7.1.1 Purchase Price



a) b) c) d) e)

Figure 28: Evolution of the retrofit price (Source: Developed for this study)

As previously discussed, the retrofit price for an AV represents the value of all the electronics and sensors that allow a vehicle of level 0 to be automated to level 4 (AV). That is, the cost to produce an AV on top of the common platform shared with ICE. In chart e) Figure 28: Evolution of the retrofit price (Source: Developed for this study) we can see that the model predicts the retrofit price of AV to be reduced from $30,000 to roughly $12,000 by the end of 2040. Although the retrofit value of the AV vehicles that OEM are currently using for testing and learning purposes are in the range of $100,000, it is reasonable to expect that once AV are offered commercially (and the sensors they integrate produced in industrial quantities), the cost is reduced to this level (in fact, Waymo announced in March 2020 that the retrofit value of its fifth generation of AV based upon the Jaguar I-Pace has been reduced by half compared to the earlier generation).

The evolution of R&D spending is at the core of the reductions in the retrofit cost. This has two components: one internal, as a percentage of the sales revenue (irrelevant for AV until after 2030), and one external, from external investors entering the market. The evolution of the external funding invested in AV R&D during the years 2016 and 2017 (e.g., $2,2B in Cruise or the $2,2B in Waymo) explains the spike in the R&D Total AV which can be seen in chart a) Figure 28: Evolution of the retrofit price (Source: Developed for this study). After that, it is reasonable to expect that external investment in AV will stabilize in the range of $5B per year. This also explains the increase in the gradient of the AV knowledge and normalized knowledge during these years, which can be seen in charts b) and c). The

[8] The reader is to consider that the simulation has been performed starting 2010 (point 0 on the X axis of the charts) and extending for 30 years beyond that to 2040.

knowledge is normalized with regard to the amount needed for full maturity in each of the powertrains considered. In this regard, the amounts considered in Nieuwenhuijsen et al. (2018:325) of €6B for BEV and €50B for AV have been increased significantly to $200B for BEV and $300B for AV to compensate for the significant external investment in R&D. Even though these values can be considered high, they are reasonable considering the fact that Waymo and Cruise (the AV venture of Alphabet and GM) have currently a market value of $20B and $19B respectively.

Although it is assumed that OEM may slightly increase the percentage of sales they invest in BEV R&D later (see the slightly positive slope in the BEV total R&D after 2030 in chart a) Figure 28: Evolution of the retrofit price (Source: Developed for this study)), this is not enough to compensate the depreciation of the existing knowledge; therefore, the final consequence will be that accumulated knowledge will show a slight reduction, as seen in charts b) and c) in Figure 28: Evolution of the retrofit price (Source: Developed for this study). Finally, chart d) shows how the technology maturity develops as the knowledge increases.

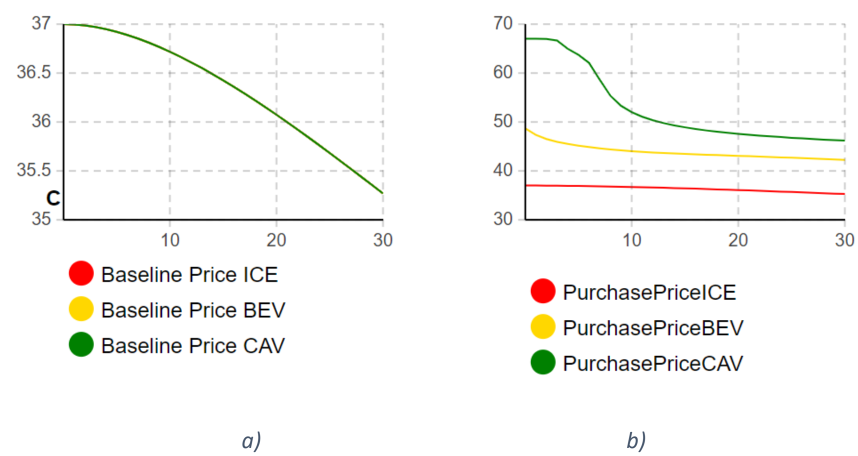


Figure 29: Evolution of the baseline price and purchase price (Source: Developed for this study)

As mentioned before, the cost and the evolution of the baseline price is the same for the three alternatives (see the superimposed line in the chart a) in the figure above), starting at $37,000 in 2010 and reducing to $35,300 in 2040. As a result of the reductions in the retrofit component, the purchase price of AV is significantly reduced, narrowing the gap to ICE from $30,000 to $12,000 at the end of the period. The gap for BEV is above what MIT (2019:16) predicts, which estimates this range to be between $10,000 in 2019 to $5,000 in 2030, and highlights the conservative assumptions of this study. It is also to be noted that the purchase price of AV starts reducing significantly as the R&D starts to increase in 2015, although level 4 will not be available until 2024, where the price is expected to have decreased to a purchase price in the range of $53,000. GM is currently offering the 2020 Bolt EV Premier electric vehicles at a discounted starting price of $34,000, which would seem to confirm that the forecast of an average price of $42,000 for BEV in 2040 is a credible assumption.

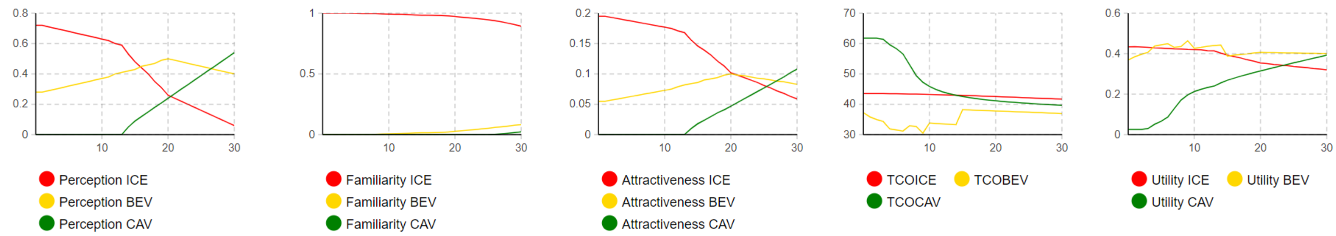
The table below offers a comparison of the initial values of the retrofit and the baseline prices used in the base model and those proposed by Nieuwenhuijsen et al. (2018:324). Besides noting that the numbers can only be partially compared (e.g., the number for BEV in the base model pairs with the pricing for level 1 in Nieuwenhuijsen which, although has the same level of automation, features an ICE powertrain), the most significant issue is the difference between the initial pricing used in Nieuwenhuijsen for AV and the number used in the base model (see Table 31: Comparison of initial pricing between the base case and Nieuwenhuijsen et al. (2018:324) [Source: Developed for this study]). Even though this is a highly hypothetical assumption, given the lack of maturity of the market, the number used for the base model is aligned with those presented at the world congress in AV safety and regulation in Detroit held during October 23–25, 2018 in Novi, Michigan (Nieuwenhuijsen's estimations were made three years before).

Reference	Powertrain	ICE	BEV	CAV
	Automation	**Level 0**	**Level 1**	**Level 4**
Nieuwenhuijsen et al. (2018:324) (€)	Baseline	20,000	30,000	200,000
	Retrofit	0	1,000	200,000
Base Model ($)	Baseline	37,000	37,000	37,000
	Retrofit	0	10,000	30,000

Table 31: Comparison of initial pricing between the base case and Nieuwenhuijsen et al. (2018:324) [Source: Developed for this study]

7.1.2 Utility

The decision to purchase depends on the utility, which is the sum of two factors: its TCO and its attractiveness. At the same time, this last factor is a function of the customer's perceived value in terms of comfort, safety and convenience, and their familiarity with this option.



a) *b)* *c)* *d)* *e)*

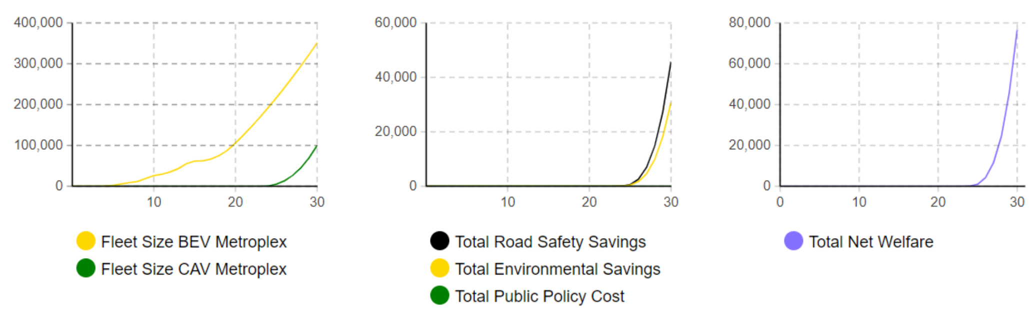
Figure 30: Evolution of the utility (Source: Developed for this study)

Chart a) in Figure 30: Evolution of the utility (Source: Developed for this study) reflects the assumption that while the user is increasingly familiar with BEV, since its distribution started in significant quantities mid-2010s, AV will need another twenty years, until the mid-thirties, for its familiarity to increase substantially.

The utility of AV keeps growing at a steady pace during the twenties and the thirties (chart e) in Figure 30: Evolution of the utility (Source: Developed for this study)) because although the TCO slows its improvement, this is compensated by a growing improvement in the perception of the technology as a result of increased familiarity.

7.1.3 Net Welfare

Chart a) in Figure 31: Evolution of fleets, cost and savings, and net welfare (Source: Developed for this study) offers a glimpse of the evolution of the BEV and AV fleets in the Metroplex, which will reach 100,000 vehicles in the case of AV and slightly over 350,000 in the case of BEV. Chart c) shows the total benefits for the net welfare of AV even when no incentive is available. In this case, the addition of the road safety and the environmental savings reaches $76M.



a) *b)* *c)*

Figure 31: Evolution of fleets, cost and savings, and net welfare (Source: Developed for this study)

Some other relevant insights worth a further discussion:

- The utility of the BEV is so high that BEV users changing to AV are virtually non-existent, and the sales of AV come primarily from ICE users switching over to AV and exogenous growth.
- The sales of BEV in the Metroplex at the end of the simulation period in 2040 will almost equal the sales of ICE.

7.2 Limitations

As discussed, this research intends to offer an exploratory approach to the net balance of the common good produced when incentivizing AV in TEXpress and examine its effects on our organization. In spite of this cautionary warning, there are assumptions (those made in section 2.1.3.3) that, when taken to the extreme, may condition this exploratory result. The purpose of this section is twofold: one, to give a hint about how fragile and uncertain these results may be and, two, open doors to new avenues for further research.

7.2.1 Local Relevance to the Metroplex

As discussed in sections 4.1.1.2 and 4.1.1.3, Texas is in a prime position to incentivize the diffusion of AV, as the annual emission of electric vehicles is low and the road fatalities very high. There is room for improvement when incentivizing AV in all electrical vehicles. This is not the case for many other states, which either have better road safety ratios or lower overall emissions. This constraints the value of this research when generalizing the results.

7.2.2 Negative Externalities

Section 5.1.1 presented the key drivers and consequences that could underlie the diffusion of AV. Reviewing the potential consequences presented in this section, it could be argued that while the research takes into consideration the most relevant positive externalities, it sidelines the negative externalities caused by an increased diffusion of AV, such as urban sprawl, congestion (traffic increases due to empty trips and the reduction in cost per mile), and employment (both direct and indirect as a result of a more efficient use of the vehicle). The net welfare presented in section 7.1.3 must be qualified by this limitation.

7.2.3 Evaluation of the Positive Externalities

The literature review offers ample evidences to quantify the positive externalities created by improving the road safety and the environment. Nevertheless, should the diffusion of BEV accelerate beyond the threshold that marks its self-sufficiency, the appetite of public agencies to incentivize its diffusion would not only decrease but eventually become unpopular. On the other hand, although the research has considered only the local benefits of increasing the road safety in the Metroplex, these savings are spread over a significant number of stakeholders, and it may be difficult to build a mechanism to compensate the agency in charge of financing the incentive.

7.2.4 Model Structure

Great care has been taken when ensuring that the structure of the different sub models is as unbiased as possible and that the values of the variables are supported by empirical research found in the literature review. Nevertheless, considering that AV unfold on a global scale, trying to forecast its diffusion in a local socio-technical environment as the Metroplex is rather unpredictable and full of external dependencies. Such uncertainty is exacerbated by the combination of three different factors: assumptions, SD structure and variable definition, and public policies.

7.2.5 AV Level 4 as the Vector for the Diffusion

This is probably one of the most significant assumptions made to architect the model, as it refers to the availability of AV Level 4 in the midterm for private use (parallel to ride-sharing and ride-hailing) and the Managed Lanes as the most likely ODD (see section 2.1.3.3) to support its diffusion. There are other approaches to support the diffusion of AV, either priming fleets of robotaxis in which AVs are not offered for private use or supporting a direct introduction of Level 5 without the restriction of the ODD. However, either of the two alternatives would render the considered model and most of the conclusions of the project useless.

7.2.6 AV Powered by a BEV Powertrain

As noted in section 2.1.3.3, this study stems from the core assumption that two of the 3R revolutions (BEV and CAV) considered by Sperling (2018) are intrinsically connected, presenting the latter as a natural continuation of the former. This assumption also informs the way I use MLP to analyze the local socio-technical regime in the Metroplex and the most likely transition path as discussed in 4.3. Should this basic assumption prove untrue, the validity of the complete study could be questioned, including the literature review, the viability of the incentives considered, and the value of the positive externalities created. The contribution of the latter topic to reducing the emissions of CO_2 would be reduced, although the consequences may not be that relevant, as even those that do not support this assumption advocate the use of hybrid powertrains (Ford seems to be supportive of this approach).

7.2.7 External Research and Development Budget

The model showed the importance of external R&D budgets in reducing the purchase price of AV (the retrofit price), thus boosting their diffusion. Although the recent purchase of Moovit by Intel at $900M seems to confirm the validity of the data forecasted in Table 15: External R&D budget (Source: Developed for this study), section 5.2.3.1.2 shows how difficult it is to properly gauge the appetite of investors to provide a constant flow of external investment to the suppliers of OEM, especially in the lower tiers. Furthermore, it is also difficult to gauge how the established OEM manufactures will slice the percentage of sales that they invest in R&D among the different fleets.

In this regard, increasing the effectiveness of the technology transfer (how efficiently the knowledge matures the technology) will boost these alternatives whose diffusion depends significantly on reducing the retrofit price. An increment in the effectiveness from the 50% of the base model to 75% increases the diffusion of AV in the Metroplex almost by 15% from 320,000 to 380,000. This shows how sensitive the outcomes of the model are from the value of this single variable.

7.2.8 Customer Attitude

The evolution of customer's attitudes towards a technology that may disrupt many dimensions of their social life and will go through a transition where the advantages will not be easily seen (and the risks and performance highly scrutinized by the media) is another of the fundamental limitations of the study. The perception of the users and its weight in the utility of AV will have a heavy impact on the diffusion and the value seen, and there is ample evidence that it may oscillate wildly depending on a multitude of factors. Cybersecurity and the recent hacking of a Tesla vehicle may be one of the factors which may raise the concerns of the consumer beyond what is expected and seriously hurt the evolution of trust which has been considered in the base case.

The user's perception of the rent created by the incentive when compared to an up-front discount is another element of uncertainty, given the debate in previous research.

7.2.9 Policy Framework

Although the case for Texas in general, and the Metroplex in particular, as an appropriate candidate to support the diffusion of such a disruptive technology as AV is well established, the lack of consistent and stable institutionalized rules and national policies has been long considered as one of the most prominent challenges when discussing the diffusion of AV and BEV (Ryghaug and Toftaker, 2014:146; Nykvist and Nilsson, 2015:38). Texas is not immune to it.

MLP has shown how relevant the position of local agencies is when supporting a common strategy to reduce the levels of CO_2 emissions in the Metroplex and the number of deaths caused by traffic accidents. Nevertheless, the feasibility of public agencies as diverse as those responsible for road safety and the environment aligning behind a common vision that recognizes the importance of AV to reach their goals is subject to further research and is clearly one of the threats to the feasibility of the incentive.

7.2.10 Travel Behavior

The manner in which the demand of AV for our services will react to the incentive is another topic that adds uncertainty to the result of the study and may question its results. The relationship between the perception of cost and the demand is widely researched and its relationship proven; for example, the usage of a company car and the number of miles driven. The extent to which incentivizing the use of AV in the TEXpress network will increase its usage and as a result increase the cost of the incentive is an issue for further research as it may quickly negate the benefits of the policy.

7.2.11 Carsharing

The impact of carsharing is another significant factor to be considered while evaluating how the demand may condition the results of the study (our parent company has just announced an agreement with Groupe Renault to provide a free-floating carsharing service in Paris). Although the impact of carsharing on car ownership is a very contentious topic and is far from being proven (in many of the cases where it has been empirically proven, it has affected mainly the ownership of older vehicles), should this have a significant impact, congestion in the free lanes may be reduced and with this the value of the incentive as perceived by the user. The extent to which COVID-19 will alter the willingness to ride with strangers in the same car is yet another variable which adds uncertainty to this topic.

7.2.12 The Metroplex as a Stable Socio-Technical System

The MLP analysis has shown a socio-technical system where landscape, regime, and niche would seem to be well aligned to favor the diffusion of AV. The possibility that the landscape is not able to hold this position steady for a period as long as the one considered in this study, is to be seen as one more element of uncertainty.

7.3 Research questions

At the core of any research endeavor is the need to answer research questions in a way that the scientific validity can be ensured, and the merit of the study cannot be challenged. Nevertheless, as discussed in the introduction to this study, given the very uncertain environment in which the diffusion of AV unfolds, this is meant to be an exploratory research.

With this in mind, the research questions were not predicated on the expectation to get a conclusive result but as an anchor to learn future outcomes. Although the conclusions may seem overwhelming, the study provides some interesting findings which are not meant to be the end of a journey, but a starting point to take action in new avenues of research.

1. How will incentivizing the usage of TEXpress by AV facilitate its diffusion in the Metroplex? The sensitivity of the AV fleet to the TEXpress incentive has demonstrated the efficacy of such an incentive to boost the penetration of AV in the Metroplex, increasing the market share from 2.4% in a no incentive case, to 7.4% when the full toll value is incentivized.
2. What will be the extent of diffusion? Litman (2020:24) predicts that by the 2040s AV will be available with moderate price premium and will amount to between 10% and 20% of the vehicle fleet. Our forecast predicts that by 2040 the retrofit price will be $11,000 in the base case, and the diffusion will range from 3.6% to 7.4% depending on the scenario. It is reasonable then to expect our forecast to set AV average penetration in the 2040s in the Metroplex in line with Litman's (2020:24) expectations, more when considering that the high incentive case predicts a year-to-year growth of over 22% during the last five years of the simulation.
3. What will the net balance be for the public good? Increasing road safety and improving our environmental conditions seem to be powerful arguments for lawmakers to support the diffusion of AV. In all cases there is a high likelihood that the balance of the incentive is positive (even in a no incentive scenario) or that at least a revenue neutral balance may be achieved.
4. What are the actionable implications for the organization resulting from the research? Although the model offers a positive net balance for the public good under all the considered scenarios, the uncertainties identified have proven to be a source of significant misalignment within the organization. This suggests the need to act internally before approaching the external stakeholders. Some of these actions may have long-term implications (e.g., education), but others may have a more short-term effect. Among the latter, the research concluded that approaching the T&R team to consider the results in the demand modeling of the projects was the appropriate action.

7.4 Importance of the research

The contribution of this research shall be measured both in terms of the methodology applied and in terms of the systematic approach to the RQ. While there is a research stream that mixes SD with either MLP or AR for multiple purposes ranging from triangulation to information, the combination of these methods is very limited in transportation MMR research. Furthermore, as noted before, research which considers both internalities and externalities when obtaining the balance of costs and benefits to the public good is still more limited.

7.5 Implications of the research

7.5.1 For my Organization

This research may have a twofold implication on our organization. The first is a more short-term implication that considers our capacity to properly forecast the impact of AV on the demand of our projects (and therefore their value), while the second may reshape the way we operate our assets once the penetration of AV reaches a certain threshold.

Certainly, the first implication is more appealing for our organization than the second. Quoting one of the participants of the LS, "I think our company would only change if you could prove that T&R could be more aggressive". While this research has demonstrated the convenience for the public good (and for us as developers) to incentivize AV to use TEXpress, it would be worthwhile to be able to demonstrate that in the absence of such an incentive, TEXpress would be able to increase its demand as a result of an increase in the diffusion of AV.

From an operational standpoint, one may argue that an increasing number of AV in the Metroplex will also underline the need to homogenize the level of service provided by the multiple jurisdictions operating locally, including a wide range of public agencies (19 counties, TxDOT, and NTTA among them) and private operators. They may be forced to change the way they operate to enhance the consistency of the services provided across the whole network, including pavement marking and vertical signaling, EMS services, traffic lights, management of work zones, accidents, etc. In particular, it will signal the need to be interoperable, ensuring the cybersecurity of the communications across wide areas operated by different operators, and eventually the need to share services between them.

The need to ensure the road safety of all drivers (AV and non-AV) by developing orchestrated and connected corridors as well as an immediate focus on physical improvements, increasing sensorization, and 5G / V2X connectivity in the corridor will also increase the likelihood of having significant organizational changes.

As one of the LS participants noted, "I think the concessionaire's responsibility for road safety will change". Grantors might demand more concessionaires to better serve AV, requiring the ability to meet tougher key performance indicators and higher flow. This will increase the level of service and the cost incurrent by the concessionaire while eventually increasing the capacity.

Building on these ideas, the LS questioned whether "the true value of infrastructure is the infrastructure itself or being the master information processor" and concluded that these may reshape our organization by significantly limiting the scope and autonomy of our operations, encouraging collaboration with other road operators, and opening the door for new business opportunities.

The research has also shown that these changes may not be required in the short term, as the diffusion of AV will not take off until after 2030. The urgency and need to prepare our organization to face the challenges posed by AV will certainly be one of the key internal topics in furthering this project.

7.5.2 For my Management Practice

My management practice is essentially focused on technology and operations, so the implications of the research in terms of the traffic demand is not of import.

Concerning the former, while the LS was aligned around viewing the quantitative results of the research as conclusive, they acknowledged a level of uncertainty and suggested keeping the action internal to our organization before reaching out to our external partners. As a practitioner, this is a double-edged conclusion. On the one hand, it confirms the need to expand the resources that our organization is devoting to R&D in the realm of AV, but on the other, it reduces the pressure to take decisions, given the uncertainty and the long time before the diffusion of AV would take off. These two opposite (and unexpected) consequences will condition the actionability of the next steps and my capacity to influence the organization.

On a different note, the research reveals the importance of using modeling (and SD in particular) as a technique to frame, understand, and discuss complex issues and problems and AR as a process of inquiry when acting. Both methods are currently being introduced to my team as part of our practices.

8 Conclusion

The ubiquitous presence of AV on our roads will create both positive and negative externalities in terms of road safety, environment, employment, and even the way we live and mobilize (e.g., urban sprawl). Given the important consequences that this process may have for private developers of infrastructure, including our capability to predict demand or the organizational changes it may cause, improving the understanding of the transition path is seen as a competitive advantage for our organization.

Localized in the socio-technical environment of the Metroplex, this research highlights that it is in the convenience of the public good to accelerate this trend by discounting the toll fees for AV in the TEXpresss road network while also interrogating the actions and organizational impact our organization may have to face.

The research stems from two core tenets: one which posits AV level 4 as the vector to drive the diffusion of AV and the other which takes the transition to BEV as a reference.

Regarding the former, the private use of AV level 4 in ODD zones such as the TEXpress network our company operates (in opposition those that consider fleets of level 5 robotaxis powered by hybrid powertrains as initial vectors for AV diffusion) is supported by the literature review. As I wrap up this study, Volvo has just presented the 2022 models of their successful BEV offering (Polestar 3 and XC40 Recharge) including an AV level 4 option. This is an encouraging sign, as it confirms several of my assumptions including AV powered by electrical powertrains, intensive cost reductions in the short term, and the significance of level 4.

BEV have been in the market for the last couple of decades, and the need and appropriateness of incentivizing its diffusion is the subject of a lively debate amongst policymakers. The barriers to its massive deployment are similar to those faced by AV, and together with the robust research stream on this topic, it makes an excellent case for reference. However, research that takes a holistic approach to the diffusion process is limited, as most of the studies focus on one or several of its causes or consequences. The need for a systematic approach to this topic, including a well-to-wheel analysis of all the externalities created, is an idea that has emerged again and again in this research. In this regard, the inclusion of road safety and environment into the balance of positive externalities produced by an AV incentive is one of the novel contributions of the present research.

The research provides evidence that when a systematic approach is considered, incentivizing the diffusion of AV in the Metroplex by offering a free ride on TEXpress increases the penetration of AV and results in a positive balance for the public good. Nevertheless, the incentive by itself does not materially change the rate of diffusion since it increases mildly during the twenties, not growing significantly until well into the 2030s in all scenarios. This supports the transition path suggested by the MLP analysis that, given the conditions of the socio-technical system, the two technological transitions (from ICE to BEV and to AV) may be chained within a single and continuous transition path.

Having said that, the study acknowledges its broad limitations. They result not only from the many uncertainties that influence how the transition process will unfold but also from the limited number of externalities modeled. This led the LS to conclude that although the quantitative result offered by the model may appear to be compelling to the policymakers, an internal action within our own organization needs to take precedence in order to explore the identified avenues for research and the changes that this process will cause to our organization.

An important part of the contribution of this study is undoubtedly owing to the innovative nature of the approach taken for the research methodology, which follows an MMR approach in which MLP, SD, and AR are used not only for their own merits but also (and mainly) due to the value shown when mixed together.

This is represented by MLP not being used to shape the quantitative model in terms of its boundaries, soft variables, and retrofitting loops but to facilitate the qualitative evaluation of the results of the model, providing a structured analysis of the local socio-technical system in which the transition takes place. Furthermore, the study does not limit the role of AR to introducing participative action and critical reflection, but it also reflects on how AR could be used to support and facilitate the escalation of the change to the whole organization, should the stakeholders decide to pursue the actionable knowledge discussed here.

It is common knowledge that academic rigor depends on the extent to which the findings can be generalized. In this case, such generalization is hostage to two antagonistic forces. One which posits the global nature of the automotive industry and another which highlights the influence of the local circumstances in terms of incentives, public policies, electric generation and recharging, etc. It is fair to admit that using MLP and AR has revealed the complexity in localizing transitions that happen at a global scale to a socio-technical system, even one as big as the Metroplex.

Appendix 1: References

Abbas, K., Bell, M.G.H. (1994) "System Dynamics Applicability to Transportation Modelling" Transportation Research Vol. 28A, No. 5, pp. 373-400 Elsevier Science Ltd.

Akkermans, H., Bertrand, W. (1997) "On the usability of quantitative modelling in operations strategy decision making" International Journal of Operations & Production Management, Vol. 17 No. 10, 1997, pp. 953-966.

Albin, S. (1997) " Building a System Dynamics Model Part 1: Conceptualization" MIT System Dynamics in Education Project. D-4597.

Alessandrini, A., Campagna, A., Delle Site, P., Filippi, F. Persia, L. (2015) "Automated Vehicles and the Rethinking of Mobility and Cities" Transportation Research Procedia 5 (2015) pp. 145 – 160.

Alternative Fuels Data Center (2019) "Emissions from Hybrid and Plug-in Electrical Vehicles" Department of Energy. Downloaded from https://afdc.energy.gov/vehicles/electric_emissions.html on April 21, 2019

Anderson, L., Thorpe, R. (2004) "New perspectives on action learning: developing criticality" Journal of European Industrial Training Vol. 28 No. 8/9, 2004 pp. 657-668.

Arbib, J., Seba, T. (2017) "Rethinking Transportation 2020-2030: The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries" A RethinkX Sector Disruption Report. May 2017.

Argyris, C., & Schon, D. (1978). Organizational learning: A theory of action perspective. Reading, MA: Addison-Wesley.

Autoalliance (2019) "State Facts: Autos Drive texas Forward" Downloaded on February 10, 2019 from https://autoalliance.org/in-your-state/TX/.

Bale, C. (2017) "Participatory modelling: A review of applications in energy whole-systems modelling to support decision making" School of Chemical and Process Engineering and School of Earth and Environment, University of Leeds, Leeds, LS2 9JT Bale (2017) 28.

Bansal, P., Kockelman, K. (2017) "Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies" Transportation Research Part A 95 (2017) pp. 49–63.

Bansal, P., Kockelman, K. (2018) ”Are we ready to embrace connected and self-driving vehicles? A case study of Texans” Transportation (2018) 45:641–675 https://doi.org/10.1007/s11116-016-9745-z.

Barabba, V., Huber, C., Cooke, F., Pudar, N. Smith, J., Paich, M. (2002) “A Multimethod Approach for Creating New-Business Models: The General Motors OnStar Project” INTERFACES, © 2002 INFORMS Vol. 32, No. 1, January-February 2002, pp. 20-34.

Baum, F., MacDougall, C., Smith, D. (2006) “Participatory action research” J Epidemiol Community Health 2006; 60 pp. 854–857. doi: 10.1136/jech.2004.028662.

Bento, A., Kaffine, D. Roth, K. Zaragoza-Watkins, M. (2014) “The Effects of Regulation in the Presence of Multiple Unpriced Externalities: Evidence from the Transportation Sector” American Economic Journal, Economic Policy Vol 6, No 13, August 2014.

Berkeley, N., Bailey, D. Jones, A. Jarvis, D. (2017) “Assessing the transition towards Battery Electric Vehicles: A Multi-Level Perspective on drivers of, and barriers to, take up” Transportation Research ARt A 106 (2017) pp. 320–332.

Berkhout, F., Smith, A. Stirling, A. (2003) “Socio-Technical regimes and transition contexts” The Freeman Centre University of Sussex. Science and Technology Policy Research Paper No 106.

Biondi, E., Boldrini, C., Bruno, R. (2016) “The Impact of Regulated Electric Fleets on the Power Grid: the Car Sharing Case” 2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI).

Blincoe, L. J., Miller, T. R., Zaloshnja, E., Lawrence, B. A. (2015) “The economic and societal impact of motor vehicle crashes” 2010 (Revised) Report No. DOT HS 812 013. Washington, DC: National Highway Traffic Safety Administration.

Blok, A., Sharpanskykh, A., Vert, M. (2018) “Formal and computational modeling of anticipation mechanisms of resilience in the complex sociotechnical air transport system” Blok *et al. Complex Adapt Syst Model (2018) 6:7* https://doi.org/10.1186/s40294-018-0058-2.

Borshchev, A., Filippov, A. (2004) “From System Dynamics and discrete Event to Practical Agent Based Modelling: Reasons, Techniques, Tools” XJ Technologies and St. Petersburg Technical University.

Breetz, H. L., Salon, D. (2018). "Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 U.S. cities," Energy Policy, Elsevier, vol. 120(C), pages 238-249.

Carley, S., Siddiki, S., Nicholson-Crotty, S. (2019) “Evolution of plug-in electric vehicle demand: Assessing consumer perceptions and intent to purchase over time” *Transportation Research ARt D 70 (2019) pp. 94–111.*

Caulfield, C.W., Maj, S.P. (2001) “A Case for System Thinking and System Dynamics” Proceedings of 2001 IEEE International Conference on Systems, Man and Cybernetics. (pp. 2793-2798). Tucson, USA. IEEE.

Chen, Z., He, F., Zhang, L., Yin, Y. (2016) “Optimal deployment of autonomous vehicle lanes with endogenous market penetration” Transportation Research Part C 72 (2016) pp. 143–156.

Chong, F. (2017) “Australia Infrastructure: Deep domestic pockets” IPE Real Assets. January/February 2017 issue.

Coghlan, D., Brannick, T. (2014) “Doing Action Research in your Own Organization” 4th Edition SAGE Publications Ltd.

Coghlan, D., Pedler, M. (2006) “Action learning dissertations: structure, supervision and examination”, Action Learning: Research and Practice, 3:2, pp. 127-139.

Cordill, A. (2012) “Development of a Diffusion Model to study the Greater PEV Market” A Thesis Presented to The Graduate Faculty of The University of Akron.

Coyle, G. (2000) “Qualitative and quantitative modelling in system dynamics: some research questions” System Dynamics Review Vol. 16, No. 3, (Fall 2000) pp. 225–244.

CPB (2018) “Safer Roads with Automated Vehicles?” International Transport Forum. Corporate Partnership Board Report.

Ding, Z., Gong, W., Shenghan, L., Wu, Z. (2018) “System Dynamics versus Agent-Based Modeling: A Review of Complexity Simulation in Construction Waste Management” Sustainability 2018, 10, 2484.

EIA (2019) “Light-Duty Vehicle Stock by Technology Type” Downloaded from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=49-AEO2019&region=0-0&cases=ref2019&start=2017&end=2050&f=A&linechart=ref2019-d111618a.4-49-AEO2019&map=&sourcekey=0 on May 10, 2020

Eker, S., Zimmermann, N., Carnohan, S., Davies, M. (2017) “Participatory system dynamics modelling for housing, energy and wellbeing interactions” Building Research and information.

ETSC (2016) "Prioritizing the Safety Potential of Automated Driving in Europe" European Transport Safety Council. April 2016.

EVNT (2020) "EVNT Data and Fact Sheets" Downloaded from https://www.dfwcleancities.org/evnt*) on May 10, 2020.*

Fagnant, D.J., Kockelman, K. (2015) "Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations" Transportation Research Part A 77 (2015) pp. 167–181.

Favarò F.M., Nader N., Eurich S.O., Tripp M, Varadaraju N. (2017) "Examining accident reports involving autonomous vehicles in California". PLoS ONE 12(9): e0184952 https://doi.org/10.1371/journal.pone.0184952.

Figenbaum, E. (2017) "Perspectives on Norway's supercharged electric vehicle policy" Environmental Innovation and Societal Transitions 25 (2017) pp. 14–34.

Flood, R.L. (2000) "The relationship of Systems Thinking to Action Research" *Handbook of Action Research*, pp. 133-144, edited by Hilary Bradbury and Peter Reason (Sage, London, 2000).

Forrester, J. W. (1961) "Industrial Dynamics" MIT Press 1961-12, 1961

Fraedrich, E., Beiker, S., Lenz, B. (2015) "Transition pathways to fully automated driving and its implications for the sociotechnical system of automobility" Eur J Futures Res (2015) 3: 11 DOI 10.1007/s40309-015-0067-8.

Frost and Sullivan (2017) "R&D on Autonomous, Connected, and Electrification Technologies Creates Double-digit Growth Opportunities" downloaded from https://ww2.frost.com/category/news/press-releases/automotive-transportation/ on Sept 18, 2017.

Gawron, J.H. Keoleian, G.A., De Kleine, R.D., Wallington, T.J. Kim, H.C. (2018) "Life Cycle Assessment of Connected and Automated Vehicles: Sensing and Computing Subsystem and Vehicle Level Effects" Environ. Sci. Technol. 2018, 52, pp. 3249−3256.

Gayá, P., Reason, P. (2009) "Initiating Action Research: Challenges and paradoxes of opening communicative space" Volume 7 (3). Pp. 243-262

Geels, F. W. (2005) "The Dynamics of Transitions in Socio-technical Systems: A Multi-level Analysis of the Transition Pathway from Horse-drawn Carriages to Automobiles (1860–1930)" Technology Analysis & Strategic Management Vol. 17, No. 4, pp. 445–476, December 2005.

Geels, F.W. (2007) “Transformations of Large Technical Systems: A Multilevel Analysis of the Dutch Highway System (1950–2000)” Science, Technology, & Human Values Volume 32 Number 2 March 2007 pp. 123-149.

Geels, F.W., Schoot, J. (2007) “Typology of sociotechnical transition pathways” Research Policy 36 (2007) pp. 399–417.

Geels, F.W., Kemp, R., Dudley, G., Lyons, G. (2012) “Typology of sociotechnical transition pathways” Routledge studies in Sustainability Transition.

Giuffrè, T., Canale, A., Severino, A., Trubia, S. (2017) “Automated Vehicle: a Review of Road Safety Implications as Driver of Change” 27th CARSP Conference, Toronto, June 18-21, 2017

Gnann, T., Plotz, P., Kuhn A., Wietschel, M. (2015) “Modelling market diffusion of electric vehicles with real world driving data – German market and policy options” Transportation Research Part A 77 (2015) pp. 95–112.

Greene, D.L., Park, S., Liu, C. (2014) “Analyzing the transition to electric drive vehicles in the U.S.” Futures 58, pp. 34–52.

Greenwood, D. and Levin, M. (2007) “Introduction to action research”. 2nd edn. Thousand Oaks, CA: Sage.

Gruel, W., Stanford, J.M. (2016) “Assessing the Long-Term Effects of Autonomous Vehicles: a speculative approach” Transportation Research Procedia 13 (2016) pp. 18 – 29.

Haghani, A., Lee, S.Y., Byun, J.H. (2002) “A System Dynamics Approach to Land Use Transportation System Performance Modeling” Journal of Advanced Transportation, Vol. 37, No. I , pp. 1-41

Hars, A (2016) “Top misconceptions of autonomous cars and self-driving vehicles”, v1.3. Inventivio Innovation Briefs 2016-09, Nuernberg, 2016

Hayden, F.G. (2006) “ The Inadequacy of Forrester System Dynamics Computer Programs for Institutional Principles of Hierarchy, Feedback, and Openness”. JOURNAL OF ECONOMIC ISSUES Vol. XL No. 2 June 2006.

Head, B.W., Alford, J. (2015) “Wicked Problems: Implications for Public Policy and Management” Administration & Society 2015, Vol. 47(6) pp. 711–739.

Hidrue, M.K., Parsons, G.R., Kempton, W., Gardner, M.P. (2011) “Willingness to pay for electric vehicles and their attributes” Resource and Energy Economics 33 (2011) pp. 686–705.

Holland, S.P., Mansur, E.T., Muller, N.Z., Yates, A. J. (2016) “Are There Environmental Benefits from Driving Electric Vehicles? The Importance of Local Factors” American Economic Review, 106 (12) pp. 3700–3729.

Holmström , P. (2017) “Bringing System Dynamics into Action Research” THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY. Department of Technology Management and Economics. CHALMERS UNIVERSITY OF TECHNOLOGY.

Ivankova, N.V., Creswell, J.W., Stick, S.L. (2006) “Using Mixed-Methods Sequential Explanatory Design: From Theory to Practice” *Field Methods*, Vol. 18, No. 1, February 2006 pp. 3–20.

Jenn, A., Springel, K., Gopal, A.R. (2018) “Effectiveness of electric vehicle incentives in the United States” Energy Policy 119 (2018) pp. 349–356.

Kalra, N. Paddock S.M. (2016) “Driving to safety: How many miles of driving would it take to demonstrate autonomous vehicle reliability?” Transportation Research Part A 94 (2016) pp. 182–193.

Kelley Blue Book (2019) “What Is 5-Year Cost to Own?” Downloaded from https://www.kbb.com/new-cars/total-cost-of-ownership/ April 21 2019.

Kemmis, S., McTaggart, R. (2015) “Participatory Action Research Communicative Action and the Public Sphere” Chapter 10. Strategies of Qualitative Inquiry (fourth edition), Norman K. Denzin Yvonna S. Lincoln, SAGE Publications, 2015.

Kerry, C. F., Karsten, J. (2017)“Gauging investment in self-driving cars” Brookings Institution Washington DC.

Kihm, A., Trommer, S. (2014) “The new carmarket for electric vehicles and the potential for fuel substitution” Energy Policy 73, pp. 147-157

Köhler, J. Geels, F., Kern, F., Onsongo, E., Wieczorek, A. (2017) “STRN A research agenda for the Sustainability Transitions Research Network” Sustainability Transitions Research Network (STRN) December 2017.

Kopainsky, B., Luna-Reyes, L.F. (2008) "Closing the Loop: Promoting Synergies with Other Theory Building Approaches to Improve System Dynamics Practice" Systems Research and Behavioral Science 25, pp. 471-486 (2008).

KPMG (2012) "Self-driving cars: The next revolution" KPMG Car Group, Center for Automotive Research .

Lachman, D.A. (2013) "A survey and review of approaches to study transitions" Energy Policy 58 (2013) pp. 269–276.

Lake, D.L. (2014) "Jane Addams and Wicked Problems: Putting the Pragmatic Method to Use" Faculty Peer Reviewed Articles. 5. http://scholarworks.gvsu.edu/lib_articles/5.

Lavasani , M., Jin, X. (2016) "Market Penetration Model for Autonomous Vehicles on the Basis of Earlier technology Adoiption experience" Transportation Research Record Journal of the Transportation Research Board January 2016.

Litman, T.A. (2020) "Autonomous Vehicle Implementation Predictions. Implications for Transport Planning" Victoria Transport Policy Institute.

Litman, T.A. (2021) "Autonomous Vehicle Implementation Predictions. Implications for Transport Planning" Victoria Transport Policy Institute.

Liu, J., Kockelman, K.M., Boesch, P.M., Ciari, F. (2017) "Tracking a system of shared autonomous vehicles across the Austin, Texas network using agent-based simulation" Transportation (2017) 44 pp. 1261–1278.

Longo, M., Maffezzoni, P., Zanielli, D., Lutz, N.M., Daniel, L. (2017) "A Predictive Model to Support the Widespread Diffussion of Electric Mobility" 978-1-5090-6484-7/17 2017 IEEE pp. 327-332.

Mao, C., Zou, M., Liu, Y., Xue, W., Li, M. (2015) "Comparison of Agent-Based Modeling and Equation-Based Modeling for Transportation Behavioral Studies" 15th COTA International Conference of Transportation Professionals (CICTP 2015).

Markard, J., Raven, R., Truffer, B. (2012) "Sustainability transitions: An emerging field of research and its prospects" Research Policy 41 (2012) pp. 955–967.

Markard, J., Truffer, B. (2008) "Technological innovation systems and the multi-level perspective: Towards an integrated framework" Research Policy 37 (2008) pp. 596–615.

Marshall, J. and Reason, P. (2007) “Quality in research as “taking an attitude of inquiry”. Management Research News. 30 (5): PP. 368-380.

Massiani, J. (2013) “The use of Stated Preferences to forecast alternative fuel vehicles market diffusion: Comparisons with other methods and proposal for a Synthetic Utility Function” Working Papers Department of Economics. Università Cà Foscari No 12/WP/2013.

Massiani, J., Gohs, A. (2015) ”The choice of Bass model coefficients to forecast diffusion for innovative products: An empirical investigation for new automotive technologies” Research in Transportation Economics 50 (2015) pp. 17-28.

Mazur,C. (2015) “ Assessing Transition Policies for the Diffusion of Electric Vehicles” Submitted in Part fulfilment of the requirements for the degree of Doctor of Philosophy in System Innovation and Sustainability of Imperial College London, February 2015.

McDowall, W. (2014) “Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling” Futures 63 (2014) pp. 1–14.

McGee, P. (2020) “Self-driving industry takes to the highway after robotaxi failure” Financial Times July 19, 2020.

Michalek, J.J., Chester, M. Jaramillo, P. Samaras, C. Shiau, C.N., Lave, L.V. (2011) “Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits” Proceedings of the National Academy of Sciences of the United States of America, October 4, 2011 vol. 108 no. 40 pp. 16554–16558.

MIT Energy Initiative (2019) “Insights into Future Mobility” Cambridge , MA: MIT Energy Initiative.

Mitropoulos, L. K., Prevedouros, P. D., Kopelias, P. (2017) “Total cost of ownership and externalities of conventional, hybrid and electric vehicle” Transportation Research Procedia 24 pp. 267–274.

Mok, B., Johns, M., Lee, K.J., Miller, D., Sirkin, D. Ive, P. Ju, W. (2015) “Emergency, Automation Off: Unstructured Transition Timing for Distracted Drivers of Automated Vehicles” 2015 IEEE 18th International Conference on Intelligent Transportation Systems.

Moradi, A., Vagnoni, E. (2018) “A multi-level perspective analysis of urban mobility system dynamics: What are the future transition pathways? Technological Forecasting & Social Change 126 (2018) pp. 231–243.

Mustafee, N., Brailsford, S., Djanatliev, A., Eldabi, T., Kunc, M., Tolk, A. (2017) "Purpose and Benefits of Hybrid Simulation: Contributing to the Cobergence of ITS definition" Proceedings of the 2017 Winter Simulation Conference.

NATURVÅRDS VERKET (2019) "Environmental objectives in the mountain landscape" Report 6366.

NCHRP (2017) "Strategies to Advance Automated and Connected Vehicles" Briefing document of the Transportation Agencies National Cooperative Highway Research Program Research Report 845: Advancing Automated and Connected Vehicles: Policy and Planning Strategies for State and Local Transportation Agencies.

NHTSA (2017) "NPRM Federal Motor Vehicle Safety Standards; V2V Communications" DEPARTMENT OF TRANSPORTATION National Highway Traffic Safety Administration 49 CFR Part 571 [Docket No. NHTSA-2016-0126] RIN 2127-AL55.

NHTSA (2018) "2017 Fatal Motor Vehicle Crashes: Overview" Traffic Safety Facts Research note. DEPARTMENT OF TRANSPORTATION National Highway Traffic Safety Administration. October 2018.

NHTSA (2020) "Automated vehicles for Safety" DEPARTMENT OF TRANSPORTATION National Highway Traffic Safety Administration, 2020

Nieuwenhuijsen, J., Correia, G.H.A., Milakis, D. van Arem, B., van Daalen, E. (2018) "Towards a quantitative method to analyze the long-term innovation diffusion of automated vehicles technology using system dynamics" Transportation Research Part C 86 (2018) pp. 300–327.

Noto, G. (2017) "Combining System Dynamics and performance management to support sustainable urban transportation planning" Journal of Urban and Regional Analysis", vol. IX, 1, 2017, pp. 51 - 71

NRC (2013) "Transitions to Alternative Vehicles and Fuels" National Research Council of the National Academies. The National Academies Press.

Nykvist, B., Nilsson, M. (2015) "The EV Paradox – A multilevel study of why Stockholm is not a leader in electric vehicles" Environmental Innovation and Societal Transitions 14 (2015) pp. 26–44.

Nzembayie, K. (2017) "Using Insider Action Research in the Study of Digital Entrepreneurial Processes: A Pragmatic Design Choice" *The Electronic Journal of Business Research Methods Volume 15 Issue 2 2017*, pp. 85-98 available online at www.ejbrm.com.

Oughton, E., Tyler, P. (2013) “Infrastructure as a complex adaptive system” Engineering and Physical Sciences Research Council. Infrastructure Transitions Research Consortium. Working paper series.

Oyo, B., Williams, D., Barendsen, E. (2009) “Integrating Action Research and System Dynamics: Towards a Generic Process Design for Participative Modelling” Proceedings of the 42nd Hawaii International Conference on System Sciences – 2009.

Papadoulis, A.,Quddus, M., Imprialou, M. (2019) “Evaluating the safety impact of connected and autonomous vehicles on motorways” Accident Analysis and Prevention 124 (2019) pp. 12–22.

Peng, M.W. (2010) “Research Streams” Mike W. Peng (Research Streams) www.mikepeng.com (October 1, 2010).

Penmetsa, P., Adanu, E.K., Wood, D., Wang, T., Jones, S.L. (2019) “Perceptions and expectations of autonomous vehicles – A snapshot of vulnerable road user opinion” Technological Forecasting & Social Change 143 (2019) pp. 9-13.

Phillips, E. (2018) “The Future of Autonomous Vehicles in American Cities”, 21 N.Y.U. J. Legis. & Pub. Pol'y 287.

Pitchbook (2020) “Investors hit the breaks on automotive start-ups” download on February 27, 2020, from https://www.wired.com/story/investors-hit-brakes-automotive-startups/.

Plötz, P., Gnann, T., Wietschel, M. (2014) “Modelling market diffusion of electric vehicles with real world driving data — Part I: Model structure and validation” Ecological Economics 107 (2014) pp. 411–421.

Propfe, B., Kreyenberg, D., Wind, J., Schmid, S. (2013) “Market penetration analysis of electric vehicles in the German passenger car market towards 2030” International Journal of Hydrogen Energy 38 (2013) pp. 5201-5208.

Rabalais, A. (2017) “Drive down to electric avenue: Taking Electric Vehicle Incentives Higher” 5 LSU J. Energy L. & Resources 427 (2017).

Radzicki, M.J., Tauheed, L. (2009) “Notes and Communications In Defense of System Dynamics: A Response to Professor Hayden” JOURNAL OF ECONOMIC ISSUES Vol. XLIII No. 4 December 2009.

Rees, D., Stephenson, J., Hopkins, D., Doering, A. (2017) “Exploring stability and change in transport systems: combining Delphi and system dynamics approaches” Transportation (2017) 44 pp.789–805.

Regan, E. (2018) "Coming Disrutive technology and Mobility Change: A new Landscape for Tolling and Project Financing" Public Works Financing June 2018, Vol 338 pp. 18-19.

Rittel, H.W.J., Webber, M.M. (1973) "Dilemmas in a general theory of planning". Policy Sci 4, pp. 155–169 (1973). https://doi.org/10.1007/BF01405730

Roth, J. (2007) "Insider action research:Facing the challenges of new capability development within a biopharma company" *Action Research* Volume 5(1): pp. 41–60 SAGE Publications.

Ryghaug, M., Toftaker, M. (2014) "A Transformative Practice? Meaning, Competence, and Material Aspects of Driving Electric Cars in Norway" *Nature and Culture* 9(2), Summer 2014: pp. 146–163 Berghahn Journals.

Schoettle, B., Sivak, M. (2015a) "A Preliminary Analysis of Real-World Crashes Involving Self-Driving Vehicles" The University of Michigan Transportation Research Institute. Report number: UMTRI-2015-34.

Schoettle, B., Sivak, M. (2015b) "Potential impact of self-riving vehicles on household vehicle demand and usage" The University of Michigan Transportation Research Institute. Report number: UMTRI-2015-3.

Seetharaman, P., Errampalli, M., Mukhopadhyay, D., Gangopadhyay, S. (2009) "Comparative Evaluation of Mode Choice Modelling by Logit and Fuzzy Logic" Proceedings of the Eastern Asia Society for Transportation Studies, Vol.7, 2009.

Sheldon, T. De Shazo, J.R. (2017) "How does the presence of HOV lanes affect plug-in electric vehicle adoption in California? A generalized propensity score approach" Journal of Environmental Economics and Management 85 (2017).

Shepherd, S., Bonsall, P., Harrison, G. (2012) "Factors affecting future demand for electric vehicles: A model based study" Transport Policy 20 (2012) pp. 62-74.

Shewmake, Jarvis, L. (2014) "Hybrid cars and HOV lanes" Transportation Research Part A 67 (2014) 304–319.

Siddiki, S., Dumortier, J., Curley, C., Graham, J.D., Carley, S., Krause, R.M. (2015) "Exploring Drivers of Innovative Technology Adoption Intention: The Case of Plug-In Vehicles" Review of Policy Research, Volume 32, Number 6 (2015).

Sperling, D. (2018) “Three Revolutions: Steering Automated, Shared, and Electrical Vehicles to a Better Future” IslandPress.

Statista (2018) “Selected Automakers’ R&D intensity worldwide as of June 2018”

Struben, J. Sterman, J.D. (2008) “Transition challenges for alternative fuel vehicle and transportation systems” Environment and Planning B: Planning and Design 2008, volume 35, pp. 1070-1097.

Tashakkori, A., & Teddlie, C. (1998). “Mixed Methodology: Combining Qualitative and Quantitative Approaches” (Vol. 46). Thousand Oaks, CA: Sage Publications.

Teose, M., Ahmadizadeh, K., Lu, Z., Ellner, S.P., O’Mahony, E, Smith, R.L., Gomes, C., Grohn, Y. (2011) “Embedding System Dynamics in Agent Based Models for Complex Adaptive Systems” Proceedings of the Twenty-Second International Joint Conference on Artificial Intelligence.

TERP (2020) ‘Texas Emissions Reduction Plan’ downloaded from https://www.tceq.texas.gov/airquality/terp on January 19, 2020

Thun, J., Größler, A., Milling, P.M. (2000) “The Diffusion of Goods Considering Network Externalities: A System Dynamics-Based Approach” 18th International Conference of the System Dynamics Society.

Townsend (2014) “Re-programming mobility: The Digital Transformation of Transportation in the United States”. Rudin Center for Transportation Policy & Management.

Turnheim, B., Berkhout, F., Geels, F.W., Hof, A., McMeekin, A., Nykvist, B., Van Vuuren, D.P. (2015) ” Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges” Global Environmental Change 35 (2015) pp. 239-253.

TxDOT (2017) “2017 District Traffic Web Viewer” Downloaded from http://txdot.maps.arcgis.com/apps/webappviewer/index.html?id=06fea0307dda42c1976194bf5a98b3a1 on January 31, 2019.

TxDOT (2019) “Innovative Transportation Projects in Texas” Downloaded from https://www.txdot.gov/inside-txdot/division/planning/innovative-projects.html on January 19, 2019.

TxETRA (2020) “About TxETRA” Downloaded from https://txetra.org/ on January 19, 2020

Ulli-Beer, S. Grösser, S., Wokaun, A., (2011) "How does the Multi-Level Perspective help to enhance a System Dynamics analysis of a specific transition challenge?" Conference Proceedings of the International System Dynamics Conference in Washington DC USA, July, 2011.

Ulli-Beer, S. (2013) "Conceptual Grounds of Socio-Technical Transitions and Governance" Dynamic Governance of Energy Technology Change, Sustainability and Innovation, DOI 10.1007/978-3-642-39753-0_2.

USDOT (2017) "USDOT AV Proving Grounds" Downloaded from www.nationalavpg.com on January 10, 2019

US Inflation Calculator (2020) "Inflation Calculator" Downloaded from *https://www.usinflationcalculator.com/ on June 20, 2019*

Van Bree, B., Verbong, G.P.J., Kramer, G.J. (2010) "A multi-level perspective on the introduction of hydrogen and battery-electric vehicles" Technological Forecasting & Social Change 77 (2010) pp. 529–540.

Voinov, A., Bousquet, F. (2010) "Modelling with stakeholders" Environmental Modelling & Software 25 (2010) pp. 1268-1281.

Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A., Ramu, P. (2016) "Modelling with stakeholders e Next generation" Environmental modelling & Software 77 (2016) pp. 196-220.

Wesseling, J.H., Farla, J.C.M., Sperling, D., Hekkert, M.P. (2014) "Car manufacturers' changing political strategies on the BEV mandate" Transportation Research Part D 33 (2014) pp. 196–209.

Whitmarsh, L. (2012) "How useful is the Multi-Level Perspective for transport and sustainability research?" Journal of Transport Geography 24 (2012) pp. 483-487.

Wisdom, J.P., Brian Chor, K.H., Hoagwood, K.E., Horwitz, S.M. (2014) "Innovation Adoption: A Review of Theories and Constructs" Adm Policy Ment Health. 2014 Jul; 41(4): 480–502.

Yearworth, M., White, L. (2015) "Soft Engineering: anticipating an increasingly messy landscape for engineering practice" Paper presented at First International Conference on Anticipation, Trento, Italy.

Yu, H., Mu, D. (2016) "Carbon Emission Research of Beijing Transportation System Based On SD" 978-1-5090-1102-5/16 (2016) IEEE.

Zhang, B. Tay, F.E.H. (2017) “An Integrated Approach using Data Mining and System Dynamics to Policy Design: Effects of Electric Vehicle Adoption on CO2 Emissions in Singapore” Springer International Publishing AG 2017, P. Perner (Ed.): ICDM 2017, LNAI 10357, pp. 258–268, 2017.

Zmud, J.P., Sener, I.N. (2017) “Towards an Understanding of the Travel Behavior Impact of Autonomous Vehicles” Transportation Research Procedia 25 (2017) pp. 2500–2519.

Appendix 2: System Dynamics Models

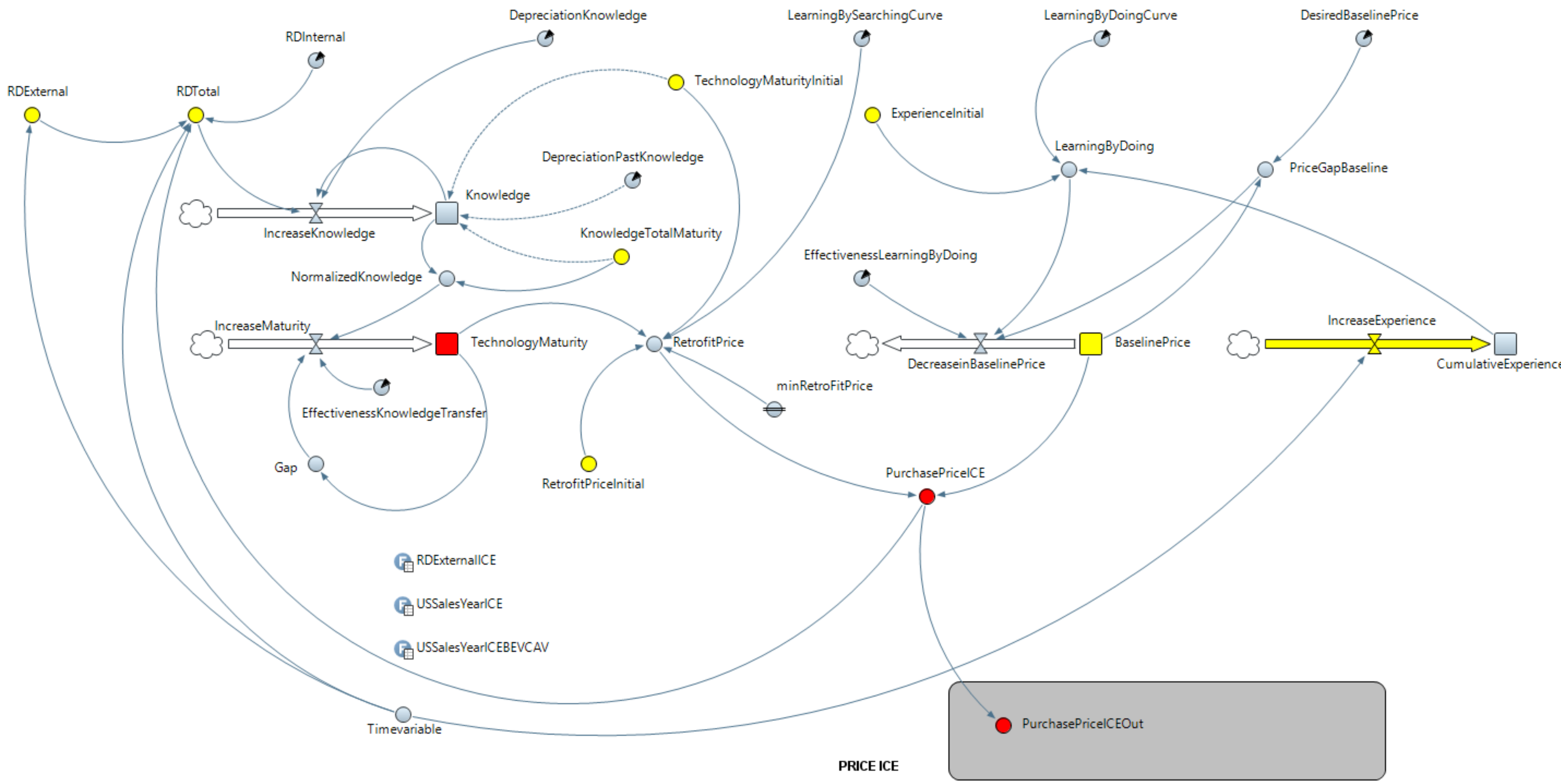


Figure 32: Submodel Price ICE (Source: Developed for this study)

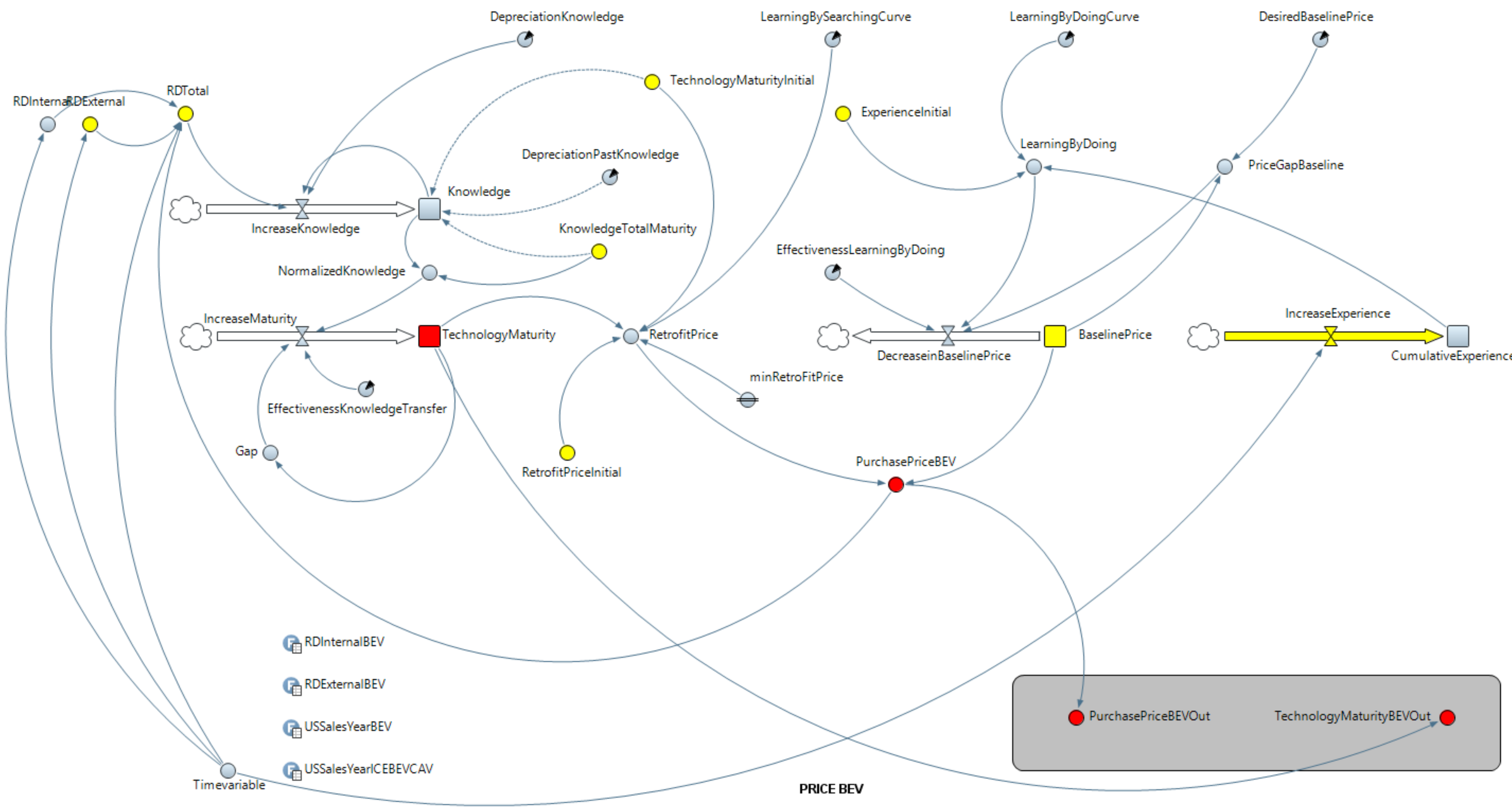


Figure 33: Submodel Price BEV (Source: Developed for this study)

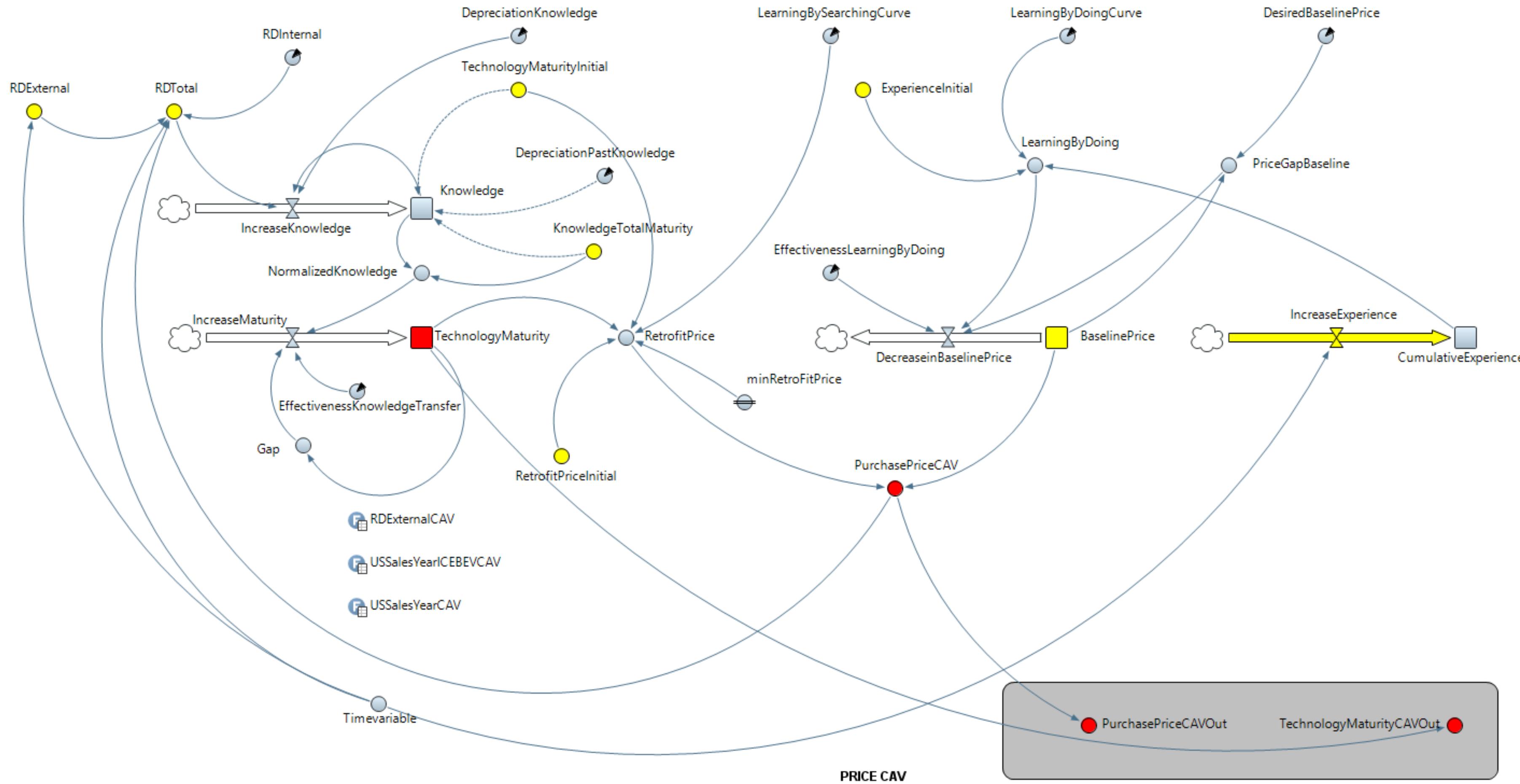
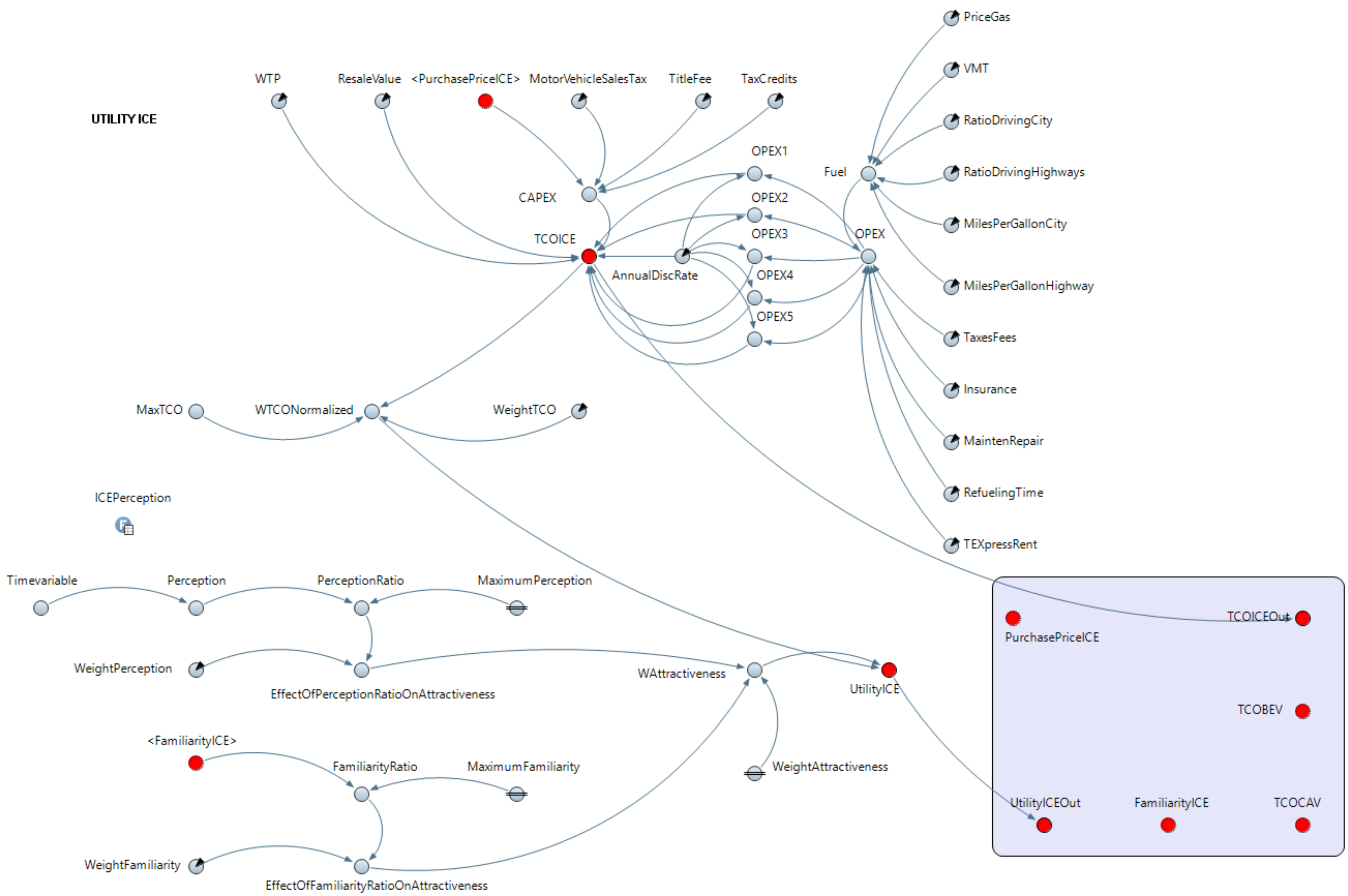
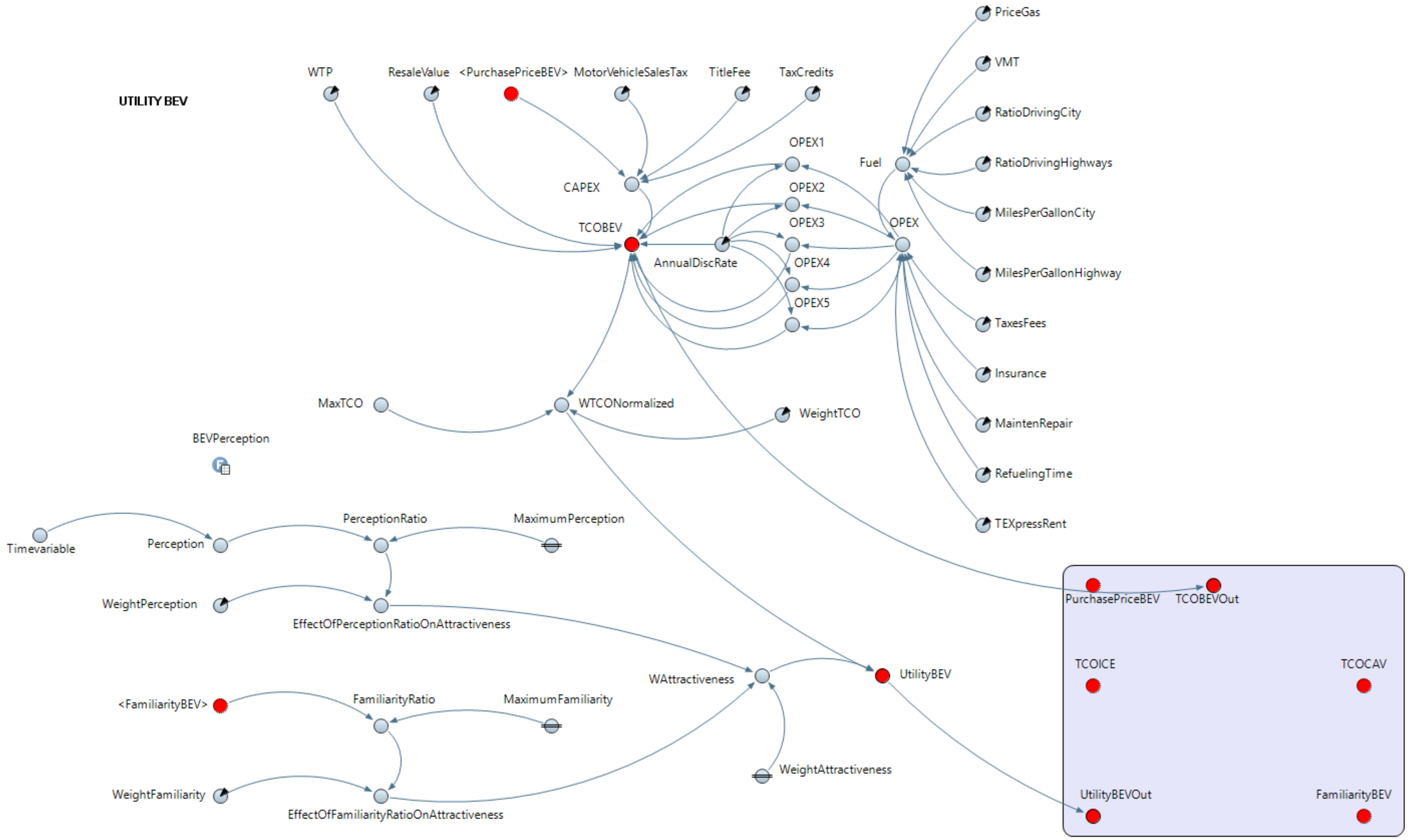


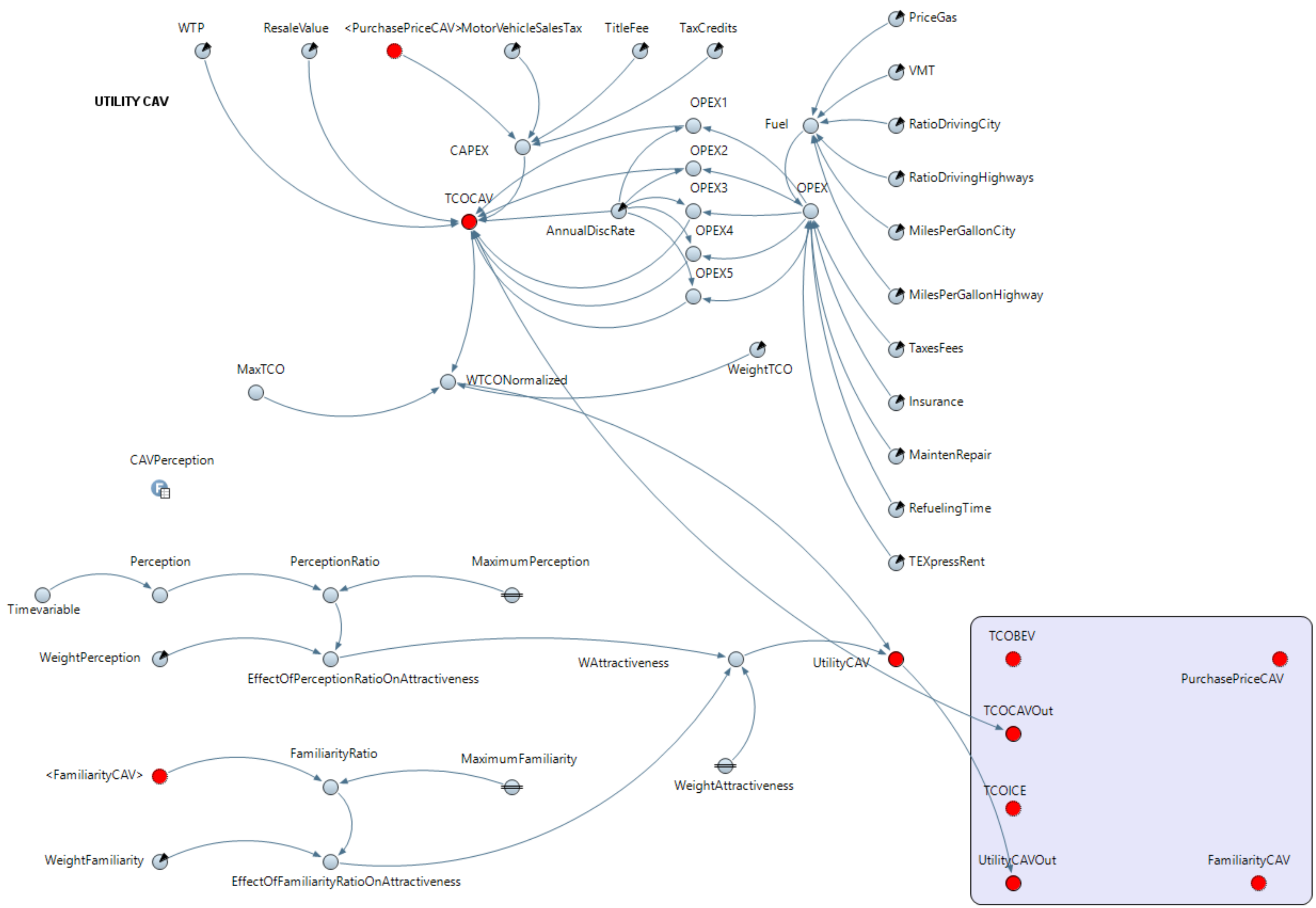
Figure 34: Submodel Price AV (Source: Developed for this study)

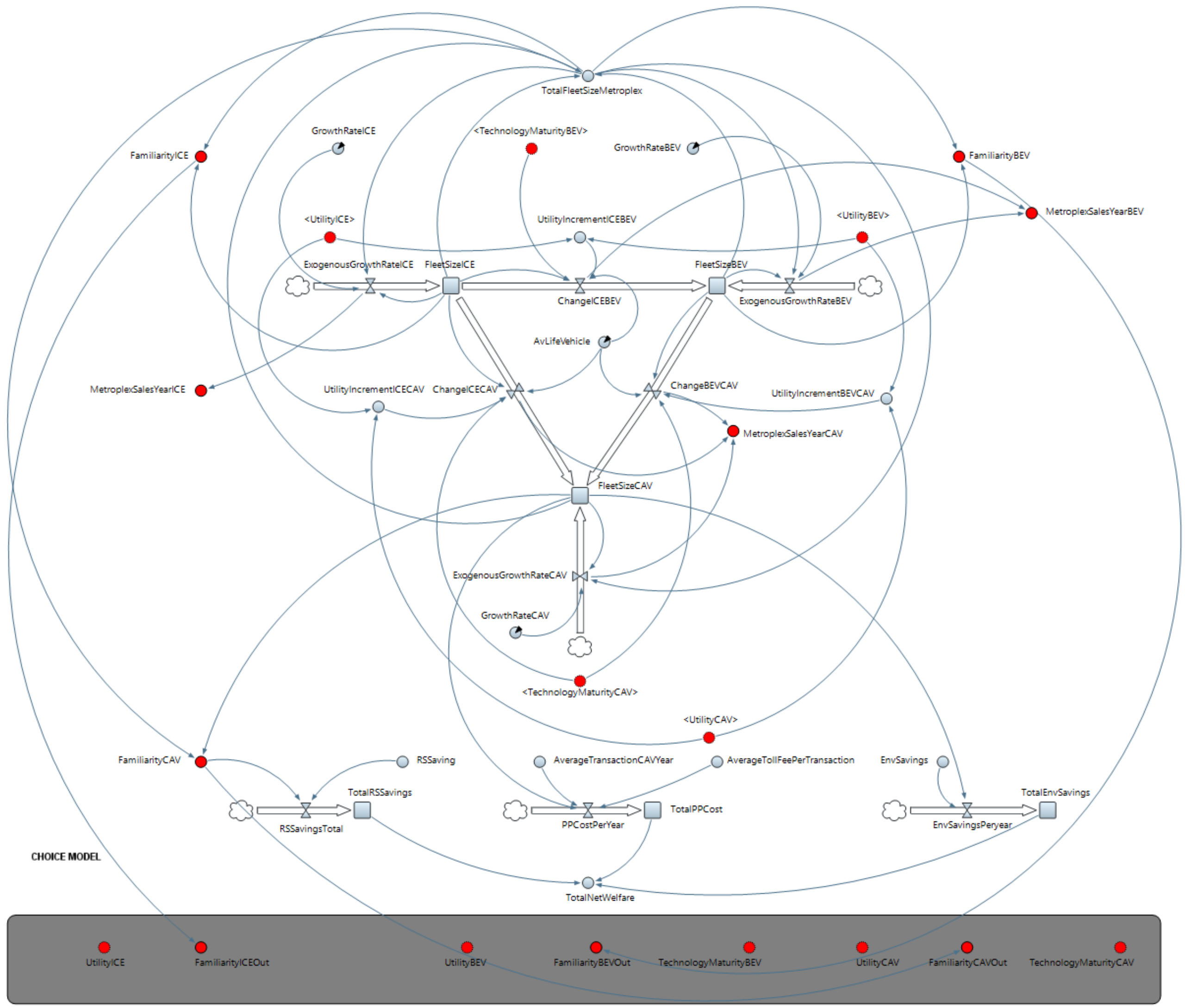
UTILITY ICE



WTP
ResaleValue
<PurchasePriceICE>
MotorVehicleSalesTax
TitleFee
TaxCredits
PriceGas
VMT
RatioDrivingCity
RatioDrivingHighways
MilesPerGallonCity
MilesPerGallonHighway
TaxesFees
Insurance
MaintenRepair
RefuelingTime
TEXpressRent
CAPEX
TCOICE
AnnualDiscRate
OPEX1
OPEX2
OPEX3
OPEX4
OPEX5
Fuel
OPEX
MaxTCO
WTCONormalized
WeightTCO
ICEPerception
Timevariable
Perception
PerceptionRatio
MaximumPerception
WeightPerception
EffectOfPerceptionRatioOnAttractiveness
WAttractiveness
UtilityICE
<FamiliarityICE>
FamiliarityRatio
MaximumFamiliarity
WeightAttractiveness
WeightFamiliarity
EffectOfFamiliarityRatioOnAttractiveness
PurchasePriceICE
TCOICEOut
TCOBEV
UtilityICEOut
FamiliarityICE
TCOCAV


UTILITY BEV
WTP
ResaleValue
<PurchasePriceBEV>
MotorVehicleSalesTax
TitleFee
TaxCredits
PriceGas
VMT
RatioDrivingCity
RatioDrivingHighways
MilesPerGallonCity
MilesPerGallonHighway
TaxesFees
Insurance
MaintenRepair
RefuelingTime
TEXpressRent
Fuel
OPEX
OPEX1
OPEX2
OPEX3
OPEX4
OPEX5
CAPEX
TCOBEV
AnnualDiscRate
MaxTCO
WTCONormalized
WeightTCO
BEVPerception
Timevariable
Perception
PerceptionRatio
MaximumPerception
WeightPerception
EffectOfPerceptionRatioOnAttractiveness
WAttractiveness
UtilityBEV
<FamiliarityBEV>
FamiliarityRatio
MaximumFamiliarity
WeightFamiliarity
EffectOfFamiliarityRatioOnAttractiveness
WeightAttractiveness
PurchasePriceBEV
TCOBEVOut
TCOICE
TCOCAV
UtilityBEVOut
FamiliarityBEV


UTILITY CAV
WTP
ResaleValue
<PurchasePriceCAV>
MotorVehicleSalesTax
TitleFee
TaxCredits
PriceGas
VMT
RatioDrivingCity
RatioDrivingHighways
MilesPerGallonCity
MilesPerGallonHighway
TaxesFees
Insurance
MaintenRepair
RefuelingTime
TEXpressRent
Fuel
OPEX1
OPEX2
OPEX3
OPEX4
OPEX5
OPEX
CAPEX
TCOCAV
AnnualDiscRate
MaxTCO
WTCONormalized
WeightTCO
CAVPerception
Perception
PerceptionRatio
MaximumPerception
Timevariable
WeightPerception
EffectOfPerceptionRatioOnAttractiveness
WAttractiveness
UtilityCAV
<FamiliarityCAV>
FamiliarityRatio
MaximumFamiliarity
WeightFamiliarity
EffectOfFamiliarityRatioOnAttractiveness
WeightAttractiveness
TCOBEV
PurchasePriceCAV
TCOCAVOut
TCOICE
UtilityCAVOut
FamiliarityCAV



TotalFleetSizeMetroplex
GrowthRateICE
<TechnologyMaturityBEV>
GrowthRateBEV
FamiliarityICE
FamiliarityBEV
MetroplexSalesYearBEV
<UtilityICE>
UtilityIncrementICEBEV
<UtilityBEV>
ExogenousGrowthRateICE
FleetSizeICE
FleetSizeBEV
ChangeICEBEV
ExogenousGrowthRateBEV
AvLifeVehicle
MetroplexSalesYearICE
UtilityIncrementICECAV
ChangeICECAV
ChangeBEVCAV
UtilityIncrementBEVCAV
MetroplexSalesYearCAV
FleetSizeCAV
ExogenousGrowthRateCAV
GrowthRateCAV
<TechnologyMaturityCAV>
<UtilityCAV>
FamiliarityCAV
RSSaving
AverageTransactionCAVYear
AverageTollFeePerTransaction
EnvSavings
TotalRSSavings
RSSavingsTotal
PPCostPerYear
TotalPPCost
TotalEnvSavings
EnvSavingsPeryear
CHOICE MODEL
TotalNetWelfare
UtilityICE
FamiliarityICEOut
UtilityBEV
FamiliarityBEVOut
TechnologyMaturityBEV
UtilityCAV
FamiliarityCAVOut
TechnologyMaturityCAV

Appendix 3: General settings

The model settings are as follows:

1. The time unit is the calendar year running from 2010 to 2040.
2. The initial volume considered for every fleet matches the Ground truth for 2010 as shown in the table below (values Dec 31). This assumes that BEV were not available until 2010, and AV Level 4 will not be commercially available to consumers until 2024, although they can be operated earlier by commercial fleets.

	2010	**2023**	**2040**
ICE	3,104,302	Model	Model
BEV	104	Model	Model
CAV	0	0	Model

3. All original dollar values have been inflated to $2019 with the ratios shown below:

Inflation Rate	2010-2019	16.60%
	2015-2019	7.30%
	2014-2019	7.40%

Appendix 4: Values of parameters in System Dynamics Models

	Stock	Units	InitialValue		
			ICE	BEV	CAV
			SAE L0	SAE L1	SAE L4
1	Knowledge	$000	N/A	N/A	N/A
2	TechnologyMaturity	Dimensionless	0.9	0.1	0.0001
3	BaselinePrice	$000/car	37	37	37
4	CumulativeExperience	car	113,602,000	113,602,000	113,602,000

	Flow	Units	Value		
5	IncreaseKnowledge	$000/time	Output	Output	Output
6	IncreaseMaturity	1/time	Output	Output	Output
7	DecreaseBaselinePrice	$000/car/time	Output	Output	Output
8	IncreaseExperience	car/time	Output	Output	Output

	Dynamic Value	Units	Value		
9	RDExternal	$000/time	Table	Table	Table
10	RDTotal	$000/time	Output	Output	Output
11	Gap	Dimensionless	Output	Output	Output
12	LearningByDoing	Dimensionless	Output	Output	Output
13	PriceGapBaseline	$000/car	Output	Output	Output
14	Purchase Price ICE BEV CAV	$000/car	Output	Output	Output
15	NormalizedKnowledge	Dimensionless	Output	Output	Output
16	KnowledgeTotalMaturity	$000	1.00E+08	2.00E+08	3.00E+08
17	KnowledgeGapBaseline	Dimensionless	Output	Output	Output
18	TechnologyMaturityInitial	Dimensionless	0.9	0.2	0.01
19	ExperienceInitial	car	113,602,000	113,602,000	113,602,000
20	RetrofitPrice	$000/car	Output	Output	Output
21	RetrofitPriceInitial	$000/car	0	10	30
22	minRetrofitPrice	$000/car	0	5	10

	Dynamic Value	Units	Value		
23	RDInternal	Dimensionless	0.057	Table	0.057
24	DepreciationPastKnowledge	Dimensionless	0.5	0.5	0.5
25	DepreciationKnowledge	1/time	0.05	0.05	0.05
26	LearningBySearchingCurve (log scale)	Dimensionless	10	10	10
27	LearningBySearchingCurve (effect increase maturity)	Dimensionless	0.4	0.4	0.4
28	LearningByDoingCurve (log scale)	Dimensionless	2	2	2
29	LearningByDoingCurve (effect increase experience)	Dimensionless	0.05	0.05	0.05
30	DesiredBaselinePrice	$000/car	30	30	30
31	EffectivenessLearningByDoing	1/time	0.2	0.2	0.2
32	EffectivenessKnowledgeTransfer	Dimensionless	0.75	0.75	0.75

	Table	Units	Value		
33	RDInternalBEV	Dimensionless			
34	RDExternal ICE BEV CAV	$000/time			
35	USSalesYear ICE BEV CAV	car/time			

Variable/Parameter/Table		Units	Value		
			ICE	**BEV**	**CAV**
			SAE L0	**SAE L1**	**SAE L4**
1	TEXpressRent	$000/car	0.0	0.0	0.36
2	WTP	$000/car	0.00	7.50	7.50
3	Resalevalue	$000/car	7.60	15.36	15.36
4	Purchaseprice	$000/car	Input	Input	Input
5	MotorVehicleSalesTax	Dimensionless	6.25%	6.25%	6.25%
6	TitleFee	$000/car	0.033	0.033	0.033
7	TaxCredits	$000/car	0	0	7,500
8	PriceGas	$000/Gallon	0.00222	N/A	N/A
9	VMT	Miles / car	15.6	N/A	N/A
10	RatioDrivingCity	Dimensionless	0.49	N/A	N/A
11	RatioDrivingHighways	Dimensionless	0.51	N/A	N/A
12	MilesPerGalonCity	Miles / Gallon	26	N/A	N/A
13	MilesPerGalonHighway	Miles / Gallon	34	N/A	N/A
14	TaxesFees	$000/car	0.104	0.104	0.104
15	Insurance	$000/car	1.291	1.291	1.291
16	MaintenRepair	$000/car	0.808	0.808	0.808
17	RefuelingTime	$000/car	0.140	N/A	N/A
18	Fuel	$000/car	Output	Output	Output
19	OPEX	$000/car	Output	Output	Output
20	CAPEX	$000/car	Output	Output	Output
21	DiscountRate	Dimensionless	7.00%	7.00%	7.00%
22	MaxTCO	$000/car	64	64	64
23	WeightTCO	Dimensionless	0.50	0.50	0.50
24	WTCONormalized	$000/car	Output	Output	Output
25	WeightAttrativeness	Dimensionless	0.50	0.50	0.50
26	Perception	Dimensionless	0.01	0.20	0.70
27	PerceptionRatio	Dimensionless	Output	Output	Output
28	MaximumPerception	Dimensionless	1.00	1.00	1.00
29	WeightPerception	Dimensionless	0.20	0.20	0.20
30	EffectOfPerceptionRatioOnAttractivenes	Dimensionless	Output	Output	Output
31	Familiarity	Dimensionless	N/A	N/A	N/A
32	FamiliarityRatio	Dimensionless	Output	Output	Output
33	MaximumFamiliarity	Dimensionless	1.00	1.00	1.00
34	WeightFamiliarity	Dimensionless	0.20	0.20	0.20
35	EffectOfFamiliarityRatioOnAttractivenes	Dimensionless	Output	Output	Output
36	Utility	Dimensionless	Output	Output	Output
37	XXXPerception		Table	Table	Table

	Stock	Units	InitialValue		
			ICE	BEV	CAV
			SAE L0	SAE L1	SAE L4
1	FleetSizeICE	car	3,104,406		
2	FleetSizeBEV	car		0.08	
3	FleetSizeCAV	car			0
4	TotalRSSavings	$000	0	0	0
5	TotalPPCost	$000	0	0	0
6	TotalEnvSavings	$000	0	0	0

	Flow	Units	Value		
			ICE	BEV	CAV
			SAE L0	SAE L1	SAE L4
8	ExogenousGrowthRateICE	car/time	Output	Output	Output
9	ChangeICEBEV	car/time	Output	Output	Output
10	ExogenousGrowthRateBEV	car/time	Output	Output	Output
11	ChangeICECAV	car/time	Output	Output	Output
12	ExogenousGrowthRateCAV	car/time	Output	Output	Output
13	ChangeBEVCAV	car/time	Output	Output	Output
14	RSSavingsPeryear	$000/time	Output	Output	Output
15	PPCostPeryear	$000/time	Output	Output	Output
16	EnvSavingsPeryear	$000/time	Output	Output	Output

	Variable	Units	Value		
			ICE	BEV	CAV
			SAE L0	SAE L1	SAE L4
17	TotalFleetSize	car	Output	Output	Output
18	UtilityCAV	Dimensionless	Input	Input	Input
19	UtilityBEV	Dimensionless	Input	Input	Input
20	UtilityICE	Dimensionless	Input	Input	Input
21	FamiliarityICE	Dimensionless	Output	Output	Output
22	FamiliarityBEV	Dimensionless	Output	Output	Output
23	FamiliarityCAV	Dimensionless	Output	Output	Output
24	TechnologyMaturityCAV	Dimensionless	Input	Input	Input
25	TechnologyMaturityBEV	Dimensionless	Input	Input	Input
26	TotalNetWelfare	$000	N/A	N/A	0

	Parameter	Units	Value		
			ICE	BEV	CAV
			SAE L0	SAE L1	SAE L4
27	GrowthRate	1/time	1.4%	1.4%	1.4%
28	AverageLifetimeVehicle	time	10.4	10.4	10.4