Are robotaxis worth it ? On-demand Autonomous Vehicle Mobility Services in heterogeneous Territories : A Cost Benefit Analysis

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Dedication

Je me permets de changer de langue pour cette partie. L'anglais est la langue technique de ce manuscrit mais la gratitude que je ressens doit s'exprimer dans ma langue maternelle.

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Abstract

The 2010s has seen a spectacular interest for autonomous vehicles (AV). The new market opened by the promises of improved safety and comfort pushed car makers and newcomers, such as tech companies, to invest in the development of autonomous vehicles. The scientific literature has also taken interest in the topic and produced analysis to investigate the expected impact of this emerging mode of transportation. These works have mostly focused on the operational ability of on-demand autonomous vehicles services to replace services which are actually operated by conventional car, including the private use of the car. This thesis aims to provide an economic evaluation of on-demand autonomous vehicles services in different territories to complete the existing scientific literature.

This thesis aims to answer the following research questions: What are the performances of AV-based services by considering the perspectives of the main stakeholders (i.e., users, operators and public authorities)? Are there more relevant AV-based services than others? Which is the most suitable operating model of AV-based services to deploy in each type of territory (i.e., urban, peri-urban and rural)?

First, a bibliometric analysis and a meta-analysis is carried out to understand the focus of the literature and its main results. Then, a cost-benefit analysis framework suited to the evaluation of autonomous vehicles services is developed. The methodology is applied to three case studies, in Berlin (urban setting), the Communauté d'agglomération de Paris-Saclay (periurban setting) and Dourdan (a rural territory south of Paris). Each time, the MATSim agent-based mobility model is used to forecast the expected use of the AV services considered, and provide the necessary inputs for the cost-benefit analysis.

The contributions of this thesis are both methodological and empirical. The methodological contribution lies in the development of a CBA framework and a parametrical set of reference values for autonomous vehicle services. Regarding the empirical contribution, the meta-analysis shows that on-demand AV services would increase travel distances in most cases, but could allow to cut down the required fleet size by half. Our case studies corroborate and extend these results with a more comprehensive evaluation. In the Berlin case study, introducing AVs would lead to an increase in congestion, leading to a decrease in the consumer surplus and a negative net present value. This suggests that automation in urban settings should firstly focus on heavier modes of transportation, such as bus lines or rail lines. The Paris Saclay case

study led to more promising results thanks to an intermodal (train – AV) scenario which allowed to significantly increase the average occupancy per vehicle and increase accessibility for many users, at the cost of lower patronage for the competing bus lines. On-demand AVs could replace low occupancy bus lines depending on territories. Considering the potentially substantial infrastructure costs, AVs could be implemented under a Stop-Based routing to limit the network length to equip. In the Dourdan rural case study, on-demand AVs suffer from low occupancy, especially when the service does not offer ridesharing (with a significant share of deadheading). This low economic performance of AV services in rural territories suggests that these should only be introduced for specific purposes – such as providing a mobility solution for specific populations – or in combination with other mobility policies. This case study highlights the importance of infrastructure costs, which are even more prevalent for low demand densities.

This work contributes to better understanding the potential impacts of on-demand AVs. It provides first recommendations on how to introduce AVs depending on the territorial context in order to mitigate the undesirable externalities and limit the possibly large financial costs, especially regarding the infrastructure.

Résumé

La décennie 2010 a été marquée par un intérêt pour les véhicules automatisés (VA). Le nouveau marché ouvert par les promesses d'une sécurité et d'un confort améliorés a incité les constructeurs automobiles et de nouveaux venus à investir dans le développement des VA. La littérature scientifique s'est également intéressée à ce sujet et a produit des analyses pour étudier l'impact attendu de ce nouveau mode de transport. Ces travaux se sont principalement concentrés sur la capacité opérationnelle des services de VA à la demande pour remplacer les services aujourd'hui assurés par les voitures conventionnelles.

Cette thèse propose une évaluation socioéconomique des services de VA à la demande dans différents territoires en répondant aux questions de recherche suivantes : Quelles sont les performances des services basés sur les VA en tenant compte des perspectives des principales parties prenantes (c'est-à-dire les usagers, les opérateurs et les autorités publiques) ? Certains services de VA sont-ils plus pertinents que d'autres ? Quel modèle opérationnel est le plus adapté à déployer dans chaque type de territoire (urbain, périurbain et rural) ?

Une méta-analyse est réalisée pour appréhender l'état de l'art et ses principaux résultats. Ensuite, un cadre d'analyse coûts-bénéfices (ACB) adapté à l'évaluation des services de VA est développé. La méthodologie est appliquée à trois cas d'étude (urbain, périurbain et rural), à Berlin, à la Communauté d'agglomération de Paris-Saclay et à Dourdan (sud de Paris). Le modèle de simulation de mobilité multi-agents MATSim est utilisé pour déterminer la fréquentation des services de VA et fournir les entrées nécessaires pour l'ACB.

Les contributions de cette thèse sont à la fois méthodologiques et empiriques. La contribution méthodologique réside dans le développement d'un cadre d'ACB et d'un ensemble de valeurs de référence pour l'évaluation socioéconomiques des services de VA. En ce qui concerne la contribution empirique, la méta-analyse montre que les services de VA à la demande augmenteraient les distances parcourues, mais pourraient permettre de réduire de moitié la taille de la flotte requise. Nos études de cas corroborent et étendent ces résultats par une évaluation plus complète. A Berlin, l'introduction des VA entraînerait une augmentation de la congestion, entraînant une diminution du bien-être des usagers. Cela suggère que l'automatisation dans les environnements urbains devrait d'abord se concentrer sur les modes de transport plus lourds, tels que les lignes de bus. À Saclay, un scénario intermodal (train–VA) a permis d'augmenter

l'occupation moyenne des véhicules et d'améliorer l'accessibilité pour certains utilisateurs, au détriment d'une fréquentation plus faible pour les lignes de bus. Les VA à la demande pourraient remplacer les lignes de bus à faible occupation selon les territoires. Compte tenu des coûts d'infrastructure qui pourraient être importants, les VA pourraient opérer un schéma de desserte de point-à-point basé sur les stations de bus pour limiter la longueur du réseau à équiper. Dans l'étude de cas rural de Dourdan, les VA souffrent d'une faible occupation, en particulier lorsque le service ne propose pas de covoiturage. Cette faible performance économique des services de VA dans les territoires ruraux suggère qu'ils ne devraient être introduits que pour des besoins spécifiques - tels que fournir une solution pour des populations spécifiques. Cette étude de cas souligne l'importance des coûts d'infrastructure, dont l’importance relative croît dans les territoires de faible densité.

Ces travaux contribuent à une meilleure compréhension des impacts potentiels des services de VA à la demande. Ils fournissent les premières recommandations sur la manière d'introduire les VA en fonction du contexte territorial afin de limiter les externalités indésirables et de réduire les coûts financiers potentiellement importants, en particulier en ce qui concerne l'infrastructure.

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List of Acronyms

ABM	Agent-based model
AET	Access and Egress Time
AMOD	Autonomous Mobility On Demand
AV	Autonomous Vehicles
AVO	Average Vehicle Occupancy
AVS	Autonomous Vehicles Service
BCR	Benefit Cost Ratio
CBA	Cost Benefit Analysis
CEA	Cost Effectiveness Analysis
CPS	Communauté d'agglomération Paris Saclay
CS	Consumer Surplus
D2D	Door-to-Door
DGITM	General direction of infrastructures, transportation and mobilities
DRT	Demand Responsive Transport
EE	Economic Evaluation
EIA	Environmental Impact Assessment
EOL	End-of-Life
EV	Electric Vehicles
FS	Fleet Size
GDP	Gross domestic product
GHG	Greenhouse gases
ICEV	Internal Combustion Engine Vehicles
IDF	Ile-de-France
INSEE	National Institute of Statistics
IRR	internal rate of return
IVTT	In-Vehicle Travel Time

KPIs	Key Performance Indicators
LCA	Lifecycle Analysis
LIDAR	Light Detection and Ranging
LIE	logsum income equivalent
LTE	logsum time equivalent
LUTI	Lad Use and Transport Interaction (model)
MCA	Multicriteria Analysis
MM	Materials and Manufacturing
Nox	Nitrogen oxides
NPV	The Net Present Value
NPV/I	NPV/investment
PM	particulate matter
PO AV	Privately Owned Autonomous Vehicles
PT	Public Transit
RoH	rule of the half
RS	Ridesharing
SAV	Shared Autonomous Vehicles
SB	Stop Based
TC	Total Cost
TT or TTT	Total Time Traveled
VKT	Vehicle Kilometer Traveled
VMT	vehicle miles travelled
VOCs	volatile organic compounds
VoT	Value of Time
VTTS	Value of Travel Time Savings
WEI	Wider Economic Impacts
WT	Waiting Time

Introduction

I. Context

Autonomous Vehicles (AV) have raised passions over the last decade. Every actor wants its share, either by developing the technology themselves as the market leader Waymo does (*DDS Wireless* 2018) or buying the expertise at an expensive price. Intel acquired Mobileye at a 15 billion dollars price, Amazon bought Zoox for 1.2 billion dollars and General Motors secured Cruise for 1 billion dollars (Palandrani 2022). Those actors are not all traditional car manufacturers but also tech companies such as Google, Nvidia or Qualcomm, with a positional advantage on the technological development. While there is a trend towards a comeback to less ambitious targets (Carey and Lienert 2023), the motivations of these private companies towards autonomous vehicles development are based on the opportunity to either produce a more advanced good than the conventional cars (with the development of advanced driver assistance systems) or to provide a mobility service to travelers. Without drivers costs, on-demand services could be implemented in place where conventional services remain currently too expensive to operate (White 2016). These potential new mobility markets motivate such investments, as the market is forecasted to exceed 30 billion dollars in 2031 (Transparency Market Research 2022). The main impact on the mobility landscape would be the shift towards a more service-based approach allowing travelers to not own (and operate) the car they are travelling with. The actors mentioned above have launched numerous experiments to assess the new technology. In Europe, several projects have been launched to guide those experiments. One can mention the European project AVENUE (6 experiments), the French projects SAM (13 experiments) or ENA (3 experiments) ("Demonstrator & Replicator sites – AVENUE"; Développement des véhicules autonomes, 2019). In China, Baidu operates autonomous taxis in Wuhan and Chongqing with the ambition to expand the service to 65 others cities (Fouquet 2022). Others experiments are more ambitious: Waymo, an Alphabet (Google) subsidiary company, operates the most important robotaxi service with 700 driverless vehicles in Phoenix (Korosec 2022). If a different order of magnitude exists between the experiments, they share one similarity. These experiments are shaped in order to test and develop the technology and do not aim to offer a full commercial service competing with existing modes of transportation. It does not allow us to understand

what the impacts of AV would be if they were to be introduced under a competitive form.

Following Berrada 52019) definitions, the "*automated cars do not have the level of intelligence or independence to make decisions by themselves*" when "*autonomous cars are theoretically cars which benefit of an autonomy when making decisions*". These "autonomous vehicles" are the fifth level of autonomy described by the Society of Automobile Engineers or SAE (Appendix Figure 1) whereas "automated" vehicles are closer to the fourth level. Automated vehicles will likely be a first step before to reach the autonomous vehicles technological level. As this thesis focuses on the impact of AVs if they were to be introduced in a large number, Autonomous Vehicles will refer to light road vehicles (no more than 15 seats), with driving abilities equal to an average human driver following Berrada's definition.

II. Expectations

While the introduction of Autonomous Vehicles was originally expected to bring many benefits, such as improving safety and reducing the cost of travel (by removing the need for a driver), it has raised several questions regarding law regulation and ethics, the acceptability of AVs, or even the very existence of the aforementioned benefits. We briefly develop the main questions related to AV before narrowing the scope in accordance with the research question of this thesis.

Among the primary anticipated advantages of autonomous vehicles (AV), a prominent one is the enhancement of road safety. Yang and Fisher (2021) underscored this notion by revealing that the assumption attributing over 90% of automobile accidents to driver error, which formed the basis for advocating the potential safety gains of autonomous vehicles, originated from studies conducted in the 1970s (Sabey and Staughton 1975; Treat et al. 1979). Since then more conservative approaches can be found in the literature but automation will surely have a net positive impact on road safety (Tafidis et al. 2021). Uncertainties remain important for mix-traffic (shared environment for conventional cars and AVs) conditions and accidents due to potential induced traffic. Despite an expected positive impact on road safety, in most countries self-driving vehicles are not allowed to drive on open roads. The National Highway Traffic Safety Administration from the U.S. Department of Transportation needed to modify legislation in order to accept vehicles without steering wheels or driver's seats (Uhlemann 2022). Except for Ireland

all European countries have signed or ratified the 1968 Vienna convention which imposed to have a driver in the vehicle (*Convention on Road Signs and Signals* 1968). The convention has been amended in 2021 include the mention of automated driving abilities and regulate its fields of application (*Décret N° 2021-873 Du 29 Juin 2021 - Légifrance*). In 2022, the United Nations Economic and Social Council has issued a proposal to allow autonomous vehicles to go up to 130km/h on rapid lanes and highways. The decision still remains in countries' hands to implement this text in their national legislation. The next following years will surely issue definitive decision on the driving responsibility in case of accidents (Hansson, Belin, and Lundgren 2021). The legislation will require to be updated continuously to keep up with the technological developments and guide autonomous vehicles implementation. This legislation will need to include ethical choices which are under private responsibility when cars are humanly-driven (Hevelke and Nida-Rümelin 2015). Could drivers be found responsible for car accident when they were not supposed to drive? Who shall bear the responsibility? The car-maker(s)? The decision-making software developer? Which decision the autonomous car should take when submitted to a trolley dilemma situation (Cunneen et al. 2019)? The ethical choice might be made before-hand as a mandatory ethics setting or by each traveler who would choose its personal ethics setting (Gogoll and Müller 2017).

The level of investments required to develop the automation of vehicles might overshadow some other barriers of the AV implementation such as the acceptability and the acceptance[1] of this new technology. Firstly, AVs could interact with agents (pedestrians, bikers, conventional car drivers…) operating in the same public space. The existing technical experiments have already suffered from incivilities (Haué et al. 2022). Since then to promote acceptability and acceptance towards the specific public, like pedestrians, Human-Machine Interface (an interface allowing interaction between software and/or hardware and humans) are developed (Bonneviot, Coeugnet, and Brangier 2021; Métayer and Coeugnet 2021). Secondly, users might need to be get used to the new mode of transportation. The literature seems to indicates that the typical profile of AV user may be the young, graduated and urbanized male (Bansal, Kockelman, and Singh 2016; Krueger, Rashidi, and Rose 2016; Moreno et al. 2018). However, the state of the art produced by (Lécureux et

[1] ("…*acceptability is one's perception of a system before use, while technology acceptance is one's perception of the system after use.",* Nadal et al., 2019)

al. 2022) showed that further research needs to be pursued to reach a consensus on the user profile.

In the context of mobility, two primary impacts are anticipated with the advent of autonomous vehicles (AVs). Firstly, AVs are expected to reduce mobility costs significantly by eliminating the need for drivers (Bösch et al. 2018; Becker et al. 2020; Tirachini and Antoniou 2020). Secondly, they are poised to facilitate the broader adoption of shared mobility solutions, encompassing both carsharing and ridesharing services. The expected benefits were numerous at first, even if the academic literature and the industrial community have taken a step back with the first promises of this technology. The expectation of the end of the "driving era" was that travelers could use their time in a more productive way than driving. It would allow them to have, *ceteris paribus*, more available time. This time could be used to work, sleep or travel more…

However, with a reduction of their time cost to travel, mobility consumer could be pushed to perform additional trips and/or longer trips in distance and time. AVs also question the use of private cars which are, on average, used only 3-4% of the time (Bates and Leibling 2012). AV could be shared with others as an on-demand service (i.e., a taxi service) when they are not used by their owner (Stocker and Shaheen 2019). Consequently, that would allow an increase in the utilization rate of cars, and a decrease in the total number of vehicles required to serve the same mobility demand. Its main downside is, similarly with a taxi service, the vehicles would need to travel empty to pick-up new travelers or reposition. When the mobility schemes shifts from a privately operated driving car to an on-demand AV service with shared vehicles, another lever to reduce the car fleet can be used. It is not a direct implication of automation per-say but it is only another step toward the sharing economy. Similarly, every AV ride might be open to the possibility of being shared with others. When trips can be mutualized, sharing rides would allow to reduce the fleet size but also the distance traveled (at the strict condition that the detours should not exceed the additional trip). In addition to the reduction of the fleet size and distances travelled, this would also allow to reduce emissions, energy consumption and congestion. The operational modes of autonomous vehicle (AV) services span a spectrum, ranging from conventional fixed-route services akin to established bus lines to the possibility of on-demand services. These diverse service configurations hold the potential to provide supplementary transportation options to travelers. For instance, they could furnish first-and-last mile connectivity with public transit. However, it is worth noting that these evolving AV services also present competitive

challenges to existing solutions, including traditional bus lines, cycling or walking. AV services might be introduced under different forms depending on territory specifications: land use, housing and jobs densities, sociodemographic profiles of potential users, existing transport supply, level of current congestion, etc. For example, in urban areas where there is a high density of population and the road is already congested, adding another mobility alternative circulating on this network might cause overload. On the other hand, in rural or low-density areas, on-demand services might struggle to find its demand. The decision to implement or not a service is political as the service's value does not lie only in its potential profits or occupancy rate. As such, it is critical to address the topic considering the point of view of the stakeholders, while also taking into account their distinct dynamics within territories. These services have the potential to enhance accessibility for individuals with reduced mobility or those who do not own personal vehicles. Several indicators, quantitative or qualitative, might help to take the decision but the requirement might vary depending on the territories. The future of AVs bears promising outcomes but at the current state, it is still a work-in-progress.

III. Problem statement

AVs are becoming more of a reality: several business and operating models have been considered and tested, billions are invested, but their impacts depend on the specificities of each territory are still not well known. Previous and ongoing experiments are more focused on evaluating technology and safety related aspects. Research studies are exploring mainly traffic impacts without performing a deep economic assessment. Thus, despite the important resources that have been deployed to develop and evaluate AV technology, the shape under which these AV would be implemented has not been assessed from an economic perspective. This thesis focuses on the mobility perspectives of on-demand mobility services and their impacts. The treatment of short and long-distance mobility is segmented in both the research and the industrial community, the scope of this thesis is limited to regional (i.e. daily short-distance trips) for concision reasons.

This thesis aims to fill this gap by investigating the following research questions: What is the performance of AV-based services by considering the perspectives of main stakeholders (i.e., users, operators and public authorities) and how does this performance vary depending on the territories? Which is the most suitable configuration/ operating model of AV-

based services to deploy on each type of territory (i.e., urban, peri-urban and rural)?

IV. Purpose, contributions and thesis overview

The main objective of this thesis is to better understand the performance of AV services from an economic perspective, and how it varies depending on the service and the territory considered. In line with this objective, this thesis proposes several contributions to the literature.

The first chapter provides an overview of the state of the art of the literature on the economic evaluation of AV services through a bibliometric analysis and a meta-analysis. Two major empirical contributions are delivered in this chapter. A bibliometric analysis of mobility simulations studies provides insights on the indicators used by the academic community to assess AVs and the models used to model and simulate the behavior of AVs and travelers. This analysis is enriched by a meta-analysis that assesses AVs services performances based on Vehicle Kilometer Traveled (VKT), Total Time Traveled, compared to other services (including several different AV services). This chapter characterizes AV services in order to better understand how the performance of the service depends on some key characteristics of the service (routing, ridesharing…).

The second chapter discusses the choice of the assessment methodology, namely cost-benefit analysis, and how it is adapted to the specificities of AV services. It thereby provides a methodological contribution through the development of a CBA framework and a parametrical set of reference values suited to the analysis of autonomous vehicle services.

In the third chapter, the economic appraisal framework is paired with agent-based simulation and applied in three case studies. The applications address different types of territories (urban, periurban and rural). The chapter concludes by providing general recommendations regarding on-demand AVs services implementation. It therefore provides contributions related to the application of the economic assessment framework to three different territory types: urban, peri-urban, and rural. It aims at identifying the most relevant AV services depending on specific socio-spatial configurations. Specifically, this thesis contributes to better understand the routing impacts of on-demand services, through the economic evaluation of door-to-door and stop-based routing. The three case studies are presented as three independent articles so that they can be read independently from

each other. The methodology is repeated in a synthesized form, for more discussion and details on the methodology, please refers to the second chapter. Finally, the conclusion summarizes the results, shares the limitations of the thesis and offers some perspectives for future research.

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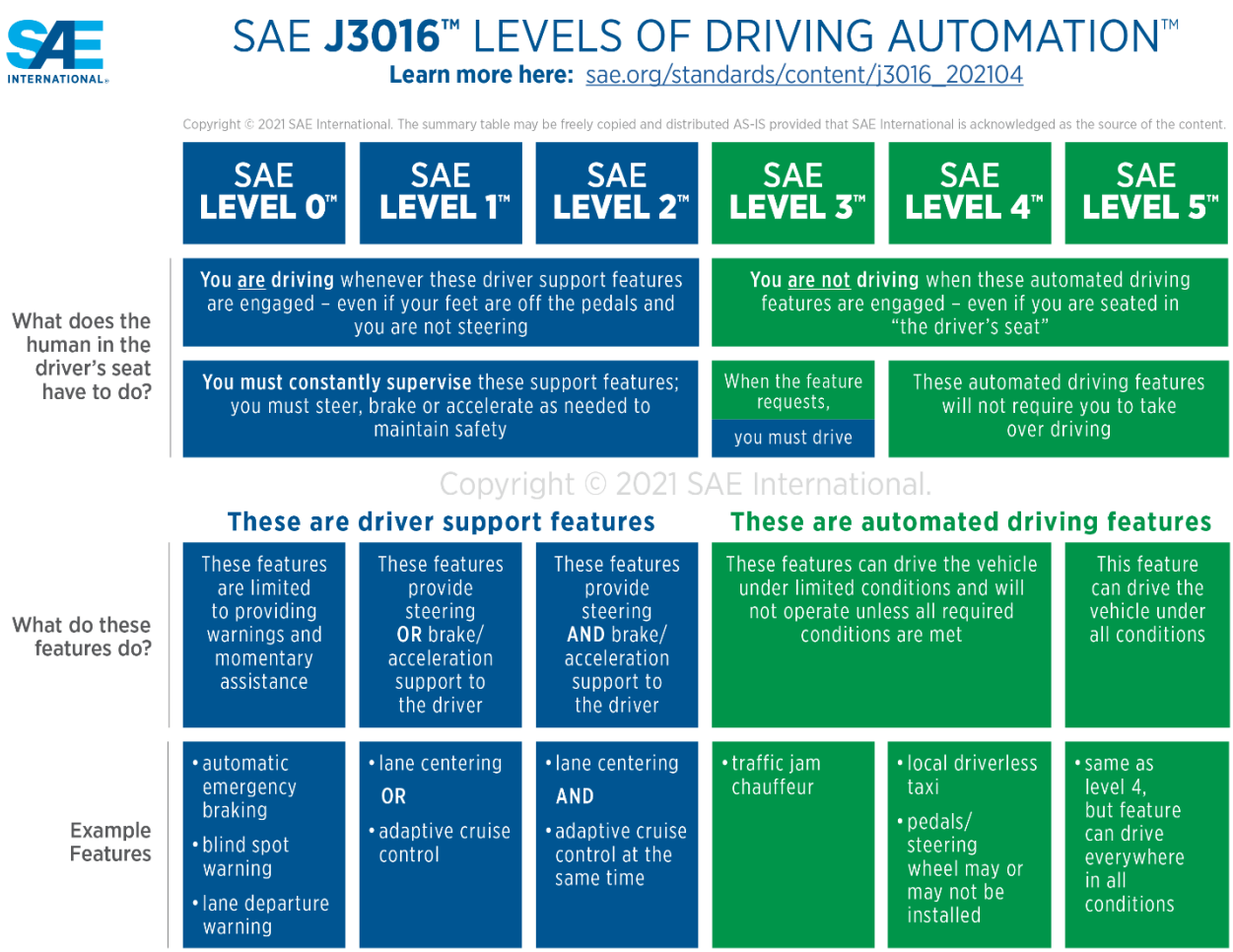


Figure 1. SAE J3016 Levels of Driving Automation

Source: Society of Automobile Engineers, URL: https://www.sae.org/blog/sae-j3016-update

Chapter 1. Economic evaluation of autonomous passenger transportation services: a systematic review and meta-analysis of simulation studies

Abstract

In order to prepare for their deployment, mobility simulations have been used since the mid-2010s to investigate the effects of Autonomous Vehicles (AV) services. The aim of this study is to provide a review of which impacts were considered in simulation studies, to what extent, and for which results, with an emphasis on economic impacts. Taking cost-benefit analysis (CBA) as a reference framework for the economic evaluation of mobility services, we first establish a list of standard impact indicators in CBA studies. We carry out a descriptive statistical analysis to investigate the use of these indicators, completed by a meta-analysis for the indicators that received sufficient coverage from the literature. The results show evidence of strong use of performance and operational indicators in the simulation literature, but also expose a lack of in-depth analysis concerning environmental and social indicators. With regard to the intensity of impacts, the introduction of autonomous taxis should increase vehicle- kilometers traveled (VKT) by +23% and travel time by +17% compared to conventional private cars. At the same time, it could help to cut 17% of the present fleet size. This performance could be improved if autonomous taxis were shared, limiting the increase of VKT to +6% at the cost of only slightly longer travel times (+20% instead of +17%), while also increasing fleet reduction by up to -55%. Compared to conventional bus or train lines, these on-demand AV services could permit travel time to be reduced by half and could also reduce financial operating costs. On the other hand, they would increase fleet size and VKT by three to seven times their initial values. AV impacts could vary considerably depending on the socioeconomic landscape of the implementation area. Our findings call for evaluating AV services from a wider perspective than operational and financial prisms alone as is currently the case, such as using cost-benefit analysis.

I. Introduction

As autonomous vehicles (AV) are becoming more of a reality, with significant technological progress (Pendleton et al., 2017) and numerous experiments (Antonialli, 2019; Stocker and Shaheen, 2019) being led across the world, an increasing number of studies are investigating the economic benefits as well as the costs that can be expected from the development of AV services. These studies have shown that the introduction of such services will have relatively diverse impacts (Narayanan, Chaniotakis, and Antoniou 2020). First, by making the act of driving no longer necessary, users will be able to engage in other activities, such as leisure or work, while sitting in their autonomous car. This is predicted to result in a weakening of the value of travel time savings for private mobility (Correia et al. 2019; Kolarova, Steck, and Francisco J. 2019; Mouhoubi, Berrada, and Christoforou 2020), and subsequently in a reduction in the generalized cost of travel. Regarding public transportation (including taxis and ride-hailing), the absence of drivers is similarly likely to result in lower operating costs as the technology matures (Anderson et al., 2016; Bösch et al., 2018). AV services are also expected to improve accessibility for people with limited motility such as the elderly, children, or adults with no driving license (Meyer et al., 2017). Since the autonomous technology should also result in smoother driving and cooperation between vehicles (e.g., platooning), substantial benefits are also expected in terms of emissions (Bauer et al., 2018), accidents (Clements and Kockelman, 2017), and congestion, as shorter headways between autonomous vehicles could allow road capacity to increase (Simoni et al., 2019). These expected benefits remain controversial, however. AV services might also lead to an increase in traffic due to the lower cost of travel - non-monetary through the cost of time for private transport, monetary through lower fares for public transit - (Fosgerau, 2019; Childress et al., 2015) or due to deadheading (Fagnant and Kockelman, 2014). Lower values of travel time savings could also exacerbate congestion by mitigating the peak spreading phenomenon (van den Berg and Verhoef 2016).[2] Combined with the fact that from a lifecycle perspective, AVs are likely to generate more emissions than conventional electric vehicles due to the additional equipment and data processing they involve, these points make the environmental impacts of AV services highly uncertain (Golbabaei, Yigitcanlar, and Bunker 2020; Wadud, MacKenzie, and Leiby 2016). Similarly, there is also strong

[2] The peak spreading phenomenon corresponds to drivers leaving before or after peak travel time to avoid congestion (Gordon, Kumar, and Richardson 1990).

uncertainty regarding the financial cost of AV services, especially infrastructure costs, which have attracted less attention in the literature.

Beyond these uncertainties, there is consensus that AV services will result in many changes to transportation supply - new services, lower operating costs - and travel demand - lower value of time, improved accessibility –, together with complex interactions between them (Bahamonde-Birke et al., 2018). In order to better evaluate the (expected) performance of AV services, a growing body of literature therefore relies on mobility simulation models in an attempt to capture these complex factors, ranging from agent-based models - such as MATSim or SimMobility - to direct demand models (Berrada and Leurent 2017). These studies substantially differ however, be it with regard to the model type used, the way performance is measured, or the services compared within a given study. Many reviews have therefore attempted to synthesize the results of this simulation literature. Berrada and Leurent (2017) provided a short qualitative review of simulation methods and the expected economic impacts (mobility, parking, accidents, environment) of AV services. Jing et al. (2020) carried out a systematic review of the agent-based simulation literature with a corpus of 44 papers, focusing on the simulation platforms used and the critical variables and output of the simulations. Golbabaei et al. (2020) also carried out a systematic review of the literature (with 81 papers) and discussed the expected impacts on urban mobility (fleet size, traffic, and congestion), urban infrastructure and land use (household location, parking spaces, pick-up/drop-off and charging stations), social and travel behavior impacts (trip and mode choice, vehicle ownership) and environmental impacts. Bahamonde-Birke et al. (2018) also discussed what they call the first-order and second-order effects of AV services using a systemic approach. Pernestål and Kristoffersson (2019) reviewed 26 papers and reported their findings on the impacts of AV services, focusing on four specific indicators: the trip (monetary) cost, vehicle kilometers traveled (VKT), fleet size, and waiting time. Other effects have been briefly discussed, such as energy consumption, land-use, and travel behavior. Soteropoulos et al. (2019) carried out a systematic review of 37 modelling studies, with a focus on vehicle kilometers traveled, vehicle hours traveled, modal shares, and land use (parking spaces, including fleet size, location choices). Narayanan et al. (2019) also conducted a comprehensive review of the literature and the reported impacts on traffic and safety, travel behavior, the economy, transport supply, land use, the environment, and governance. Their review focused on shared AV services however, in other words, the so-called “robot-taxis”. While several systematic reviews have

discussed the expected impacts of AV services, most are qualitative. No meta-analysis has been carried out to date to the best of our knowledge. Furthermore, all the above reviews discuss each impact independently, so the policy implications remain vague due to the wide array of impacts.

This work aims to better understand our current knowledge - and lack of knowledge - of the expected economic impacts of AV services through a systematic two-step review of the simulation literature. Taking cost-benefit analysis (CBA) as a reference evaluation framework (Layard and Glaister 1994), we first examine which impacts have been studied in the literature and to what extent by examining the prevalence of 22 indicators directly related to CBA. The cost-benefit analysis seeks to evaluate scenarios (e.g., a new infrastructure, transportation policy or mobility service) by assessing the various impacts, monetizing them, and adding them over time using discount rates in order to determine the value of the scenario for society. While other evaluation methods exist (such as multi-criterion analysis), cost-benefit analysis remains to date the standard evaluation framework for transportation policies across the world (Small and Verhoef 2007). This first step allowed us to establish a shortlist of key performance indicators for which enough studies were found to carry out a meta-analysis, which was conducted in a second step. While the systematic reviews kept the results attached to the articles in question, the meta-analysis provided overall (i.e., decontextualized) forecasts of the AV impacts. Four key performance indicators (KPIs) were taken into consideration: vehicle kilometers traveled (VKT), travel time, fleet size and total costs. Our meta-analysis thus provides a first quantitative estimate of the expected impact of AV services on travel demand, congestion, and system performance.

The literature review focuses on road passenger transportation and the (micro-)economic impacts of AV services for society. Applications of AVs to freight (see Flämig 2016, for a review) are studied in separate papers, with limited (if any) intersection to date with the (passenger) mobility simulation literature. Similarly, autonomous air and rail transportation are not considered in this review due to the specific nature of these modes of transport and the current focus of the simulation literature on road transportation. Our review focuses on (micro-)economic impacts, in other words, all the impacts that may be found in a standard transportation CBA (de Rus et al. 2020). The macroeconomic impacts of autonomous vehicles on economic growth or employment are considered beyond the scope of this paper as they are rarely if ever mentioned in simulation studies and are discussed in other reviews (Clements and Kockelman, 2017; Faisal et al., 2019; Clark et al., 2016). Similarly, other studies offer a broader

perspective of autonomous vehicles by considering the state of the art in research as a whole (Gandia et al. 2019), business and management research (Cavazza et al., 2019), and user acceptability (Andersson et al., 2017).

This paper completes the various systematic reviews on simulation studies in two main ways. First, using cost-benefit analysis as a reference evaluation framework, it quantifies the extent to which listed impacts have been studied in the literature, both separately and jointly. This allows us to show which impacts have been largely investigated and are therefore more likely to be correctly appraised, and which impacts have attracted less attention. By also studying the co-occurrence of impacts -seldom done in former reviews -, we show that comprehensive evaluation of AV services, such as using CBA, remain extremely rare to date, as most modeling studies focus on operational and financial performance with significantly less attention to externalities. Second, this paper provides quantitative rather than qualitative estimates of the expected impact of AVs, depending on the service characteristics for four key performance indicators: VKT, travel time, fleet size and total costs. It thus provides better insights into the effects of AV services on demand, operations and system performance, as well as insights into the influence of service characteristics in this regard.

II. Methodology

This paper investigates the expected economic impacts of autonomous vehicle (AV) services, based on findings in the (passenger) mobility simulation literature. Our methodology relies on two main steps.

The first step uses a descriptive statistical analysis to determine which impacts are studied in the literature and to what extent. Taking cost-benefit analysis (CBA) as a reference framework for the economic evaluation of mobility services, we establish a list of key performance indicators (KPIs) commonly used in CBA and measure their frequency in a first corpus of AV services modeling studies. In addition to ascertaining the current focus of the relevant literature, this enables us to determine which impacts are studied most frequently and are therefore more likely to be correctly appraised, and which are not.

Next, we carry out a meta-analysis that focuses on the four most frequently considered KPIs in order to evaluate the expected magnitude of

the associated impacts, based on the current state of the art.[3] Our first corpus is hence restricted for the sake of the meta-analysis to the subset of relevant studies (i.e., only those featuring at least one of the four KPIs), a subset that we refer to as the second corpus. Through the four KPIs considered (VKT, Travel Time, Fleet Size and Total Costs), the meta-analysis provides a first estimate of the expected impact of AV services on travel demand, congestion, and system performance.

Figure 2 summarizes the methodology used in the paper, including the data collection process. All of these steps were performed on Excel. Data are available as an online appendix.

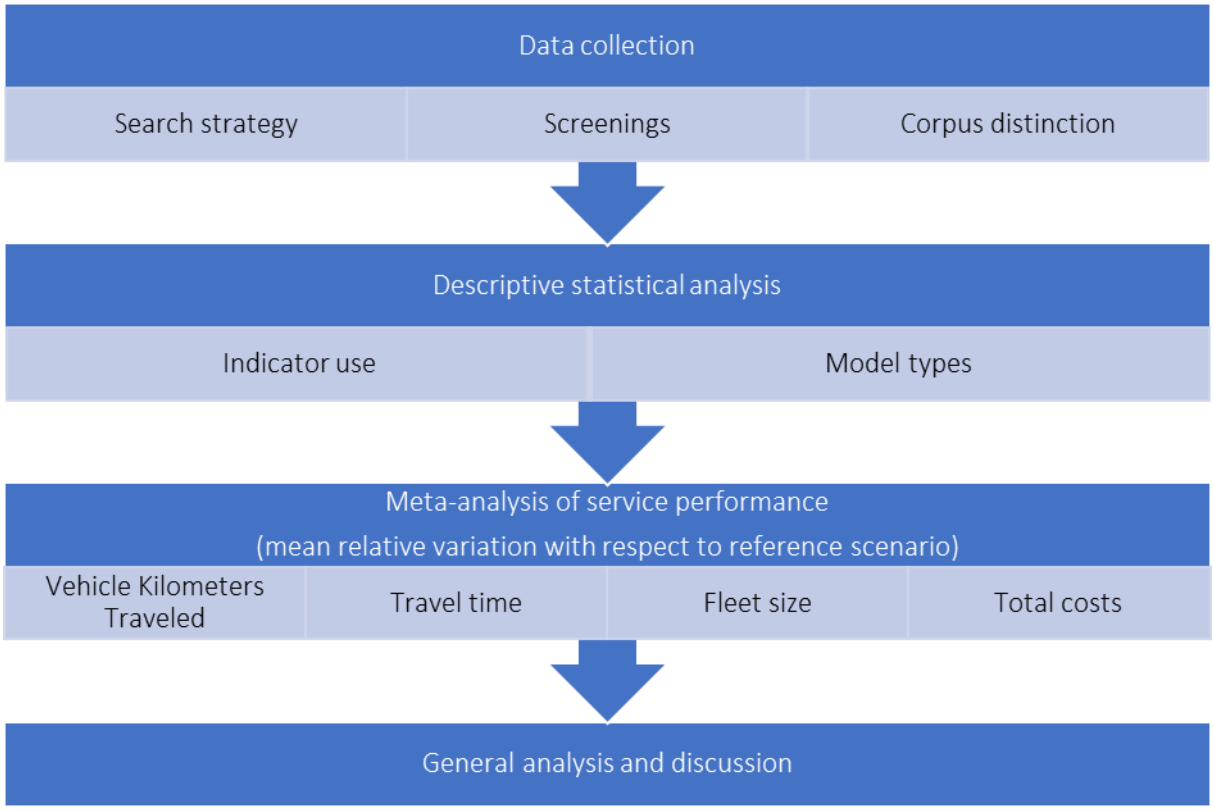


Figure 2. Methodology overview
Source: prepared by the author.

[3] The meta-analysis is "*a subset of systematic reviews; a method for systematically combining pertinent qualitative and quantitative study data from several selected studies to develop a single conclusion that has greater statistical power*" (Himmelfarb Library, Study Design 101).

We now detail the corpus selection process, the nomenclature of AV services used in our study, and the methodologies developed in the descriptive statistical analysis and in the meta-analysis.

A. Corpus selection

The selection of our two corpuses – the first for the descriptive statistical analysis and the second for the meta-analysis – also comprises two main steps. We began by collecting a preliminary corpus using a standard keyword-based search strategy augmented with a "snowball" search strategy. This corpus was then screened through the successive application of exclusion and inclusion criteria to produce our two final corpuses. As previously mentioned, the second corpus is a strict subset of the first corpus, obtained by considering additional exclusion and inclusion criteria, retaining from the first corpus only studies for which we were able to extract data for the meta-analysis.

1) Search strategy

The preliminary corpus was collected using two complementary methods. The primary one was an "All fields" search in the Web of Science database. The keywords used were "("autonomous vehicles" OR "automated vehicles") AND ("Simulation" OR "modelization" OR "modelling" OR "model") AND ("passengers" OR "mobility")". Only papers published between 1990/01/01 and 2020/10/01 were retained, so one trimester is missing for the year 2020.

This set of references was extended using a snowball search based on the survey of Berrada and Leurent (2017), which reviews transportation modeling studies on AV services. The snowball search strategy aims to collect a series of papers on a given topic by considering an initial corpus, then expanding it either with the references listed in the corpus ("reverse snowball search"), or with the papers that reference any one of the papers included in the initial corpus ("forward snowball search") (Francese and Yang 2021). The starting point can be the result of a search in scientific databases (as in Büchel et al., 2020) or (the solution we chose) an existing review on the topic of interest followed by a search on Google Scholar and Science Direct.

This twofold search strategy allowed us to obtain a large preliminary corpus of simulation studies about AV services, while limiting possible selection bias inherent to pure snowball search strategies. The Web of

Science search offers 529 papers published between 1991 and 2020 (Figure 3)**.** From 1991 and 2013, activity was relatively stable, ranging from one to three papers published a year. From 2014 and 2019, activity grew substantially, from 16 papers published in 2014 to 167 papers in 2019. The number of papers fell in 2020 due to the year being incomplete. Given that one trimester is missing, the number of papers for 2020 should be quite close to that of 2019.

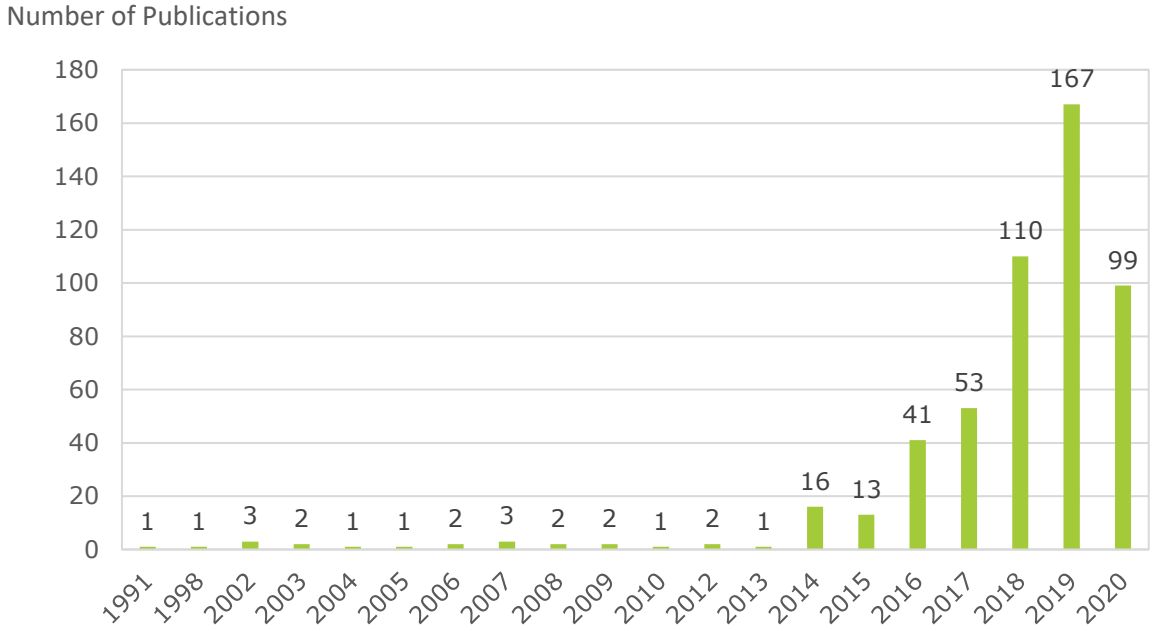


Figure 3. Number of papers per year

Source: prepared by the author based on Web of Science query, preliminary corpus excluding snowball search.

The very low number of studies prior to 2014 may be due to the choice of keywords, as "self-driving" or "driverless" might have resulted in older references. On this point, Gandia et al. (2019) recommend using "Automated" and "Autonomous" when referring to driverless technology.

2) Screening

We now detail the exclusion and inclusion criteria applied to the preliminary corpus in order to generate the first and second corpuses.

a) First corpus

The exclusion criteria for the first corpus were:

1. Studies dealing primarily with freight;
2. Parking and traffic optimization studies;
3. Studies focusing on the analysis of autonomous rail or air services (including air taxis, technical developments);
4. All papers using simulation in order to provide technical recommendations on computer driving ability. Research driven by the motivation to make autonomous vehicles a technically mature technology, especially in terms of safety, is not included in the scope of our study.

Conversely, the inclusion criteria for the first corpus were:

1. Mobility simulation studies that consider a scenario with a road-based autonomous vehicle service.
2. The autonomous level considered is SAE level 4 or 5 (see section 2.2 for definitions).
3. Rail services may be included as long as they are only used in the benchmark scenario.

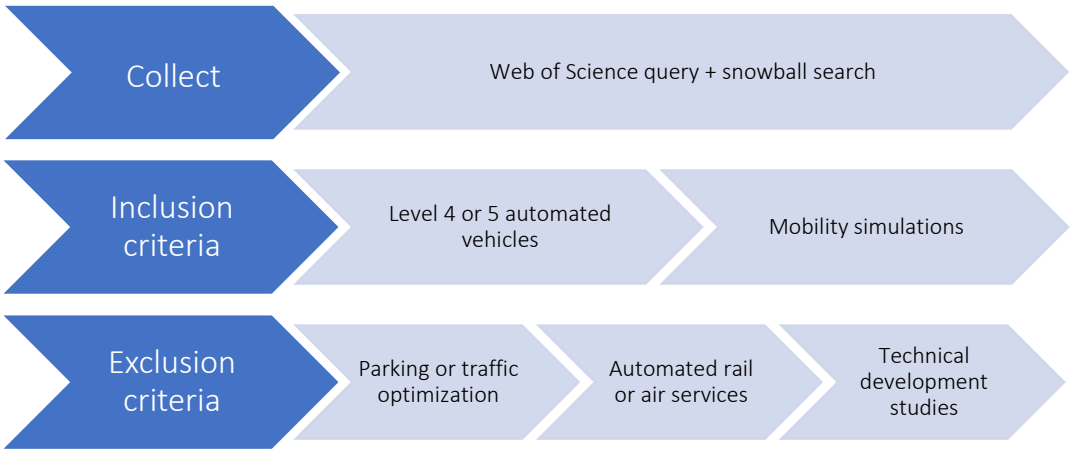


Figure 4. Selection process for the first corpus
Source: prepared by the author.

The exclusion and inclusion criteria (Figure 4) narrow the number of papers from 529 (preliminary corpus) to 84 articles (first corpus). Simulation and evaluation of AVS is a relatively recent topic in the scientific

literature. While the first published paper in the corpus dates from 2014 (Zachariah et al. 2014), almost two thirds of the corpus was published in the last three years (Figure 5), reflecting a growing trend in papers on this topic and evincing the results of the query on the Web of Science.

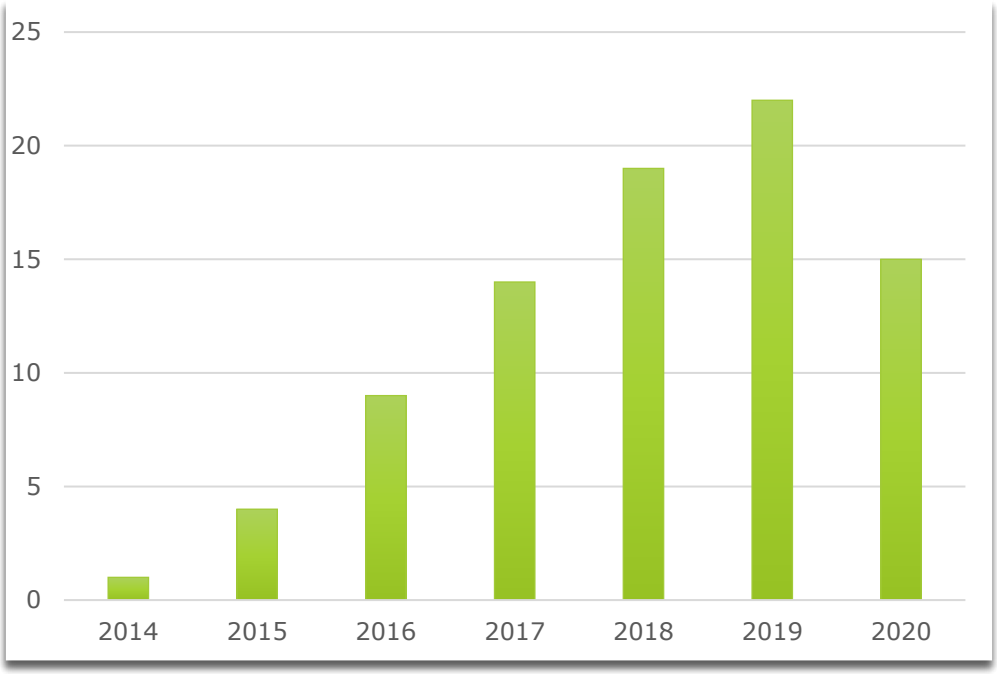


Figure 5. Publication dates
Source: prepared by the author.

The first corpus consists of 42 papers published in peer-reviewed journals, 1 thesis, 40 conference papers, and 1 technical report. Among the conference papers, the International Workshop on Agent-based Mobility, Traffic and Transportation Models, Methodologies and Applications (ABMTRANS conference) is the most represented, with 5 papers (Figure 6**)** Among the journal papers, the main source is the Transportation Research Record (the Journal of the Transportation Research Board), with 15 papers published. As expected, a fair number of papers originate from the Transportation Research series, with 7 papers in Part A: Policy and Practice, and 7 papers in Part C: Emerging Technologies.

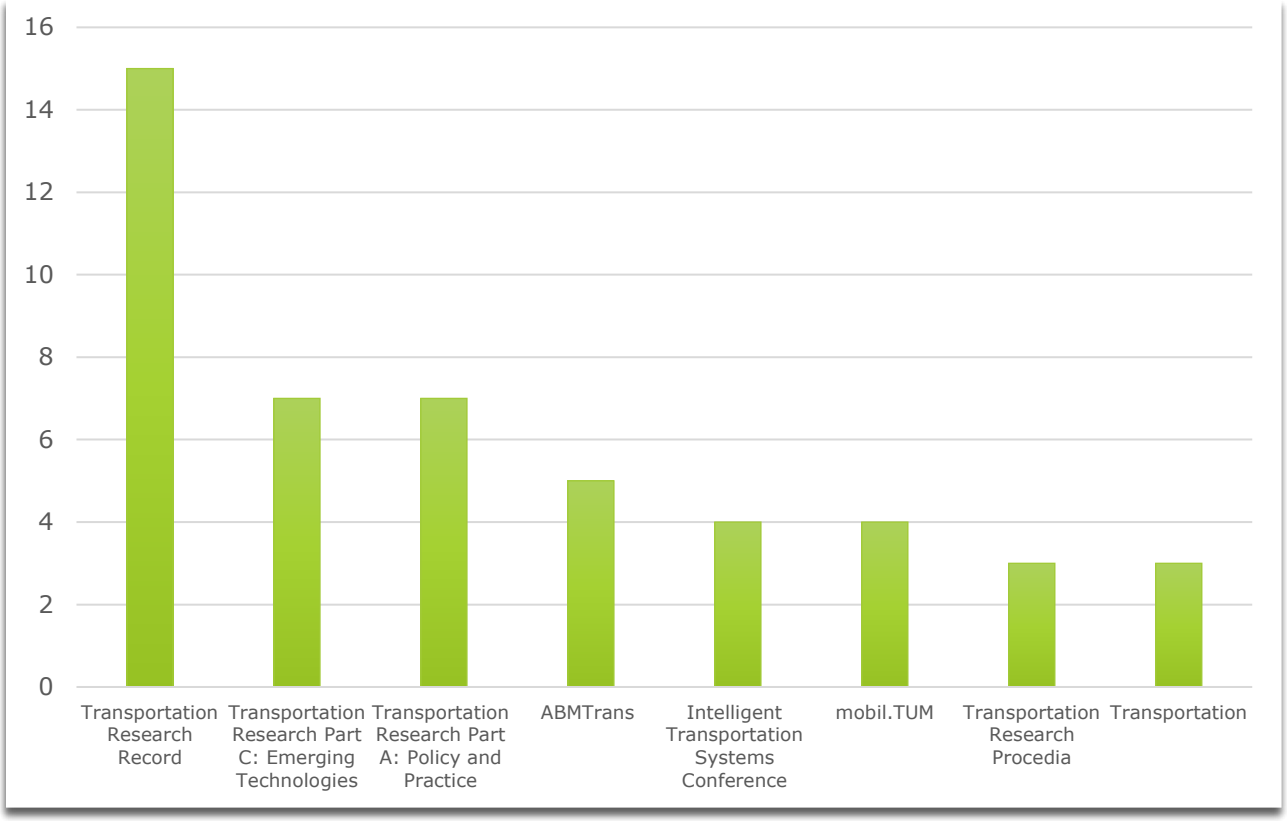


Figure 6. Main publication sources

Source: prepared by the authors. Note: this figure reports all venues with three papers or more.

The full list of reviews and conferences may be found in the Appendix (Appendix Table 6).

b) Second corpus

Relative to the first corpus, the following inclusion criteria were added to draw up the second corpus (Figure 7):

1. The study needs to compare two or more mobility services, with at least one involving autonomous vehicles.

2. The paper must evaluate in a quantitative and comparative (across the various scenarios tested in the paper) manner at least one of the four following KPIs:

- vehicle-kilometers traveled;
- travel time;
- fleet size;

- total costs.

Conversely, studies from which it was not possible to extract quantitative output of any of the four above-mentioned KPIs were not included in the second corpus. More details on the extraction and treatment of KPIs can be found in subsection 2.4.2.

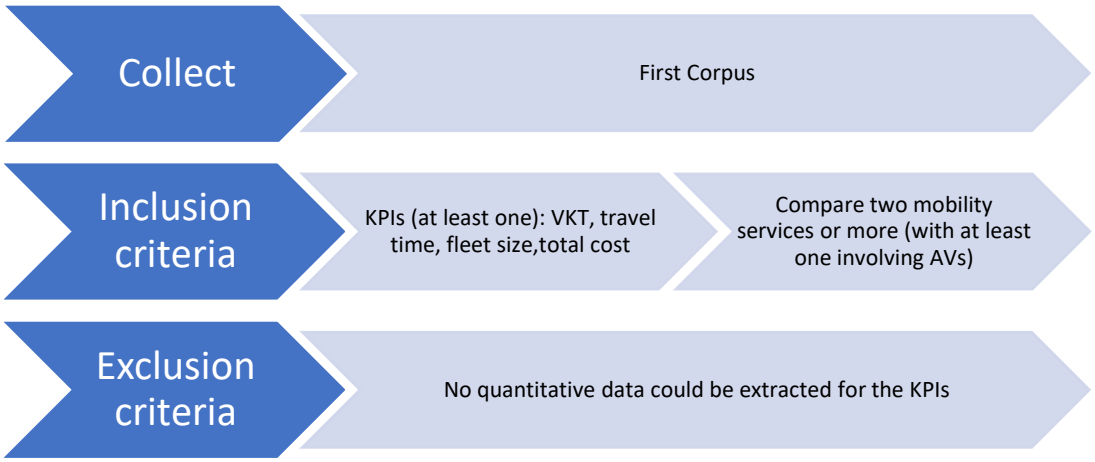


Figure 7. Selection process for the second corpus selection
Source: prepared by the author.

B. Service nomenclature

Current and prospective experiments of autonomous vehicles across the world involve a wide array of services, ranging from short-haul on-demand small autonomous vehicles (the so-called robot-taxis, see Stocker and Shasheen, 2018) to autonomous shuttles that operate on conventional stop-based and schedule-based transit lines (see AVENUE for European project). As the specific characteristics of AV services are likely to strongly influence system performance (Nagel et al., 2019), a nomenclature is a useful way to characterize them, in particular allowing us to control for the effect of service characteristics when assessing the impact of AV services in the meta-analysis.

The following nomenclature (Table 1) was built using the prior work of Antonialli (2019), Földes et al. (2016) and Földes et al. (2018) on smart mobility services. This classification also bears similarities with that of Becker et al. (2020) and Berrada (2019). It is based on the five following features:

- **Vehicle ownership and usage** reflects the responsibilities of purchasing, maintaining and sharing the vehicle, and potentially providing

a service. We distinguished between two types of ownership: individual ownership, where the vehicle is personal, and third-party ownership, where the vehicle is owned by a public or private operator/organization. Similarly, two types of usage were considered: private usage, where the owner uses the vehicle for his/her own mobility needs, and shared usage, where the owner makes the vehicle available to potential individuals to allow them to reach their destination (Berrada, 2019).

- **The ridesharing** feature determines whether the trip may be shared between two passengers or more (Berrada, 2019).

- **Service availability** is considered from two perspectives: space (by distinguishing line-based, stop-based, and door-to-door services) and time (on-demand versus scheduled service). This two-dimensional classification is derived from Berrada (2019) and offers similarities with the two operation models described in Antonialli (2019), distinguishing between Regular-Line Transport and Demand-Responsive Transport.

- **Vehicle type** mostly refers to the vehicle size, with four increasing levels of capacity. The "car category" is used for vehicles with 1 to 5 available seats, shuttles for 6 to 18 seats, and buses for more than 19 seats. The rail vehicle type includes tramways, metros, and trains (inspired by Stocker and Shaheen, 2017).

- **Automation level** describes the vehicles' automation features based on the SAE classification (SAE J3016:201806 "International Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles"). Three main levels are explored in the literature: conventional level refers to the level 0 of automation, semi-autonomous level to levels 3 and 4, and autonomous level to level 5.

SERVICE NOMENCLATURE	FEATURES	SOURCE
VEHICLE OWNERSHIP AND USAGE	Individual ownership and private usage Individual ownership and shared usage Third-party ownership and shared usage	Berrada (2019)
RIDESHARING	Yes No	Berrada (2019)
SERVICE AVAILABILITY	*Space*	
	Door-to-Door Stop-Based Line-based	Hardt and Bogenberger (2016) Berrada (2019) Antonialli (2019)
	Time	
	Scheduled On-demand	Antonialli (2019)
VEHICLE TYPE	Car Shuttle Bus Rail	Stocker and Shaheen (2017)
AUTOMATION LEVEL	Conventional (Levels 0,1,2) Semi-autonomous (Levels 3&4) Autonomous (Level 5)	SAE classification

Table 1. Strategic features of a mobility service.

Source: prepared by the authors based on above sources.

The on-demand door-to-door system collects passengers from their location and takes them to their final destination. The vehicle can either be shared (ridesharing) or used privately (private ownership or solo car sharing).

The on-demand Stop-Based system is a hybrid between conventional public transit and on-demand door-to-door services. Boarding/alighting is only permitted at stations. Again, the vehicle can be either shared or used privately.

C. Descriptive statistical analysis

The descriptive statistical analysis aims to determine which impacts are considered in the simulation literature, and to what extent, at the same time allowing us to highlight the current focus of the literature and the gaps to be filled.

1) Selection and classification of the indicators

In order to list which impacts are considered in simulation studies, we took the cost-benefit analysis as the reference evaluation framework, since it is currently standard practice in carrying out an economic evaluation of transportation investments, services, or policies (Boardman 2006; de Rus et al. 2020). We then considered a list of common CBA indicators (de Rus et al. 2020; Quinet 2013; Small and Verhoef 2007; Victoria Transport Institute 2009) and classified them into five main categories, related to:

- Service performance: includes indicators that measure service performance from a demand perspective, which are then used to compute consumer surplus,
- Operations: includes indicators that measure the operators' economic performance, which is then used to compute the operator surplus,
- Externalities: includes the main externalities captured in standard CBA: i.e., energy, greenhouse gas emissions, local pollutants, noise, safety, congestion,
- Socioeconomic: used to determine whether the study evaluates the results through the prism of some socioeconomic characteristics such as age or income level,
- Cost Benefit Analysis (CBA): refers to the standard final output of a CBA, such as the net present value.

Table 2 lists the indicators (twenty-two) identified within each category. The aim of this classification is to highlight the focus of the studies, while evaluating the capacity of the different simulation models used in the papers included. Apart from the "Socioeconomic" category, these indicators were selected for their use in CBA. The "Socioeconomic" section aims to complete the picture by adding social indicators where a few other studies, such as Tian et al. (2018), had a more technological-oriented indicator set (such as pre-collision systems or machine learning approach-based emergency brakes).

The selected indicators are usually simulation outputs. In some specific cases, they may also be considered as operational constraints to ensure a

certain quality of service: e.g., fleet size (Berrada, 2019; Vosooghi, 2019) or the required Level of Service (Navidi et al., 2017).

Category	Indicator	Definition	Source
Service performance	Waiting time		Quinet (2013), De Rus et al. (2020)
	Patronage		De Rus et al. (2020)
	Travel Time	Total travel time is composed of (a) access/egress time (only for line-based and stop-based services), (b) waiting time, and (c) in-vehicle travel time	De Rus et al. (2020)
	Vehicle Kilometers travelled (VKT)	Refers to the total distance travelled by empty and loaded vehicles. Also measured by vehicle miles travelled (VMT) in the Anglo-Saxon literature	Quinet (2013), Small (2007)
Operations	Occupancy rate	Corresponds to the average number of passengers per vehicle	Huang et al. (2020)*
	Fleet size	Refers to the total number of vehicles deployed for the service production	Bösch et al. (2016)
	Total Costs	Production costs, including at least operating costs. Fixed costs are also included in some studies	Bösch et al. (2018)
	Profits	Corresponds to the net profit for the operator, as the difference between costs and revenue	Fagnant and Kockelman (2016)
	Fare	Corresponds to the price of usage	Tirachini and Antoniou (2020)
Externalities	Local pollution	Corresponds to pollutant emissions that contribute to poor air quality, including particulate matter (PM), nitrogen oxides (NOx), and volatile organic compounds (VOCs)	De Rus et al. (2020)

	GHG emissions	Mainly include CO2 emissions due to operations. Refers to climate change	De Rus et al. (2020)
	Energy	Corresponds to energy consumption required for operations according to the motorization type of vehicle (thermal, electric, etc.)	Bauer et al. (2018)
	Noise	Refers to consideration of the noise nuisance	De Rus et al. (2020)
	Safety	Corresponds to the level of accidents with injuries and deaths	De Rus et al. (2020)
	Congestion	Corresponds to an estimation of the resources wasted in an overcrowded environment	De Rus et al. (2020)
Socioeconomic profile	Age		Urbina and Sohaee (2020)
	Gender		Hulse et al. (2018)
	Socioeconomic status	Variables describing the socioeconomic status of the household/individual, such as income, job category…	Müller et al. (2020)
	People with reduced mobility		
Cost Benefit Analysis	Net Present Value (NPV)	Corresponds to the difference between the present value of inflows and outflows over a certain period of time	Quinet (2013)
	Internal Rate of Return (IRR)	The annual growth rate an investment is expected to generate	Quinet (2013)
	Benefit Cost Ratio (BCR)	The ratio between costs and benefits, expressed in monetary or qualitative terms	Quinet (2013)

Table 2. Indicators

Source: prepared by the authors based on above sources.

** The "occupancy rate" refers to the "average vehicle occupancy" from Huang et al. (2020).*

We investigated the use of indicators in the literature with a statistical descriptive analysis examining 1) the occurrence of each indicator, 2) the occurrences of at least one indicator per category, and 3) the mean numbers of indicators per category in each paper. The analysis is followed by a qualitative discussion regarding the use of indicators in the papers reviewed.

2) Model types

In addition to the use of indicators, our analysis also investigated the types of simulation models used, providing some insights into the capacity of the various model types to simulate specific AV services or to generate distinctive outputs.

The following model types were considered, using the standard classification of transportation models (Ortúzar and Willumsen 2011; Soteropoulos, Berger, and Ciari 2019):

- Agent-based models are models where "*a system is modeled as a collection of autonomous decision-making entities called agents. Each agent individually assesses its situation and makes decisions on the basis of a set of rules.*" Bonabeau (2002)
- Four-step models are traditional mobility simulation models. They offer an aggregated view of the demand and supply of mobility (McNally, 2007).
- "*Direct demand models can be of two types: purely direct, which use a single estimated equation to relate travel demand directly to mode, journey and person attributes; and a quasi-direct approach which employs a form of separation between mode split and total (O–D) travel demand. Direct demand models are closely related to general econometric models of demand and have long been inspired by research in that area.*" (Ortúzar and Willumsen, 2011, chapter 12; Talvitie, 1973)
- Traffic models represent road traffic flows based on the vehicles' capacity to interact with each other and the infrastructure.
- Land Use/Transport Interaction "*illustrates the spatial organization of the network of socio-economic activities and describes the physical*

separation between them. The transportation system connects the various activities/land uses" Gavanas et al. (2016)

- Fleet control models are supply-focused models providing rules to assign vehicles to their goals.
- Mode choice models assign travel demand to specific modes according to their socioeconomic parameters (Ortúzar and Willumsen, 2011, chapter 6).

D. Meta-analysis

The meta-analysis completed the descriptive statistical analysis by providing a quantitative estimate of the (expected) impacts of AV services, focusing on the KPIs for which enough studies were reported in the statistical analysis.

1) Selection of indicators

According to the descriptive statistical analysis, of the twenty-two indicators scrutinized, four KPIs stand out in terms of coverage and quality of treatment.

First, the level of demand was assessed with the Vehicle Kilometers/Miles Traveled (VKT or VMT). This is a paramount KPI for mobility services as it not only relates to travel demand, but also to traffic flows, operating costs and revenues, and virtually all externalities. It is therefore a key driver of economic profitability in a CBA (Small and Verhoef 2007).

Travel time is a key performance indicator used to measure service quality. Travel time (TT) refers to the total travel time composed of (i) access/egress time (only for line-based or stop-based services), (ii) waiting time, and (iii) in-vehicle travel time. Access/egress time and waiting time may be equal to zero for some services, such as the private car. Travel time is strongly related to consumer surplus and thus to economic profitability (Small 2012). Conversely, as the service evaluated is autonomous, it has a much smaller impact on operating costs since no drivers are involved (Tirachini and Antoniou 2020). Similarly, as most AVs are electric, the impact of travel time (or more specifically of speed) on the environmental externalities is greatly reduced.

Third, fleet size is a widespread key performance indicator in the literature, especially for on-demand services, as many papers study the link between fleet size, dispatch strategies and operational performance (e.g. Hörl,

Becker, and Axhausen 2021). While it is strongly related to capital costs, it also exerts influence on traffic, congestion and/or parking needs, and environmental externalities (from a lifecycle perspective).

Finally, the total cost of a mobility service measures the total production cost of the service, including at least the operating costs and capital costs if available. Unlike Tirachini and Antoniou (2020), we did not consider user costs, as these were already captured by the travel time indicator. In the simulation literature, costs are generally averages per year that are typically derived from more precise total cost of ownership approaches that measure the cost of a vehicle over its entire lifecycle, including purchase, operations, and end of life (e.g. Ongel et al. 2019).[4] For AV public transit services (including taxi and ride-hailing), the absence of drivers could lead to a decrease in operating costs (Bösch et al. 2018). Conversely, if the AV service attracts more demand than the former conventional service, Total Costs could rise as a result. The total costs indicator thus reflects both operational and marketing performance. The choice of a total costs indicator relative to unit cost indicators (cost/km, cost/seat, or cost/passenger) relates to 1) the interest of the study of overall service performance and 2) the constitution of the cost indicators. Unit costs are frequently model inputs, often based on Bösch et al. (2018), whereas total costs reflect output from the simulation or result from an economic evaluation based on the simulation output.

2) Data extraction

The performance of the autonomous vehicle service was measured relative to another service. For each of the four KPIs (VKT, Travel Time, Fleet Size, Total Costs), we computed the mean relative variation between the reference service and the service compared. Consider for instance an AV service providing rideshared door-to-door trips, and that the VKT for this service is found to be equal to 115% that of the reference service (conventional private cars, for instance). This means that when these two services are compared in the meta-analysis, the AV taxi service will result in a +15% increase in VKT relative to conventional cars. While the usual benchmark against AV services is conventional private vehicles, some studies test AV services against conventional public transit or other AV

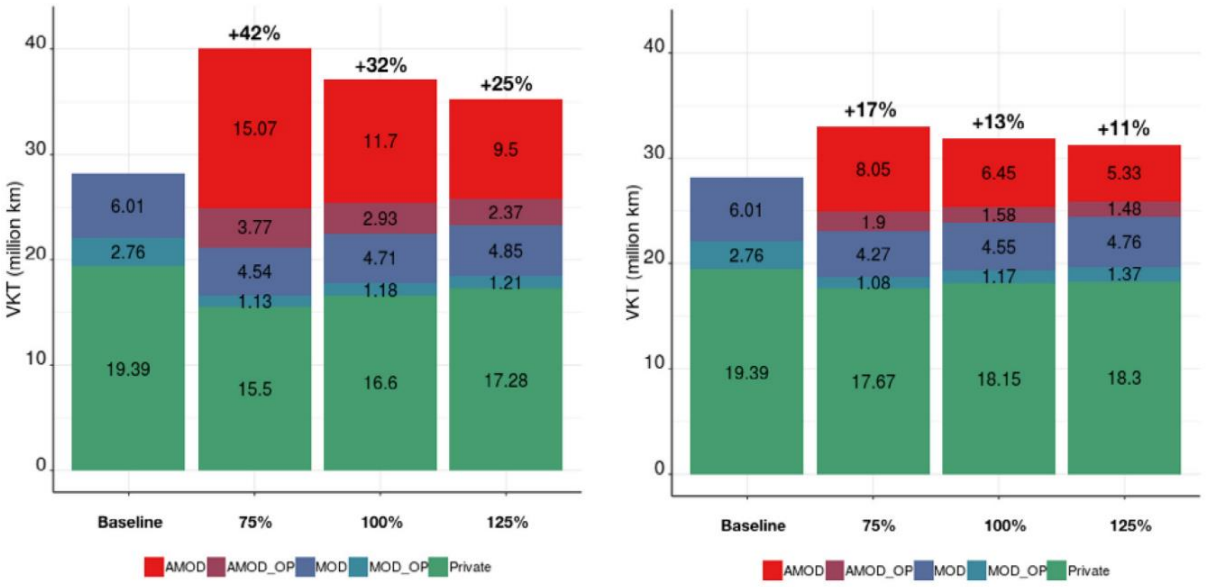
[4] The total cost of ownership approach is actually highly congruent with the cost-benefit analysis in that both consider discounted cash or monetary flows over a certain period of time.

services (e.g., by comparing AV services that offer private trips versus rideshare trips).

Studies may consider several scenarios regarding the service characteristics or the economic environment (e.g., market penetration, adoption levels). When scenarios consider different shares of Avs within the vehicle fleet, we decided to keep only the scenario with the highest penetration ratio. For instance, Llorca et al. (2017) considered two market penetration scenarios, with 20% and 40% share of Avs within the vehicle fleet, respectively. In this case, only the 40% scenario was retained. If more than one scenario with a high penetration rate is considered in a study, the KPI is averaged across the scenarios. In some cases, developed below, the performance variation needed to be estimated to obtain a proxy of the service implementation impact.

To illustrate this methodology, we put forward our main assumptions and the corresponding examples below by considering VKT as the indicator being evaluated. The methodology is similar for Travel Time, Fleet Size and Total Costs. If the scenarios involve varying fare levels, substitution rates of AV/per trip, or modal shares, then the indicator was averaged across scenarios.

In cases where the KPI evolution was combined with other modes, a ratio was used to estimate the KPI evolution. In Oh et al. (2020), VKT are estimated for two adoption level assumptions: a) a High adoption scenario and b) a Moderate adoption scenario. Again, only scenario a) was used. Moreover, the VKT for AMOD (Autonomous Mobility On Demand), which encompasses AV (autonomous taxi) and SAV (shared autonomous taxi) services, was computed as a single synthetic mode (Figure 8). Thus, to differentiate the performance of the two modes, a ratio from their respective modal shares was used to assign a proxy of the VKT of each mode.



(a) High Adoption (b) Moderate Adoption

Fig. 13. Vehicle-Kilometres Travelled (VKT).

Figure 8. Results of simulation for vehicle kilometers travelled
Source: Figure 13 from Oh et al. (2020)

The average rise in AV and SAV VKT were extracted from the average of AMOD VKT (4), in other words, AV + SAV VKT, with the average of the 3 price scenarios of the high adoption scenario, in other words:

(+42% + 32 % + 25%)/3 = + 33%, with the average ratio of modal share for AV (6.27%) and SAV (8.83%) on total AMOD modal share (15.10%) from Figure 9.

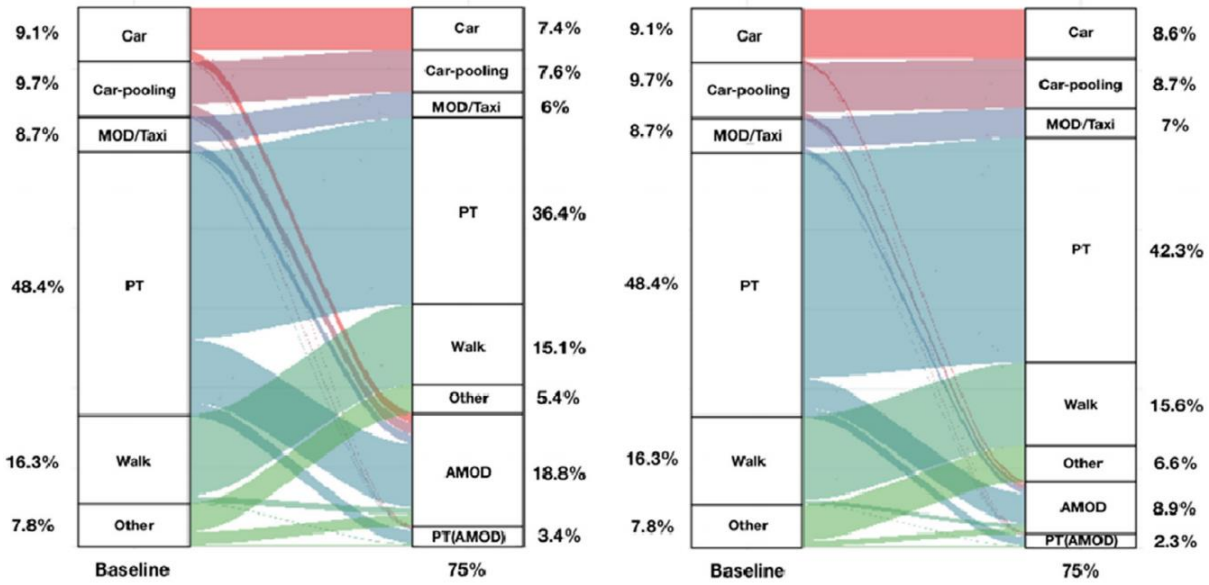


Fig. 12. Mode shifts.

Figure 9. Simulation results for modal shifts
Source : Oh et al. (2020), Figure 12

The average share of the rise of VKT from the AV and SAV is respectively: 33% x 6.27 % / 15.1% = +14% and 33% x 8.83%/15.1% = +19%.

III. Results and discussion

A. Descriptive statistical analysis

1) KPI occurrences

a) Results

The two categories of indicators investigated in all 84 papers of our first corpus (apart from one paper on operations) cover service performance and operations (Figure 10). They also feature the highest average number of indicators per paper. For service performance, the mean number of indicators per paper is 3.37 (from 4 possible indicators), and only 12 papers (14%) use less than 3 of these indicators. Surprisingly, the VKT indicator is the least represented, yet still has over 76% of occurrence (Figure 13 in Appendix). The VKT indicator may be straightforwardly computed by multiplying total ridership by the mean travel distance, which might explain why it is not always reported. Regarding operations, the average number of indicators per paper was 2.64 (from 5 possible indicators), and 43 papers (51%) use fewer than 3 of these indicators. Fare and profit are the least

represented within this category, while fleet size, total cost and utilization rate are present in respectively 83%, 73% and 55% of the corpus (Figure 14 in Appendix). In fact, a large number of papers deal with optimal fleet size and dispatching strategies (e.g. Fagnant and Kockelman 2016; Loeb and Kockelman 2019; Vosooghi et al. 2019). The latter three indicators – fleet size, utilization rate, and total costs – tend to form the crux of the analysis, while fares and profits may be disregarded in that they are more related to demand.

Externality indicators are considered at least once in fewer than two-thirds of the papers reviewed (68% of occurrence). Usage is more heterogeneous than for the two previous types of indicators (Figure 15 in Appendix): the prevalent KPI within the category is congestion (61% of occurrence), followed by energy (33%) and climate change (26% of occurrence). Local pollution (21% of occurrence) always appears together with a climate change indicator, reflecting the fact that no paper in our corpus focuses on air quality, while climate change is given slightly more attention. Noise and safety KPIs have significantly lower occurrence rates (1% and 6% respectively), and again always appear in combination with climate change KPIs (e.g. Simoni et al. 2019).

Socioeconomic profile indicators appear at least once in 21% of the corpus, with 0.31 indicators per paper on average. Moreover, only four papers include more than one socioeconomic category indicator (Berrada 2019), see Figure 16 in Appendix.

Finally, just two papers in the whole corpus (2% of the corpus) include CBA indicators, with a single indicator each time (Figure 17 in Appendix): either the BCR (Gelauff, Ossokina, and Teulings 2019) or the IRR (Fagnant and Kockelman 2016).

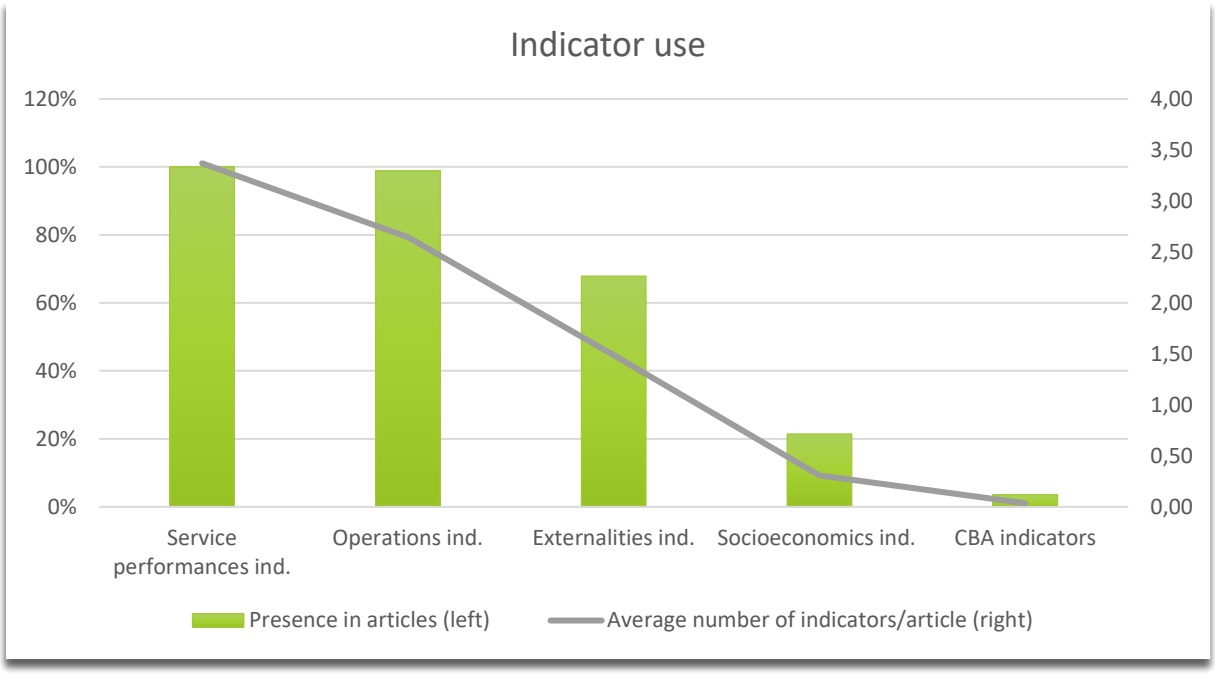


Figure 10. *Occurrences of indicators per category*
Source: prepared by the author.

b) Discussion

The analysis shows a very strong prevalence of service performance and operational indicators, reflecting the fact that most papers focus on performance from the perspective of the user or the operator, but seldom that of society as a whole. Since most AVS tested in the papers are on demand, fleet control and optimal dispatching strategies attract considerable interest (again to cite only a few Ben-Dor, Ben-Elia, and Benenson 2019; Fagnant and Kockelman 2016; Farhan and Chen 2018; Loeb and Kockelman 2019; Vosooghi et al. 2019). As result, the most frequently investigated KPIs are supply oriented, including, on the operator side, the VKT, fleet size, utilization rate, and costs, and on the user side, waiting time and travel time. Conversely, KPIs that are demand-oriented such as fares or more elaborate KPIs such as profit are covered less in the corpus.

In addition to being underrepresented compared to service performance and operational KPIs, the indicators relating to externalities tend to be those where the analysis is the least thorough. In some papers, pollutant emissions (GHG and local pollutants) and congestion are mentioned but not analyzed (Simoni et al., 2019; Zachariah et al., 2014; Heilig et al., 2017, Jäger et al., 2018). In others (Navidi et al., 2018; Wang et al., 2018; Childress et al., 2015), pollutant emissions and congestion are repeatedly proxied by the distance traveled, which indicates the general

trend but not the intensity of the trend. Furthermore, while VKT is a key driver of pollutant emissions, vehicle type (especially if the AV service is electric), average speed and congestion also have a strong influence (Grote et al. 2016), which is not captured when VKT is used as a proxy for emissions.

Socioeconomic category indicators (age, gender, income class, people with reduced mobility) are often mentioned but seldom analyzed. For instance, people with reduced mobility are mentioned once (Sieber et al., 2018), but they do not fulfill any role in the simulation process. In Meyer et al. (2017), age acts as an important parameter of the demand simulation with AV taxis since people with limited access to mobility increase the overall demand by 16%. Similarly, Puylaert et al. (2018) do not distinguish travel behavior between age or social categories, but include these parameters to determine the type of car owned. Truong et al. (2017) proceed in a similar way. In these papers, age only serves as a segmentation variable in the demand model. Only one paper carries an in-depth analysis by investigating the impact of AV service on the mobility of the age brackets with mobility issues (Kamel et al., 2018).

Cost-benefit analysis indicators are extremely infrequent: only two papers (2% of the corpus) feature them, with a single indicator in each case. Moreover, in Fagnant and Kockelman (2016), the IRR is used as a financial indicator, meaning that only the study of Gelauff et al. (2019) actually engages in a welfare analysis of AV services. Moreover, the latter study focuses on consumer surplus, and does not consider either the operator surplus or externalities such as congestion, safety and pollutant emissions. This virtual absence of cost-benefit analysis indicators is not surprising if we consider that CBA is a step further from environmental indicators which are already poorly represented within the corpus (with only 21% of occurrence). This confirms that the focus of the AV simulation literature is currently strongly oriented toward the operational design of AV services (including fleet size, dispatch and pooling strategies), rather than their strategic design, which would involve a welfare analysis (in most cases involving the computation of CBA indicators).

2) Model types

a) Results

Agent-based models (ABMs) represent the large majority (75% of the corpus) of the models used for AV simulation (Table 3). Within this category, the MATSim open-source framework is used in more than half the agent-

based model papers (41%). While in most cases, including all MATSim instances, travel demand is determined endogenously, some ABMs tend to treat travel demand as exogenous, and focus on fleet control. The agent-based modeling paradigm is then used to consider user-vehicle interactions regarding waiting times and/or pooling decisions in the matching process between users and vehicles.

Four-step models represent the second largest category, yet account for only 10% of the second corpus. Activity-based (i.e., non agent-based ones) models are an intermediate form between agent-based and four-step models: while their representation of demand is identical to that of activity-based ABMs, the transportation supply is represented in a simpler and more aggregate manner than in four-step models. This aggregate representation of supply precludes representing vehicle dispatching strategies, and thus finely analyzes the operational performance of the AV service. When four-step or activity-based models are used, the performance of the AV service is often evaluated through the lens of modal shares (Levin and Boyles 2015) or trip characteristics, such as the mean trip length or duration (Childress et al. 2015; Zhao and Kockelman 2018). Berrada (2019) is an exception as in this case a four-step model running in VISUM is coupled with VIPSIM, an agent-based fleet control-oriented model, resulting in a range of indicators closer to ABMs than to four-step and activity-based models.

Direct Demand Models are the third largest category of models, representing 6% of the papers. These models are used to generate travel demand based on supply and demand characteristics, but with no or very limited representation of spatial interactions (Anderson et al., 2006). They are often used when considering aggregate trips at the level of a country, a region, or a specific origin-destination (Ortúzar and Willumsen 2011).

Models	Use
Agent-based	75%
Four Steps	10%
Direct Demand model	6%
Traffic model	2%
LUTI	2%
Fleet control model	2%
Mode choice model	2%

Table 3. Models used in the first corpus

Source: prepared by the authors

Other models used in the corpus were only exploited twice, but not enough papers were gathered to provide conclusive evidence. This category included the use of Discrete Choice Models. Like direct demand models, these models are often preferred to four-step models – which add the generation, distribution and assignment steps to the mode choice – when spatial interactions and network effects (as when users switch from one service to another, since a change in the transportation supply or in travel conditions leads to a new supply-demand equilibrium) are not the focus of the paper. For instance, Truong et al. (2017) provide a rough estimate of the impacts of AVS in Victoria, Australia, with no spatialization of the results. Sun et al. (2020) estimate a mixed-logit mode choice model to investigate user preferences and assess whether cost savings or travel time savings are more important for users when comparing AVS with Conventional Public Transit services, meaning that, once again, spatial interactions are not a central issue. Other models were also identified in our corpus that target very specific issues that are not part of our study. For instance, LUTI (Land Use and Transport Integrated) models highlight the interaction between land use (mostly job locations and residential areas) and transportation. Fleet control models are a type of model that focus on the supply side of transportation. When simulating on-demand services, ABMs often use a fleet control module, such as the DRT module for MATSim. Lastly the traffic model provides an analysis of interactions between infrastructure and vehicles through the infrastructure characteristics and the vehicle capacities. There is less focus on the service level than on the infrastructure level, which is mainly why this type of model does not appear much in our corpus.

b) Discussion

There is thus a strong focus on agent-based models in the literature. These models emphasize analysis at tactical level, with relatively close attention to fleet optimization (compared to the four-step models). They aim to optimize operational efficiency by maximizing the utilization rate (Fagnant and Kockelman, 2016; Vosooghi and al., 2019; Llorca et al., 2017) and/or the level of service for a given fleet (Wang et al., 2018; Lu et al., 2018).

Agent-based models are more suitable to describe dynamic availability of mobility services and interactions between agents compared to four-step models. As mentioned in 2.2, the corpus is primarily composed of on-demand services: of the 63 studies made with agent-based models, 61 consider on-demand services. Thus, it is no surprise to see such widespread use of these models in the corpus.

In addition, studies that use agent-based models do not take different classes of demand into consideration (depending on their socioeconomic profile, for instance), which represents a future research path, especially since AVS show promise in improving accessibility of age brackets with mobility issues.

B. Meta-analysis of AV Impacts

For the second corpus, the papers selected use a least one of the four KPIs (VKT, travel time, fleet size and/or total costs) in a comparative form. The number of documents dropped from 84 documents in the first corpus to 48 documents in the second. The total number of services compared is 80, however, since several papers evaluate more than one AVS.

1) Results

Based on the service nomenclature defined in 2.2, we generated combinations of services that were investigated in our second corpus. Ten combinations of services were finally identified and named, as presented below in Table 4.

Service features					Service Name
PO*	No RS*	D2D*	Car	Conv.	**Private car**
PO	No RS	D2D	Car	Aut.	**Private AV**
Public	RS	D2D	Car	Conv.	**Shared Taxi**
Public	No RS	D2D	Car	Aut.	**AV**
Public	RS	D2D	Car	Aut.	**SAV**
Public	RS	SB*	Car	Aut.	**Stop Based AV**
Public	RS	D2D	Shuttle	Aut.	**Door-to-Door Shuttle**
Public	RS	SB	Shuttle	Aut.	**Stop Based Shuttle**
Public	RS	Line Based Schedule based	Bus or rail	Conv.	**Conventional Public Transit**
Public	RS	Line Based Schedule based	Shuttle	Aut.	**Line Based Shuttle**

** PO stands for "Private Ownership ; RS stands for "Ride-sharing" ; D2D stands for Door-to-door ; SB stands for Stop Based*

Table 4. List of services considered in the meta-analysis

Source: prepared by the authors.

The performance comparisons between autonomous and conventional services show strong differences depending on the service of reference. When compared to private cars, autonomous services offer overall performance variations of +/- 50% on the four indicators (Figure 11). The variations are much larger (up to +700%) when the service of reference considered is Conventional Public Transport (Figure 12).[5]

The number of papers covering comparisons between two (or more) services also indicates the interest of the academic community in such comparisons. In the corpus collected, the three most frequently compared service pairs are:

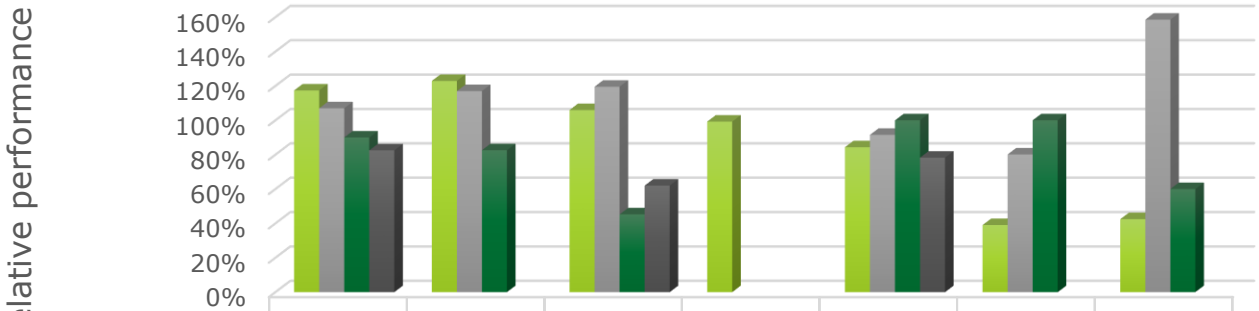
- the replacement of private cars by Private AV,
- the replacement of private cars by autonomous vehicles (AV), corresponding to autonomous taxis (shared vehicles but no ridesharing),
- the replacement of private cars by shared autonomous vehicles (SAV). [6]

These three categories represent the majority of comparisons. The next major comparison is between conventional public transit and AV/SAV (~15% of comparisons).

According to Stocker and Shaheen (2019), AV and SAV services are the main autonomous vehicle business models projected by the major manufacturers (Ford, Tesla, Daimler) and tech developers (Google or Uber). It is not surprising that academic attention also focuses on these service types. On the other hand, shuttle-based services are explored to a greater extent by public transport operators via several experiments worldwide (see SAM project).

[5] Note that the methodology adopted for data extraction, which averages indicators in the case of multiple scenarios, reduces the occurrence of extreme values in the results. It also artificially reduces data variability associated with scenario parameters, which is why the meta-analysis focuses on service characteristics only.

[6] There is no clear consensus in the literature on the definition of "Shared Autonomous Vehicles", as shared may refer either to carsharing, ridesharing, or both (Narayanan, Chaniotakis, and Antoniou 2020). Here we distinguish private AVs, AVs (carsharing) and SAVs (carsharing and ridesharing).



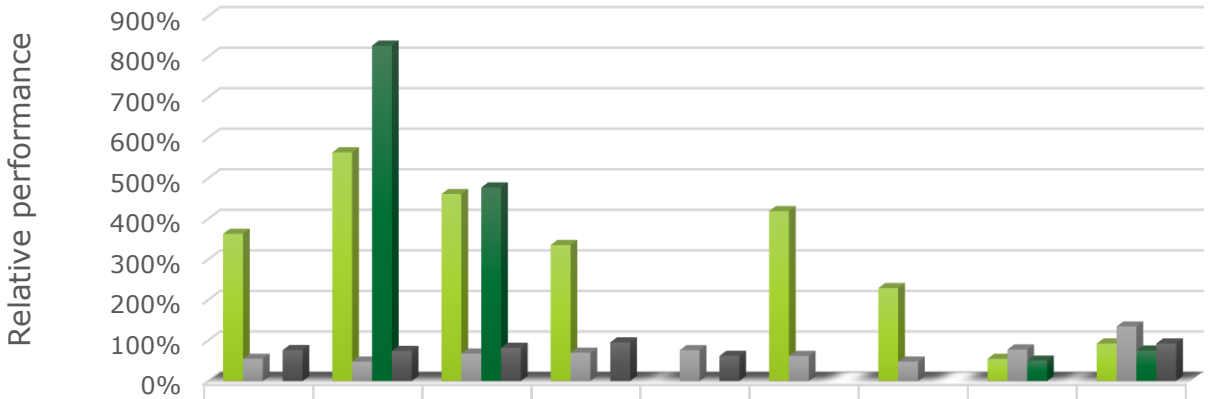
	Private AV	AV	SAV	Stop Based SAV	SAV	Stop Based SAV	Stop Based Shuttle SAV
	Private Car				AV		
Average VKT perf.	117%	123%	106%	99%	84%	39%	42%
Average TT perf.	107%	117%	120%		92%	80%	159%
Average FS perf.	90%	83%	45%		100%	100%	60%
Average TC perf.	83%		62%		78%		

Figure 11. AV On-demand service performance against conventional counterparts

Acronyms: VKT = Vehicle Kilometers Traveled, TT = Travel Time, FS = Fleet Size, TC = Total Costs

Example of interpretation: here the first comparison on the left is the performance of Private AV vs. Private Car. The four indicators (VKT, Travel Time, Fleet Size and Total Costs) are covered by the literature, and the replacement of private cars by private Avs should result, on average, in a rise of VKT and Travel Time (by respectively +17% and +7%), but also in a reduction of Fleet Size and Total Costs (respectively by 10% and 17%).

Source: prepared by the author.



	Door-to-Door Shuttle	AV	SAV	Stop Based Shuttle	Aut. Bus	Door-to-Door Shuttle	Stop Based SAV	Stop Based SAV	Stop Based Shuttle
	Conventional Public Transit					Line Based Shuttle		Door-to-Door Shuttle	
Moyenne de VKT	363%	564%	461%	335%		419%	229%	55%	92%
Average TT perf.	55%	48%	68%	70%	76%	62%	48%	78%	134%
Average FS perf.		827%	477%					50%	75%
Average TC perf.	76%	74%	82%	95%	62%				92%

Figure 12. AV service performance against Conventional Public Transport

Source: prepared by the author.

2) Discussion

Focusing first on the comparison between AV-based services and private cars, it clearly appears that the three most studied AVS (Private AV, AV and SAV) are three steps from the same ladder, trading the VKT and travel time performance of private cars against their fleet size performance at different intensities (Table 5).

Reference	New Service	VKT	Travel Time	Fleet Size	Total Costs
Private car	Private AV	+17%	+7%	-10%	-17%
Private car	AV	+23%	+17%	-17%	N/A
Private car	SAV	+6%	+20%	-55%	N/A
Public transit	AV	+464%	-52%	+727%	-26%
Public transit	SAV	+361%	-32%	+377%	-18%
AV	SAV	-16%	-8%	No variations	-22%

Table 5. Performance comparison of conventional and autonomous services

**Regarding comparisons with public transit, SAV is found to be more costly than AV (-18% versus -26%), based on 3 and 4 occurrences respectively. On the other hand, the direct comparison of AV and SAV leads to the opposite result, in other words, SAV is less costly (-22%) but based on only one occurrence. These results should thus be considered with care.*

Source: prepared by the authors.

Private AV services offer the best performance regarding Travel Time, which increases by only +7% compared to Private Car, as opposed to +17% for AV and +20% for SAV. This is mostly due to the fact that private AV do not involve waiting time as is the case for AV or SAV (Fagnant et al., 2016). If VKT and Travel Time are greater for private AVs than for Private cars (+17% and +7% respectively), it is probably because the marginal generalized cost of the former is lower than that of the latter. The expected decrease in the value of travel time savings from not having to drive (Kolarova and al., 2019; Fosgerau, 2019; Singleton, 2019; Szimba and Hartmann, 2020; Gao et al., 2019) should result in both more frequent and longer trips.

The marginal operating cost could also be lower for autonomous vehicles operated by a third party than for conventional ones. This should have a considerable impact on mobility services in which drivers' wages are an important component (Bösch et al., 2018; Bauer et al., 2018; Loeb and Kockelman, 2019). However, these analyses rely on forecasts not confirmed as yet by empirical data. Similarly, the cost analysis of Leich and Bischoff

(2018) is based on assumptions that cannot be validated based on real data, which would have a significant impact on their findings.

The effect on VKT is relatively similar for AV (+23%) and SAV (+6%) as for Private AV (+17%), but the fleet size is smaller due to ridesharing. The effect on fleet size is even greater for SAV (-55%) than for AV (-17%) since ridesharing also makes vehicles not fully loaded available to passengers (Farhan and Chen, 2018). Similarly, VKT are lower for SAV than for AV (-16%) since fewer vehicles are assigned through a centralized dispatcher, while maximizing their loading. In addition, SAV would attract at least the same number of passengers since they usually charge lower fares than AV (Simoni et al., 2019; Vosooghi et al., 2019), reducing their total generalized cost, even for less comfort and additional detours (Golbabaei et al., 2020). Ridesharing can also help to further reduce waiting times, especially during peak times, by increasing vehicle availability (Hörl, 2017). However, given that travel times include waiting times as well, the literature notes that the increase in travel time is greater for SAV (+20%) than for AV (+17%), indicating that the extra Travel Time resulting from detours exceeds the reduction in waiting times (Vosooghi et al., 2019; Farhan and Chen, 2018).

Regarding vehicles' capacity, the optimal capacity providing shared door-to-door trips is found to be between two and four seats per vehicle (Leich and Bischoff, 2018; Berrada, 2019; Zachariah et al., 2014; Gurumurthy et al., 2019; Farhan and Chen, 2018; Vosooghi et al., 2019). In fact, in general, the average occupancy is found to be about two persons per vehicle. These numbers should be taken with caution. The effect of empty kilometers traveled was not assessed in this meta-analysis and their role in the occupancy rate might be important. The average occupancy per vehicle also decreases with fleet size (Winter et al., 2018). That being said, Wang et al. (2018) published a paper on the ridesharing potential of Singapore, based on real taxi booking data, where 40% of the trips were shared by six passengers or more in taxis, showing the potential of this type of service in densely populated urban areas. Winter et al. (2018) and Navidi et al. (2017) also presented evidence of the ability of AV and SAV to take advantage of economies of scale, even if the leverage seems weaker than the conventional public transit leverage. This shows that benefits from a reduced Fleet Size are more an outcome of sharing vehicles (sequentially or simultaneously) than the effect of automation. Zhu (2019) exposed that the extrinsic monetary incentive did not provide leverage to support ridesharing policies. The automation innovation might help to promote societal changes.

We now turn our attention to the comparison between conventional public transit and autonomous services. Shuttle-based services provide a vehicle capacity of eight to fifteen seats, allowing more passengers to board than car-based services, while offering greater flexibility than conventional public transit. In this configuration, a shuttle service would save passengers time (Sieber et al., 2020; Bischoff et al., 2018; Viergutz and Schmidt, 2019), but would also offer both the service provider and passengers savings at the cost of a larger fleet (in number of vehicles, though not of the same size). This topic has attracted less attention in the academic community and even fewer studies that would correspond to the methodology established for the second corpus.

From our results (Figure 12), stop-based routing seems to be the best autonomous alternative to conventional public transit to limit externalities (here proxied by fleet size and VKT). In addition, a stop-based SAV service is also more likely to benefit from economies of scale than a door-to-door shuttle (fewer detours, thus shorter travel times and waiting times, and less congestion).

The comparison of AVS with conventional public transit suggests that AVS could be interesting in peri-urban or rural areas where conventional public transit might struggle to benefit from economies of scale, or as a feeder (first mile and last mile) service. The expected decrease in operating costs from the drivers' salaries could allow smaller and more flexible vehicles to operate, reducing both passenger waiting time and the overall system costs (Berrada and Poulhes, 2021; Schlüter et al., 2021). Another alternative is to operate buses with a higher level of service but reduced capacity (Bösch et al., 2018; Winter et al., 2018). However, these reductions come at the price of a larger fleet size and more VKT (Sieber et al., 2019; Bischoff et al., 2018; Leich and Bischoff, 2018; Bösch et al., 2018b; Merlin, 2017; International Transport Forum, 2015; Imhof et al., 2020) which might be less of a problem in rural areas, where the space dedicated to mobility has a lower opportunity cost, and the externalities generated by transport are less of an issue than in urban areas. In addition, most of the publications in our corpus focus on urban and peri-urban areas, with only two articles specifically dealing with rural areas (Viergutz and Schmidt, 2019; Sieber et al., 2020).

However, the study by Leich and Bischoff (2018) warns of the dangers of competition between conventional public transit and AVS, since AVS would take over the public transit passengers and reduce its profitability. This could result in a reduction in the level of service for public transit, which

would exacerbate the modal shift toward AV services. The study of ride hailing firms by Carballa Smichowski (2018) shows that the ride hailing companies might be prone to use predator price, which would strengthen the threat if these companies were the ones developing the autonomous vehicles. The authors therefore recommend conventional public transit operators switching to autonomous vehicles. Hatzenbühler et al. (2020) compared the performance of conventional and autonomous buses and found that autonomous bus services were less expensive to operate and provided better travel times to boot.

The idea of public transit lines being substituted by autonomous flexible vehicles is discussed not only in the academic field, but also in private industry. Rau et al. (2020) investigated the effect of autonomous shuttle pods driving through Singapore in dedicated lanes. These pods could be linked together to create little trains to absorb demand during peak hours and then divided into multiple vehicles to provide attractive Level of Service, even during off-peak times. This idea is similar to the Loop Aix-Marseille project and some Hyperloop projects (see Loop Aix Marseille and Urbanloop references).

IV. Conclusion

The regulator is the actor interested in the analysis of the externalities. As a complement to simulation models, tools have been developed (cost-benefit analysis and multicriteria analysis) to assess these issues. However, very few studies offer an analytical framework that allows the economic appraisal of AV to be carried out *in situ*.

In order to make the best strategic choice (i.e., to define the "best" mobility service with respect to the given mobility and sustainability objectives), we cannot rely on an eclectic set of indicators. The regulator needs a comparative base between projects, with the potential to rank them. The average methodology could overshadow concerns about the heterogeneity of demand during the day (peak and off-peak time), the type of territory (urban, peri-urban and rural), or the field of application of the mobility service (First and Last Mile service, for example).

The sample of articles provides interesting opposing trends between Private Car and Private AV, AV and SAV services, but the comparison of other service pairs is less robust. If autonomous taxis (AV and/or SAV) were to replace conventional private cars, they should increase VKT between +23% and +6% and Travel Time between +17% and +20% but reduce

Fleet Size by 17% to 55%. The replacement of Conventional Public Transit (traditionally operated with high-capacity vehicles and with a line and schedule base) by AV or SAV could reduce Travel Time by half and might also help to reduce overall costs. This transition to on-demand services would also extend the required Fleet Size and the VKT by three to six times the initial value.

Future studies could provide more accurate results from the mobility simulation of the type of territories or specific impact of one of the service features, such as ridesharing. In the meantime, the literature could benefit from an extended analysis of the impact of Autonomous vehicles through the socioeconomic prism.

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VI. Appendix

In order to promote transparent science, the authors made the data of both the Bibliometric analysis and the Meta-analysis available publicly.

Online Appendix 1. Autonomous Vehicles Impacts - Bibliometric analysis and Meta-analysis from mobility simulations. URL: https://figshare.com/projects/Autonomous_Vehicles_Impacts_from_mobility_simulations/125386

Journals	Occurrences
Transportation Research Record	15
Transportation Research Part C: Emerging Technologies	7
Transportation Research Part A: Policy and Practice	7
ABMTrans	5
mobil.TUM	4
Intelligent Transportation Systems Conference	4
Transportation Research Procedia	3
Transportation	3
International Conference on Traffic and Transport Engineering (ICTTE)	2
International Journal of Transportation Science and Technology	2
Transport Policy	2
Transportmetrica A: Transport Science	2
Transportation Research Part A: Policy and Practice	2
Journal of Advanced Transportation	2
Computers, Environment and Urban Systems	1
Research in Transportation Economics 62	1
Advanced Microsystems for Automotive Applications	1
Transportation Research Part D: Transport and Environment	1
EURO Working Group on Transportation (EWGT)	1
Journal of Urban Planning and Development	1
ANT 2016	1
Journal of Public Transportation	1
2015 IEEE 7th International Conference on CIS & RAM	1
Urban Rail Transit	1
European Transport Research Review	1

International Symposium of Transport Simulation	1
Environmental Science & Technology	1
Thesis	1
Arbeitsberichte Verkehrs- und Raumplanung	1
International Conference on Transportation	1
Advances in Transport Policy and Planning	1
The 10th International Conference on Ambient Systems, Networks and Technologies (ANT)	1
Springer Nature	1
International Conference on Internet of Vehicles	1
Intelligent Transportation Systems Conference	1
Sustainability	1
Institute of Electrical and Electronics Engineers Access	1
Technical report	1
Grand Total	84

Table 6. Publications

Source: prepared by the author.

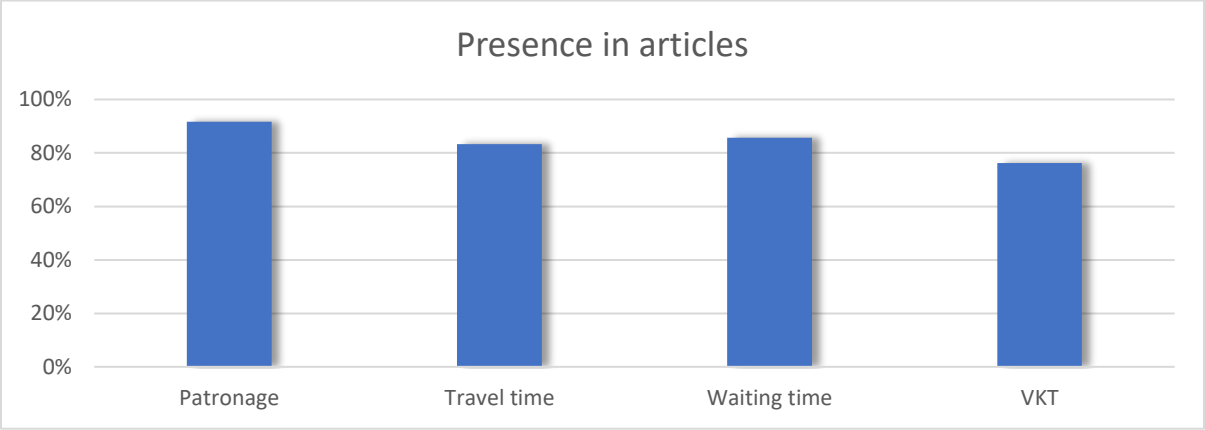

Figure 13. Service performance indicator use

Source: prepared by the author.

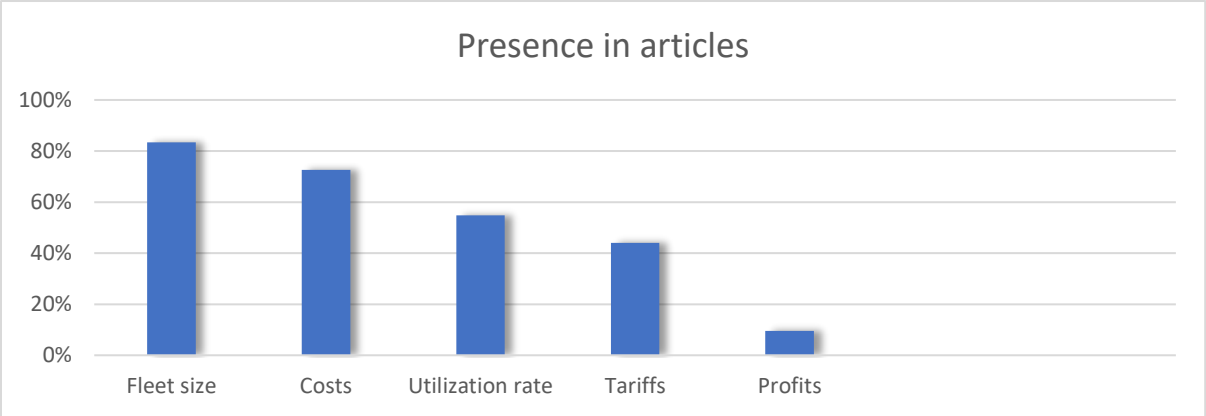

Figure 14. Operational indicators use
Source: prepared by the author.

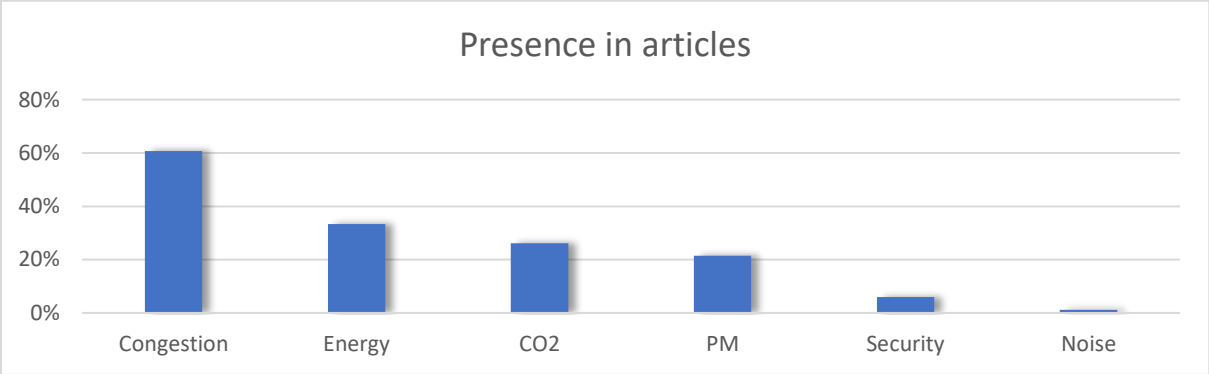

Figure 15. Externalities indicators use
Source: prepared by the author.

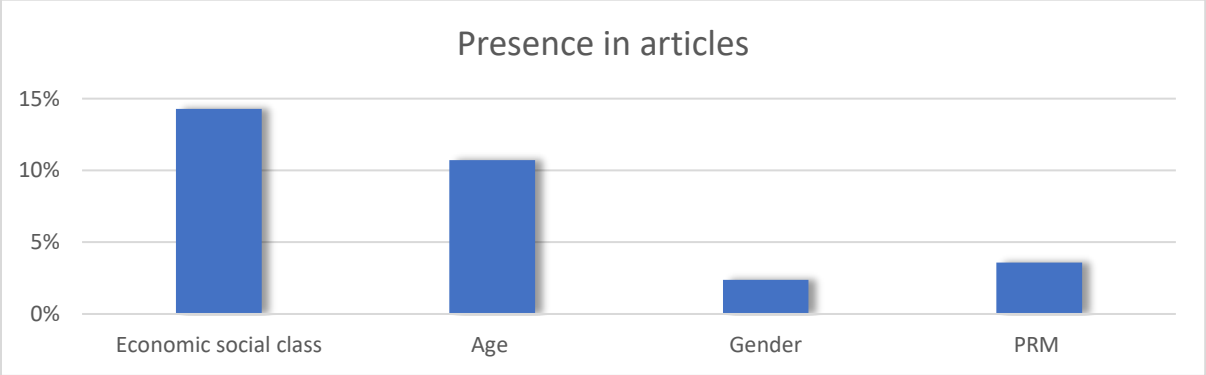

Figure 16. Socioeconomics indicators use
Source: prepared by the author.

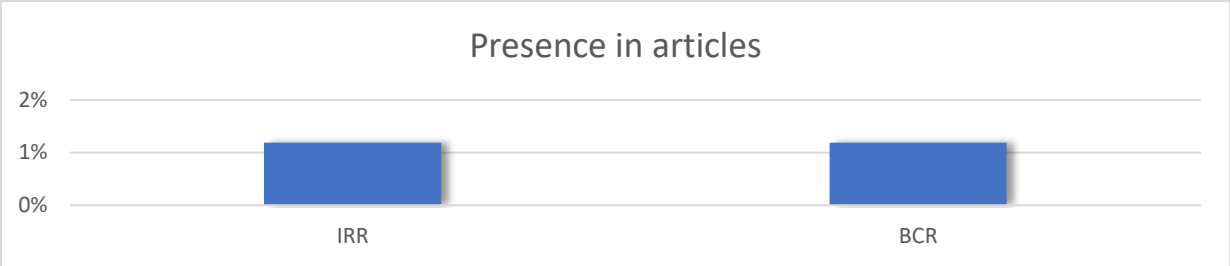

Figure 17. CBA indicator use

Source : prepared by the author.

Chapter 2. Autonomous vehicles, a Cost Benefit Analysis framework

Abstract

The last few years, an automated (or autonomous) vehicles (AV) mania has appeared (Carreyre et al., 2022). As this technology still remains at the technological development stage, the studies on the topic must be based on forecasted methodologies. Approaches such as reveled preferences studies cannot be pursued because of the immature technological object. In such situation, mobility simulations can offer a first glance at the mobility futures under some postulates.

However, the simulation community did not made use of an Economic Evaluation (EE) framework to evaluate simulations outputs yet and still remains at the operational level of evaluation. To fulfill, the thesis goals, we choose an appraisal method able to capture AV economic effects amongst the existing ones, we identify AV perturbations and adapted the existing method to apprehend most of the AV perturbations.

In the first section, the eligible appraisal methodologies will be discussed. In the second section, the history, the concepts, the main theorical discussions and the criticisms of the chosen methodology will be developed. The third section addresses the EE adaptation required to include AV and interact with an agent-based model. Fourthly, the appraisal framework is presented and discussed.

I. Introduction

Transport projects require many resources and often have long-term effects. The required assets for transport projects are quite specific, as once a road has been built, the asphalt does not retain much of its initial value (Merkert et al., 2018). These potential losses motivate the establishment of planning procedures that assess both the costs and the advantages of the project.

The economic evaluation (EE) of transport projects is the assessment of the outcomes of a transport project (de Rus et al., 2020). Transport projects have a financial cost and heterogeneous impacts. Some of these impacts are considered desirable, such as reductions in travel times, operational costs or emissions. Other impacts are undesirable, such as increases in accidents or emissions.

The EE offers a methodological framework for evaluating whether the economic impacts of a transport project offset its financial cost.

The most frequent methodologies for EE are the Cost Benefit Analysis (CBA), the Multicriteria Analysis, (de Rus et al. 2020), the Environmental Impact Assessment (Mouter, 2021) or the Cost Effectiveness Analysis (Peterson 1986)

In the last few years, an automated (or autonomous) vehicle (AV) enthusiasm has appeared (Bahamonde-Birke et al. 2018; Carreyre et al. 2022; Gandia et al. 2021; Narayanan, Chaniotakis, and Antoniou 2020; Soteropoulos, Berger, and Ciari 2019). As this technology still remains in the development stage, ex-post studies such as revealed preferences studies cannot be conducted. Most of these studies have been based on spatial simulations, mostly using agent-based models (Jing et al., 2020), or on stated preference surveys (Correia et al., 2019). However, few studies have attempted to use spatial simulation to conduct a comprehensive economic evaluation of the service. Andersson and Ivehammar (2019) used cost-benefit analysis (CBA) to evaluate the long-term large market penetration capabilities of private AV scenarios. However, they did not consider spatial simulations of traffic forecasts, modal shifts, or other factors. Kockelman et al. (2017) simulated private AV use and assessed the results through a limited CBA, taking into account only the impacts on congestion, crashes and travel time savings. Neither the operator profit nor the environmental impacts were considered. In addition, both of these abovementioned studies only considered private AVs. The research question

of this chapter can be formulated as follow: Which appraisal methodology can be used to assess AV services? How should the current evaluation framework be adapted to evaluate AVs to capture most of the new impacts? The goal is to produce a methodology for the evaluation of automated vehicle mobility services that can be used with the outputs of a mobility spatial simulation model (with a focus on agent-based models).

To fulfil these goals, I have 1) chosen an appraisal method that is able to capture the economic effects of AV services, 2) identified the specificities of AV services, 3) adapted the existing method to capture most of these specificities and 4) connected the economic appraisal framework to an agent-based simulation model.

In the first section of this paper, the eligible appraisal methodologies are discussed. In the second section, the history, concepts, main theoretical discussions and criticisms of the chosen CBA methodology are developed. The third section addresses the EE adaptation required to include AVs and interact with an agent-based model. In the fourth section, the appraisal framework is presented and discussed.

II. Appraisal methodologies

This section tries to answer the following research question: "Which appraisal methodology can be used to assess AV services?". The strengths and weaknesses of the Cost Benefit Analysis, the Multi-Criteria Analysis, the Environment Impact Assessment and the Cost Effectiveness Analysis will be discussed to understand which one is the most suited to answer our research questions.

Before reviewing the methodologies, it is helpful to note the required abilities to answer the thesis research questions, which are as follows:

What are the economic impacts of automated vehicle services on territories? Are there more interesting services than others for each territory? Which territory would benefit the most from the introduction of AV services?

The evaluation methodology must be able to:

- integrate most of the economic key performance indicators (KPIs)
- compare various alternative services (for a given territory)
- compare various projects (between territories), i.e., where AV introduction would generate the greatest social welfare gains compared to the investment needed. Project scalability is important in funding allocation.

The last item is important, as AVs are often supported as a potential means to either implement or complement public transit services in areas where the level of service is low. In these territories, the level of demand is also often low, and the ability to classify projects based on their investment efficiency allows us to compare these territories to more densely populated areas.

Another point that is not required to answer the research questions but is necessary from a technical perspective is that the methodology should be able to be coupled with a mobility simulation model.

A. Cost Benefit Analysis

Cost benefit analysis (CBA) is one of the oldest systematic and quantitative methods to evaluate transport projects. This method attempts to quantify "*the incremental changes in welfare resulting from public intervention in transport markets is to assess the change in the well-being of the individuals living in the society, and this involves calculating, in*

monetary terms, the magnitude of the potential […] gains compared with the opportunity costs of the resources diverted from other uses for the sake of the project." (de Rus et al., 2020). This methodology meets the three abovementioned prerequisites. The gains and costs in CBA include traveler gains, transport operator profits or losses and transport externalities through traditional transport KPIs. In addition to assessing the social desirability of a transport service, the CBA ranks it using a single indicator, the Net Present Value/Investment. This indicator expresses the aggregated gain or loss of the project for its stakeholders. It is used to compare transport services or projects and define investment priorities.

CBA has often been coupled with mobility simulations to obtain assessment inputs (Hyard 2012).

The CBA steps are described in Figure 18.

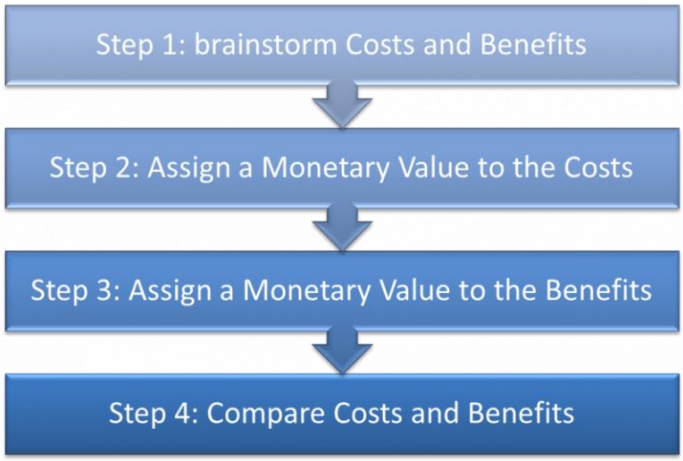

Figure 18. An outline of the main steps to execute a cost–benefit analysis.
Source: ("Cost Benefit Analysis Guidance" 2014)

B. Multicriteria analysis or multicriteria decision-making

Multicriteria analysis (MCA) is a newer method than CBA. CBA can be used as a specific MCA method; hence, some of its features may have been found much earlier, according to (Dean 2020), and its theoretical foundations were laid in the 1950s by (Charnes, Cooper, and Ferguson 1955; Kuhn and Tucker 1951).

The MCA method is based on the selection and evaluation of KPIs by experts (Annema, 2020 ; see Figure 2). This method "*explicitly considers multiple objectives and criteria (or attributes) in decision-making problems*" (Dean 2020) and allows a very flexible and modular approach to transport

appraisal. In contrast to the strict CBA structure, MCA can adapt to the situational context and needs to assign a given weight to each KPI (Dean 2020).

This allows for the integration of as many socioeconomic KPIs as needed or only the relevant KPIs in assessments. It is more flexible than the CBA method because the KPIs can be quantitative or qualitative (Broniewicz and Ogrodnik 2020).

MCA provides a mobility services comparison (compares one mobility alternative to another) for each identified KPI (Buisson 2022).

As previously mentioned, each appraisal methodology developed for a context has its own indicators. An eclectic set of KPIs may make an interproject comparison more complex and uncertain (Figure 19).

The MCA method allows more flexibility than does CBA because it is able to handle more types of KPIs (Dean 2020; Mouter et al. 2020; Barfod and Leleur 2014). However, the aims of MCA are less clear than the mono-criterion approach of CBA (Beria, Maltese, and Mariotti 2012; Dean 2020).

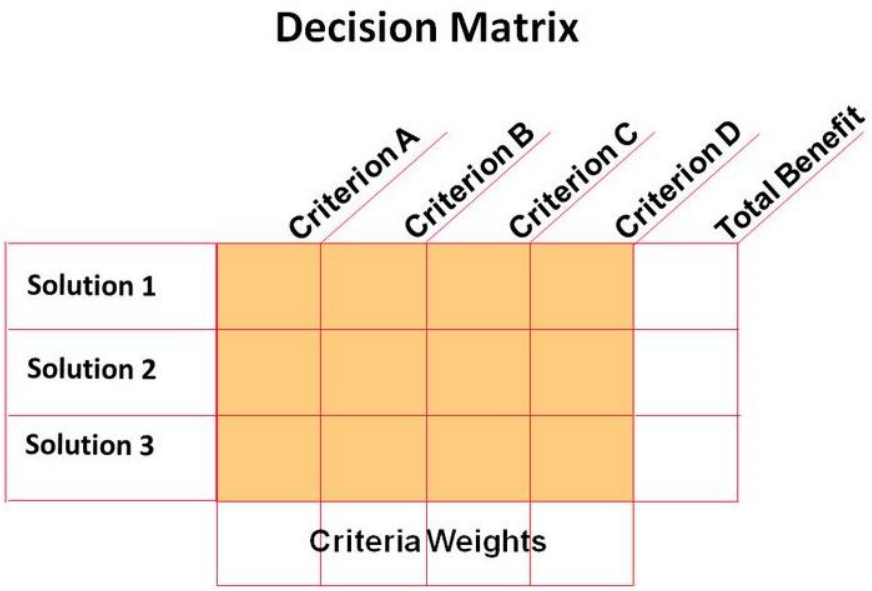

Figure 19. Multicriteria decision matrix
Source: (Prykucki 2014)

C. Environmental impact assessment

The Environment Impact Assessment (EIA) is an appraisal methodology based on the study of environmental, social and health issues.

According to (Jay et al. 2007), EIAs are defined as "*the evaluation of the effects likely to arise from a major project (or other action) significantly affecting the environment.*"

Similar to the MCA, this methodology was developed during the 1950s (Soria-Lara et al. 2020). The methodologies are very similar, and the EIA can be considered an environmentally specific MCA. The EIA methodology produces insights into the environmental impacts of a project and can produce recommendations to reduce or control negative effects.

The KPI can either be quantitative (greenhouse gas emissions) or qualitative (landscape alteration or health condition deterioration) (Figure 20). The EIA does not aim to evaluate financial KPIs such as profits or welfare gains or losses.

The EIA allows for the comparison of services but fails to incorporate social or financial KPIs.

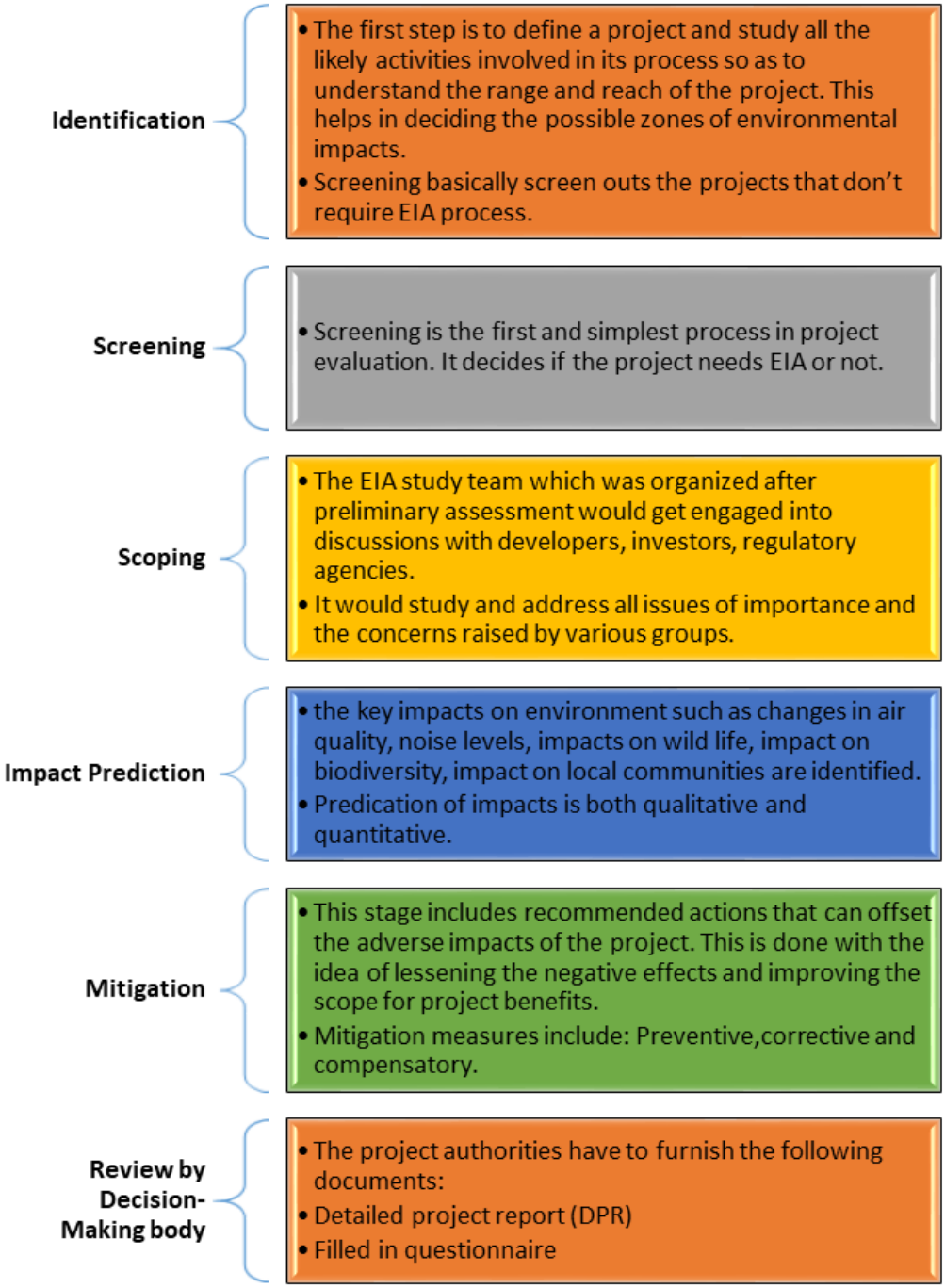

Figure 20. Environment impact assessment steps

Source:("New Environment Law (EIA Changes) Cuts Time For Hearings" 2020

D. Cost effectiveness Analysis

Cost-Effectiveness Analysis (CEA) "*is designed to include an evaluation of several different plans for achieving a specified objective*" (Peterson 1986), see Figure 21. The CEA compares alternatives and generates a ratio based on the effectiveness of a solution and its cost. Based on the example in Peterson (1986), a project on reducing highway deaths could be

evaluated based on a ratio of avoided deaths/cost of the reform, providing the price of avoided deaths per reform. Three CEA sub- types exist (Peterson 1986):

- The constant-cost analysis aims to understand which alternative would lead to the most effective effect under a fixed budget constraint.
- The least-cost analysis aims to find the least expensive alternative that meets a pre-established goal.
- The objective-level analysis can be seen as a multifactor least-cost analysis that aims to find costs associated with several levels of effectiveness.

The calculation of a CEA does not indicate the economic or financial performance of a project. Its ability to provide insights into the effectiveness of a solution makes this methodology very useful for reviewing climate change impacts ("Cost-Effectiveness Analysis" 2014) and health economics (Cookson et al. 2020).

The CEA allows solutions to be compared. If the same CEA category is used for multiple transport projects, this methodology allows them to be ranked.

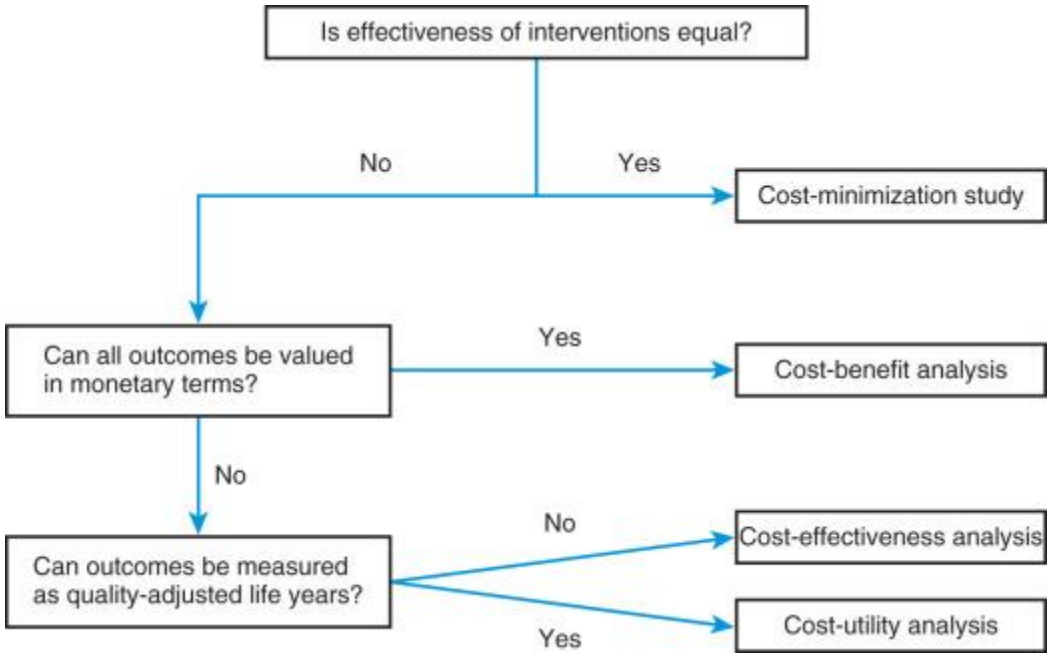

Figure 21. Cost-effectiveness plane
Source: (Themes 2020)

E. Discussion

As seen in the previous sections and in Table 7, both the cost–benefit analysis and the multicriteria analysis are able to address the research questions. Both methods can include most of the economic KPIs, compare mobility services, rank transport projects and be paired with a mobility simulation tool.

CBA has advantages in regard to ranking projects, as this was one of the main goals during its conception.

Methodologies	Captures a large set of socioeconomic KPIs	Compares transport projects	Ranks projects based on their scalability
Cost Benefit Analysis	Yes	Yes	Yes
Multicriteria Analysis	Yes	Yes	Yes, but limited
Environment Impact Assessment	No	Yes	Yes
Cost Effectiveness Analysis	No	Yes	Yes

Table 7. Appraisal methodologies summary

Source: prepared by the author.

The next section presents an in-depth presentation of a traditional CBA.

III. Cost Benefit Analysis: overview

This section presents a brief history of the Cost Benefit analysis from its origins to its actual conceptual approach. The current approach is introduced and the most important classifications are described. The third section is dedicated to on-going theoretical discussions on CBA.

A. History of the method

This section does not aim to answer the research question; rather, it offers a retrospective on the main methodology used in this thesis. The topic is heavily focused on the Western and French history of this methodology. Similar earlier or simultaneous methodologies may exist in other parts of the world, but no evidence was found for this.

History of economic calculation

Before the conceptualization of the Cost Benefit Analysis, concepts such as the Value of Time (G. S. Becker 1965) or the relation between the transport costs and the value of the land (Muth 1969; von Thünen 1826) could be found in history well before being theorized. Until the XIIIth century, no indications of economic calculations could be found. Roads were either built based on military needs or trade.

For military use, there was no need for economic calculation, as a strategic interest was considered sufficient. Notably, the concept of logistics comes from the military. A Swiss military figure named de Jomini is known for funding the theorical basis of logistics in his book "*Précis de l'art de la guerre*" (de Jomini, 1838).

The construction of these important transport and logistic infrastructures erupted in the two World Wars. In the First World War, the building of roads on the French side was seen as a major factor of the Triple Entente victory (Goya 2014). There is no need to detail the Normandy landings during D-Day, but the fact that the Allies built two artificial floating ports in Great Britain to transport them to France highlights the importance of logistics. On the other hand, the lack of trucks and gas is often mentioned as one of the reasons for the German failure in the USSR invasion.

In contrast, trade purposes have motivated discussions on the construction and maintenance of roads since at least the XVIIth century. Even if the military was not the primary concern, it still attracted major attention. The wealthier the kingdom, the higher its tax potential, which was an important factor when the military intensively relied on mercenaries. (Etner 1987, 18, 19) exposed evidence for the consideration of power in economic affairs to increase military potential.

A common approach was to list the beneficiaries of the road construction. The first people to benefit from a new road, or a well-maintained road, were the merchants (who were also transport operators at the time). Evidence of early estimations of the value of travel time savings can be found in France since the XVIIIth century. These calculations were based on the daily expenses (horses, food and inn fees) saved by the merchant using the well-maintained road compared to a scenario in which the road would not be maintained. One of the mentioned solutions that was unpopular among the physiocrats (the proto-economists) of the time (Etner 1987) and the liberals that came after them was the introduction of a toll for the road users.

The landowners near the road were identified early on as beneficiaries of the road construction (or maintenance). The road construction would increase their land value, and its maintenance would help them bring their products to the local market, reducing their transport costs. The proposal that landowners should be in charge of road preservation (by doing it themselves or paying workers to take care of it) was more popular than the toll approach.

As mentioned previously, the government may benefit from road construction. However, governments have more tools at their disposal than do merchants or landowners to take care of this issue. Governments could also pay workers to maintain the roads, but this would require raising taxes. Another way of paying for roads was to use the *corvée*, a levy to the monarch in the form of unpaid days of labour per year. This levy was often used to farm the monarch's land but could be used to do public work such as road construction and maintenance. From the Romans to the modern era, governments have also made use of their idle armies to help construct new roads (Etner 1987).

The debates on transport projects have mostly been discussed as lists of costs and advantages. These costs and advantages were sometimes expressed in units of time or money. French engineers from the Corps des ingénieurs des Ponts et Chaussées ("Bridges and Roadways Corps of Engineers") are known to be precursors on this topic (Etner 1987).

The early appearance of the origin of CBA may have been in France in the early XIXth century. A law from 1807 empowered the state to allocate subsidies based on the relative utility of a project (Porter 1995, 118). In 1834, a French ordinance enforced discussion on "*de commodo et incommodo. Or, in French, they were to identify les avantages et les inconvéniens, advantages and disadvantages*" (Porter 1995, 118).

However, if the engineers cared about the allocation of public funding, the calculations were not conducted under rigid and standardized methods (Porter 1995).

Jules Dupuit introduced the concept of consumer surplus in 1844 in "On the measurement of the utility of public works", opening the way for utility-based modern economics. He suggested using the difference between the Willingness-to-Pay and the applied price to estimate consumer interest in a project. Ironically, it introduced more economics to economic calculus, a field dominated by engineers (Dupuit being one of them) performing applied economics. Dupuit is thus considered to be one the

founding fathers of the Cost Benefit Analysis (Koopmans and Mouter 2020; Talvitie 2018).

History of the Cost Benefit Analysis theoretical concept

According to Hufschmidt (2000), the first conceptualization of the CBA is attributed to Clark in 1935 in his report on the planning of public works for the "New Deal". The report discusses most of the CBA concepts, including

"*the willingness to pay test of value, externalities, shadow price of unemployed labor, economic valuation of morbidity and mortality, and secondary benefits*" (Hufschmidt 2000).

Clark's work was formalized in the 1936 Flood Control Act, which stated that no water control project would be supported by public funds unless its benefits surpassed its costs (Porter 1995, 155). If most CBA concepts were designed prior to the Flood Control Act, 1936 was the milestone for the generalization of CBA as a systematic appraisal method.

The Kaldor-Hicks criterion (1939) "*asserts that a policy (or other change) can be considered as welfare-increasing if those who benefit can compensate those who suffer from it, creating a Pareto improvement after compensation. Standard CBAs are generally based on the Kaldor-Hicks criterion*" (Koopmans and Mouter 2020). This compensation justifies policies whenever the social gains are higher than the social losses (Persky 2001).

After these measures were introduced in the United States, CBA became mandatory for most public projects in the majority of the industrialized world (Koopmans and Mouter 2020).

Critics have raised concerns (Asplund and Eliasson 2016; Beukers 2015; de Rus et al. 2020; Hyard 2012; Litman 2019, 7–2) about the incompleteness and inadequacy of CBA, proposing new assessment methodologies such as multicriteria analysis.

From the XIXth century to our era, the economic calculation first evolved from an in-kind CBA to a monetary approach and then from a financial evaluation towards a more inclusive methodology including externalities. Criticism of this methodology has led to the design and use of complementary tools.

B. Conceptual approach

Notably, this work will focus on an ex-ante cost–benefit analysis. AVs remain yet to be developed, technologically speaking, and their experimentations (see the SAM or ENA for projects in France or the AVENUE project for a project at the European scale) remains mostly focused on technological development and acceptability.

1) General description

As mentioned in (Kast 2008), the CBA is not supposed to be considered as a reference taking over the role of public decision-makers. It is a decision support tool that provides an indication of the magnitudes of the specific KPIs of a project.

The CBA is a quantification, in monetary terms, of the welfare changes resulting from the implementation of a project compared to a base scenario (Koopmans and Mouter 2020). It aims to provide information on the social desirability of a project (de Rus et al. 2020, 6) and recommendations on the feasibility and viability of a project compared to the alternative(s).

A transport project may have heterogeneous effects on stakeholders, and some of them may benefit from the project, while others may experience losses from its implementation. This situation violates the Pareto criterion ("*a situation where no one can be made better off without making someone else worse off*" (Booth 2001).)

In transport projects, it is quite difficult to achieve the Pareto improvement in first-order conditions, as transport often generates externalities. The CBA aims to fulfil second-best conditions, a "*situation when one or more optimality conditions cannot be satisfied*" (Lipsey and Lancaster 1956). A transport project is described as desirable if its social gains are higher than its social losses (Kaldor-Hicks criterion). As CBA aims to compare (transport) projects based on monocriterion comparisons, two main indicators are used to compare scenarios to one another.

The Net Present Value (NPV) "*summarizes in a single figure the social value of the project by subtracting the costs (C) from the benefits (B), once both have been discounted with the appropriate discount rate (i)*" (de Rus 2021, 129). The first function of the NPV is to determine the social desirability of a project. Its second function is to rank projects according to their NPV/investment (NPV/I) KPI. The ratio of the NPV/I allows the social value produced by each invested euro to be calculated. It allows each project to be evaluated according to its scale. The internal rate of return

(IRR) is the discount rate value that "*makes the NPV equal to zero*" (de Rus 2021, 133).

Cost Benefit Analysis is a time-rooted approach. Based on the launch date and lifetime of a project, the projection may be affected by the discount rate and the inflation rate. The definition of these values may make a project change from being socially profitable to disadvantageous or disturb project rankings (Mouter 2018).

The discount rate is "*the opportunity cost of one unit of present consumption as consuming one unit today implies to give up 'one plus the discount rate' next year*" (de Rus et al. 2020, 29).

Similar to the value of time, there are two approaches for calculating the discount rate. The first is the descriptive approach, which "*selects discount rates that reflect the real-world market behavior of people today*" (Koopmans and Mouter 2020). The second is the prescriptive approach, which "*derives shadow prices for the parameters of an optimal growth model*" (Boardman et al. 2017, 238).

For the CBA of transport projects, mobility simulations are often used to forecast the level of demand for each alternative (including modal shift). Carreyre et al. (2022) in their literature survey showed that agent-based models are the most popular category of models to simulate the costs and benefits of AV services. Indeed, their detailed representation of agents, time and space is very well suited for on-demand services, the availability and performance of which may vary a lot in time and space depending on the number of vehicles, their location at each time of day, the dispatch strategy, etc.

2) Consumer surplus

"*The concept of consumer surplus [variation (ΔCS)]… is equal to the difference between what individuals are willing to pay (WTP) and what they actually pay (revenue represented by the price multiplied by the quantity)*" (Rus 2021, 22). In transport projects, the CS includes travel time, financial expenses, and comfort (E. Quinet 2013).

The measure of the variation of consumer surplus is based on the difference of aggregate of agent utility between two situations and its marginal utility of money. A couple of methodologies exist to estimate agent utility, which are discussed in more detail in section "Log-sum or Sum of the Surpluses?".

3) Operator surplus

The operator is the business(es) in charge of a project. For transport projects, the operator surplus is the aggregation of costs and revenues related to the project (i.e., the profits). The surplus of the operator is already a monetised value, as it is embodied by the profit size. Transport projects sometimes involve more than one operator in their analysis, either because the transport operator is different from the infrastructure manager or because the transport project introduces competition (and then involves at least two parties). In this case, the surplus of each operator must be made available, even if it is aggregated in the operator surplus.

As private operator costs are often unavailable, the operator costs are based either on the activity ratio or unit costs. When the cost estimation is based on the activity ratio, if the activity expands by 20%, the overall costs also increase by 20%. This method is effective when detailed cost information is unavailable but it is a simple approach that does not allow in-depth analysis. On the other hand, if the cost estimation relies on unit costs, the calculations are more elaborate but provide more details on the cost parameters. This method requires robust data but allows the sensitivity analysis to be performed based on sub-cost items.

Revenues for the operator(s) are based on the fares paid by the users. These fares equal the financial expenses of the consumers.

4) Externalities

"*Externalities refers to situations when the effect of production or consumption of goods and services imposes costs or benefits on others which are not reflected in the prices charged for the goods and services being provided*" ("OECD Glossary of Statistical Terms - Externalities - OECD Definition").

Transport projects are important contributors to climate change but also to more local pollutants, such as particulate matter (PM) emissions, noise or accidents (Delucchi 2000; E. Quinet 2013). Unintended effects, including landscape and habitat degradation, are also included in the externalities.

These deteriorations in living conditions or the natural environment cannot be attributed with certainty to either the consumer or the operator. Accidents may concern consumers as much as operators. Noise impacts and PM emissions are considered local pollutants and can impact consumers,

operators and local populations that are not consumers of the transport projects. Under these conditions, externalities are considered another agent.

If externalities were not included in the CBA, the evaluation would be distorted, as some members of society would be affected by the effects without being considered.

Externalities effects valuation is tied to social willingness to pay or willingness to accept (Rus 2021, 89).

IV. Application

A. Application approach

1) Cost Benefit Analysis steps

The CBA application can be divided into the following steps (Figure 22):

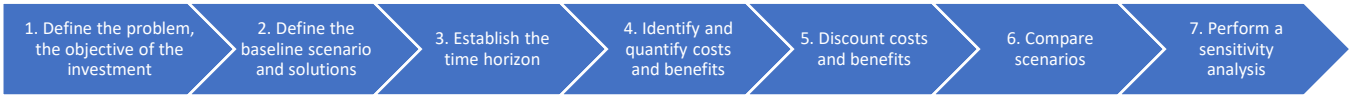

Figure 22. Cost Benefit Analysis steps

Source: "Étapes de l'analyse avantages-coûts" table in the translated and adapted (Ministère Transports Quebec 2016, 7).

This thesis chapter has already covered the first step in its introduction. The definition of the base cases and scenario are handled on a case by case basis and are not addressed in this chapter. The time horizon is defined on a case by case basis. The following sections aim to first identify the AV costs (step 4) and benefits, second, to quantify them (step 4) and last, to discount the costs and benefits (step 5). The comparison methodology is detailed in section VI.

B. Implementing the CBA framework in an agent-based model: the MATSim case

A mobility simulation model is a schematic and simplistic representation of the mobility process. In this section, MATSim specifications will be introduced. The choice for this specific model results from (Carreyre et al. 2022). As discussed below, MATSim fits the specific needs (ability to simulate on-demand and dynamic supply) of this thesis. This model is also very popular in the scientific community (Carreyre et al. 2022). Many cases of

its use have been made openly available in the MATSim Scenario Gallery ("Scenarios," MATSim.org).

1) MATSim introduction

"MATSim is an activity-based, extendable, multi-agent simulation framework implemented in Java. It is open-source and can be downloaded from the Internet. […]. MATSim is based on the co-evolutionary principle. Every agent repeatedly optimizes its daily activity schedule while in competition for space-time slots with all other agents on the transportation infrastructure […]. A MATSim run contains a configurable number of iterations, represented by the loop of Figure [Figure 23] *and detailed below. It starts with an initial demand arising from the study area population's daily activity chains. The modeled persons are called agents in MATSim. […] During iterations, this initial demand is optimized individually by each agent. Every agent possesses a memory containing a fixed number of day plans, where each plan is composed of a daily activity chain and an associated score. The score can be interpreted as an econometric utility"* (Horni et al. 2016, 4).

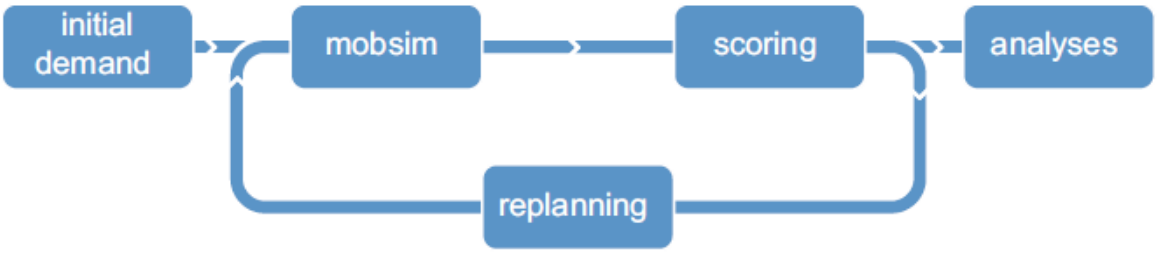

Figure 23. MATSim loop, sometimes called the MATSim cycle.
Source: The Multi-Agent Transport Simulation MATSim by Horni, Nagel and Axhausen

2) CBA specifications

a) Available modes

MATSim allows us to simulate a multimodal environment. The most common modes have been developed by the community. Driving private cars, walking or riding (private car passenger) are often the default modes in open access MATSim scenarios. For this thesis, on-demand services were expected. Maciejewski and Nagel (2013) developed a MATSim module for managing dynamic vehicle routing problems. MATSim offers the ability to simulate:

- Door-to-door, stop-based services
- Shared or private rides

Based on this work, Bischoff and Maciejewski (2016) and Nagel et al. (2019) simulated automated taxis in Berlin. MATSim has proven its ability to simulate automated vehicle services with dozens of studies on the topic (Carreyre et al. 2022).

b) Scoring

The scoring function is also a powerful tool when using MATSim for evaluation purposes. Each plan has an associated score based on activity chains and transport costs.

"*For the basic function, utility of a plan $S_{plan}$is computed as the sum of all activity utilities $S_{act,q}$ plus the sum of all travel (dis)utilities $S_{trav,mode(q)}$ with N as the number of activities. Trip q is the trip that follows activity q. For scoring, the last activity is merged with the first activity to produce an equal number of trips and activities*" (Nagel et al. 2016) (see Chapter 3 of the MATSim Book for more details).

$$S_{plan} = \sum_{q=0}^{N-1} S_{act,q} + \sum_{q=0}^{N-1} S_{trav,mode(q)}$$

This score is similar to the concept of utility in economics. It can be valuated in a monetary format. Nagel et al. (2016) drew attention to the correlation during the MATSim plan innovation leading to homogeneous scores and introduced a fix that will be presented later. The logsum evaluation based on MATSim score (see section IV.B.2 for more details), could allow a comparison of two situations considering the overall agent utilities, including the travel utility, the performed activities utility and the respect for the schedule utility. Benjamin Kickhöfer explored this topic in his thesis and later on in the MATSim Book (Kickhöfer 2014; Kickhöfer, Nagel, and Nagel 2016). See the "B" section for more details.

As the score is an individual parameter for each agent, the score variation from the implementation of a new scenario may be used to identify those who experience gains and losses from the new policy.

As it would be developed in the "Logsum or Sum of the surpluses" section, the expected consumer surplus from the logsum methodology can be expressed as follows:

$$E(CS_n) = \left(\frac{1}{\alpha_n}\right) \ln\left(\sum_{j=1}^{J} e^{V_{nj}}\right) + C$$

In a scenario comparison, C ("*an unknown constant that represents the fact that the absolute value of utility can never be measured*" (Kickhöfer et al. 2016) has a neutral effect.

Kickhöfer et al. (2016) recommends using the following expression:

$$Logsum_n = EMU_n = ln \sum_{i=1}^{J} e^{V_i} \leq ln \sum_{i=1}^{J} e^{V_1} = \ln(J.\ e^{V_1}) = lnJ + ln\, e^{V_1} = V_1 + lnJ$$

$$Logsum_n = EMU_n = ln \sum_{i=1}^{J} e^{V_i} \geq ln\, e^{V_1} = \ln(e^{V_1}) = V_1$$

Then:

$$V_1 \leq Logsum_n \leq V_1 + lnJ$$

EMU: Expected maximum utility

V_i: Observed utility from plan i

V_1: Observed utility from the plan with the best score.

J: Number of plans of the agent

When two or more scenarios are compared, the use of the V_1 + lnJ or V_1 value for consumer surplus is neutral, as the differences will originate from the V_1 values of each scenario. The simulations for both scenarios will be based on the same number of plans in the MATSim agent memory, and the lnJ from scenario 1 will be the same as the lnJ from scenario 2. An equivalent approach is the use of the best plan from the selection.

In MATSim, the score is often based on the time and monetary costs of travel, modal choice and schedule respect.

The monetary valuation of this score (here, only the best score is retained) can go through two equivalent methodologies. For equity-related questions, only the time equivalent method will be used.

$$\Delta m_j = \left(\frac{\Delta V_j}{\Delta t}\right)^{-1} \Delta V_j \times VTTS$$

$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1}$ is the inverse marginal utility of time

ΔV_j is the variation in utility between two states. It represents the utility gain or losses due to a policy implementation.

Δt_j is the number of hours required to counterbalance the policy implementation in agent utility.

Δm_j is the monetary compensation required to balance the policy implementation.

3) Technical pipeline – simulation to evaluation process

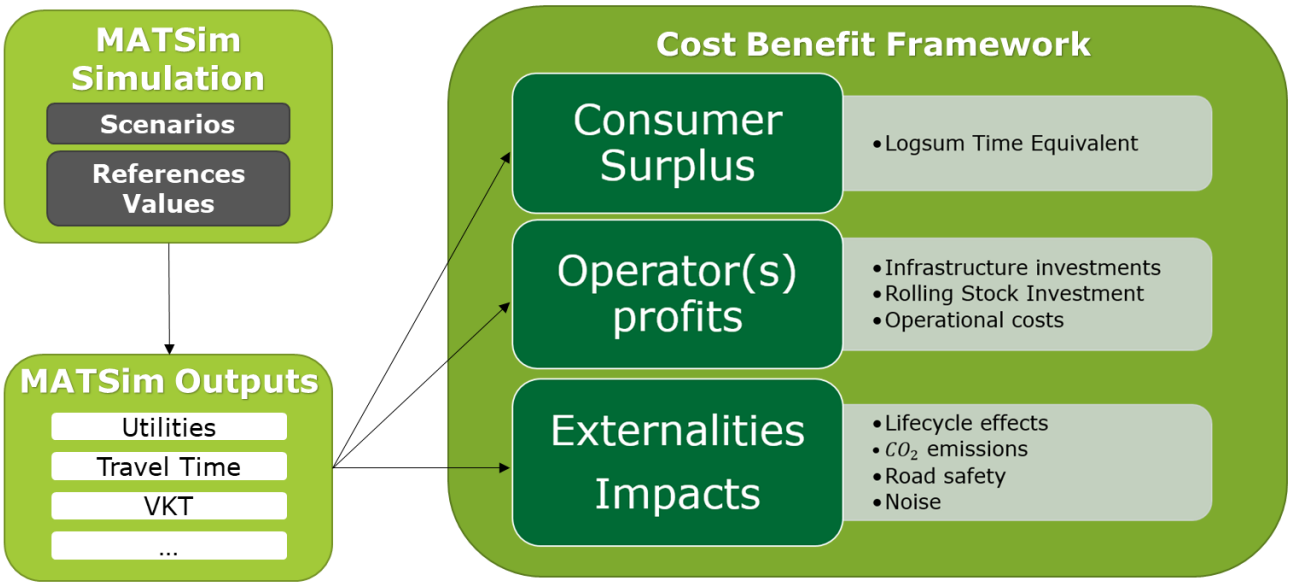

Figure 24. Simulation to evaluation pipeline
Source: prepared by the author

The simulation to evaluate the pipeline (Figure 24) starts by implementing scenarios in the mobility simulation model MATSIM. The simulation model provides "raw data" such as travel distances, waiting times, or vehicle kilometers travelled. The Cost Benefit Analysis calculator valuates the raw data into a monetised surplus for three agent categories, the consumers, the operator(s) and the rest of the world (i.e., those suffering from externalities). The logsum (time-equivalent) method is known to obtain robust results when performed based on multiagent

simulation outputs (see dedicated section for more details). It also provides enlightening insights into the distribution of gains or losses among individuals.

4) Log-sum or Sum of the Surpluses?

a) Conceptual discussion

The variation of consumer surplus (ΔCS) is the monetised value related to the gains or losses of the consumer utility mobility. The ΔCS is an utilitarian approach to calculating mobility (Dupuit 1844). The methods to assess the utility gains or losses of the consumer vary, and two approaches are considered in this section. The Rule of the Half (RoH) is based on a the assumption of an linear demand and the sum of consumer surpluses (Rus 2021, 28). The logsum method is derived from agent utility (de Jong et al. 2007), used for random utility models, such as multinomial logit model. If these approaches have a theoretical common background and produce equivalent results, their expressions and applications may generate disruptions.

The goal of this comparison is to provide insights into the differences between both of these main ΔCS estimations. These methodologies approach the subject with two main differences, the first based on the scope of the utility and the second on the utility parameters.

b) Rule of a Half

The rule of the half (RoH) based on the sum of surplus methodology (Rus 2021) allows us to estimate the difference in consumer surplus. When a supply shock lowers the price of a service and indirectly increases the quantity consumed, the induced demand valuation may be hard to estimate when the demand curve is unknown.

$$\Delta \mathrm{CS}_{total} = \sum \int_{P_1}^{P_0} D(c)\, dc$$

$$\approx \frac{1}{2} \sum (\mathrm{q}^0 + \mathrm{q}^1)(P^0 - P^1)$$

$$= \sum q^0 (P^0 - P^1) + \frac{1}{2} \sum (q^0 - \mathrm{q}^1)(P^0 - P^1)$$

$$= \Delta \mathrm{CS}_{Existing\ Demand} + \Delta \mathrm{CS}_{Induced\ Demand}$$

D is the demand curve for the good or service consumed

$\boldsymbol{q_0}$ is the initial quantity consumed

$\boldsymbol{q_1}$ is the quantity consumed after the supply shock

$\boldsymbol{P_0}$ is the initial generalised price

$\boldsymbol{P_1}$ is the generalised price after the supply shock

The surplus for existing consumers from a supply shock is the previously-consumed quantity times the generalized price variation:

$$CS_{Existing\ Demand} = (P_0 - P_1) \times q_0$$

If the demand function is linear, a good estimation of the induced demand surplus can be calculated as follows:

$$CS_{Induced\ Demand} = (P_0 - P_1) \times (q_1 - q_0)/2$$

This relation represents the ABE triangle shown in Figure 25.

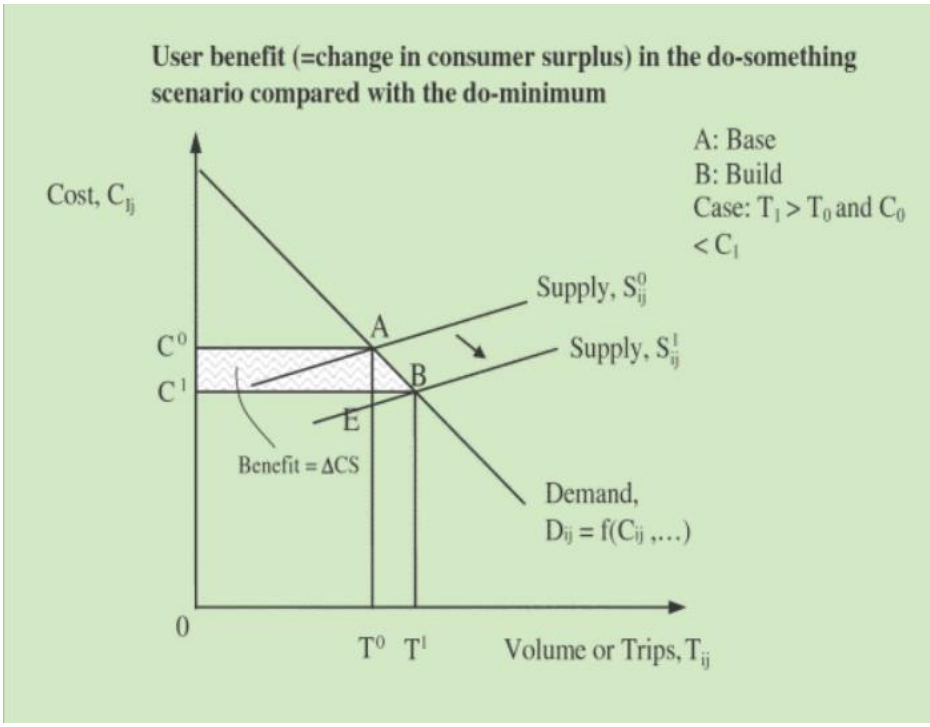

Figure 25. 'Guide for Conducting Benefit-Cost Analyses of Multimodal, Multijurisdictional Freight Corridor Investments'
Source: NAP.edu https://doi.org/10.17226/24680.

According to (Héran 2009), the generalized price is "*the sum of the private cost of travel (Cp) and the cost of travel time (Ct). This first cost is the product of the distance traveled (d) by the cost per kilometer (k). And the second is the product of travel time (Td) by the value of time.*"

Bates and Axhausen (2003) found this method to have quite reliable results with minimal error compared to the real value of ΔCS due to the demand curve convexity slightly overestimating the RoH. However, this method has trouble estimating ΔCS when carrying out the evaluation of a "new mode" and requires the estimated losses for other modes (Bates and Axhausen 2003, 59). With the introduction of a new mode of transportation, P_0 is unknown, and the RoH estimation of induced demand cannot be performed.

To conclude, the RoH provides a good estimate of the consumer surplus variation as long as the demand function remains linear. This methodology also allows to use equity values, and to differentiate gains and losses between existing users and new users. On the other hand, the RoH is not very well suited to evaluate introducing a new mode as opposed to upgrading an existing mode.

c) Logsum

The logsum is an appraisal methodology for consumer surplus based on a set of alternatives for the agents. In the case of the logit choice model, consumer welfare can be calculated as "*log of the denominator of a logit choice probability, divided by the marginal utility of income, plus arbitrary constants"* (de Jong et al. 2007). "*Consumer welfare refers to the individual benefits derived from the consumption of goods and services. In theory, individual welfare is defined by an individual's own assessment of his/her satisfaction, given prices and income. Exact measurement of consumer welfare therefore requires information about individual preferences*" ("OECD Glossary of Statistical Terms - Consumer Welfare Definition" 1993, 13).

The following expressions (CS_n; $E(CS_n)$) come from the work of (de Jong et al. 2007). However, the authors referred to "consumer surplus" as "*the utility (also taking account of the disutility of travel time and costs), in money terms*" and the "Total consumer surplus" as the "*the weighted sum of [Expected consumer surpluses]*". For the sake of consistency in this thesis, consumer surplus and total consumer surplus are referred to as "consumer welfare" (CW) and "consumer surplus", respectively.

When an alternative n with the greatest utility is chosen, the CW is calculated as follows:

$$CW_n = \left(\frac{1}{\alpha_n}\right) U_n = \left(\frac{1}{\alpha_n}\right) \max_j U_{nj}$$

α_n is the marginal utility of income (dU_{nj}/ dY_n),

Y_n is the income of person n.

U_n is the utility of person n.

The expected CW becomes: $E(CW_n) = \left(\frac{1}{\alpha_n}\right) \ln\left(\sum_{j=1}^{J} e^{V_{nj}}\right) + C$

C is an unknown constant that represents the fact that the absolute value of utility can never be measured (Nagel and Kickhöfer, 2016). The constant disappears during the CBA comparison step if the number of agents and plans remain unchanged among the scenarios.

Note that the division by α_n in the consumer surplus formula translates utility into monetary units (e.g., dollars, euros) since $1/\alpha_n$ = (dY_n/ du_{nj}). It monetises the agent utilities with an income equivalent, which is developed below.

The income effect on VoT in consumer surplus estimation is technically more difficult to address than in the sum of surpluses situation. Kickhöfer (2014, p. 52) explained the difficulty of monetising the sum of the agent utilities. Two main methodologies can be used.

The logsum income equivalent (LIE) is the monetisation of agent utilities based on the marginal utility of income (previously expressed as α_n). It is the aggregation of monetised agent utilities.

The logsum time equivalent (LTE) is the expression of agent utilities in a time resource format. The changes in consumer surplus between the two scenarios would be expressed by the number of hours required to balance the change. This number of hours is then valued through equity values, exactly as in the RoH valuation methodology. It allows the integration of equity issues in the logsum methodology.

Based on (Kickhöfer 2014, 55), the Logsum expression in Time Equivalent (LTE) can be expressed as follows:

$$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1} \Delta V_j = \Delta t_j$$

$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1}$ is the inverse marginal utility of time

ΔV_j is the variation in utility between two states. It represents the utility gain or loss due to the implementation of a policy.

Δt_j is the number of hours required to counterbalance the policy implementation in agent utility.

$$\Delta m_j = \Delta t_j \times VTTS_j$$

Δm_j is the monetary compensation required to balance the policy implementation.

The LTE methodology will then be estimated for consumer surplus in the case of logsum evaluation.

Technically, the logsum consumer surplus evaluation built on the simulation results can also suffer from technical constraints. Here, the use of MATSim, an agent-based model, allows us to benefit from utility agent-level insights thanks to the MATSim scoring function (see the relevant section for more details). This function represents each agent's utility (based on behavioural VoT), carry-on modal choice and assignment steps. MATSim includes travel and activity utility in the scoring. Thus, consumer surplus estimation based on MATSim scoring will assess travel and activity utility.

d) Comparison

These two methods are well-detailed in scientific studies (Abraham, Bonnafous, and Ray 2016; Bates and Axhausen 2003; de Jong et al. 2007; de Rus 2021; Etner 1987; Kickhöfer 2014; Kickhöfer, Nagel, and Nagel 2016), but none of these studies offer an in-depth comparison as well as the research of Ma et al. (2015) does from both theoretical and practical perspectives.

The RoH and logsum measures should provide similar results when the demand follows a linear or near-linear curve (Ma, Kockelman, and Fagnant 2015). A gap in the evaluations will appear and widen as the demand curve diverges from a linear model. Ma et al. (2015) pointed out that the RoH

methodology usually estimates larger differences than the logsum methodology except when the travel cost variation is important; then, the RoH could underestimate the consumer surplus variation.

Some technical issues can also be found with simulation and evaluation pairing. First, equity VoT is not introduced at the same step of the evaluation process. The value of time (VoT) is one of the most important values for transport modelling and transport evaluation. The VoT values retained for the MATSim score and the RoH estimation can be different. Benjamin Kickhöfer made clear that if the VTTS used were the same as the behavioural ones used in the simulation process, the result would be exactly the same between an L-IE and the L-TE as the one obtained through the income equivalent method. The introduction of behavioural or equity VTTS in the evaluation process are made on different steps (Figure 26). Second, the consumer surplus scope can be different. The RoH CS aims to evaluate consumer surplus variation based on only the travel utility, as LTE and LIE, but when estimated through MATSim scoring, it will evaluate consumer surplus variation based on the travel and activity utility.

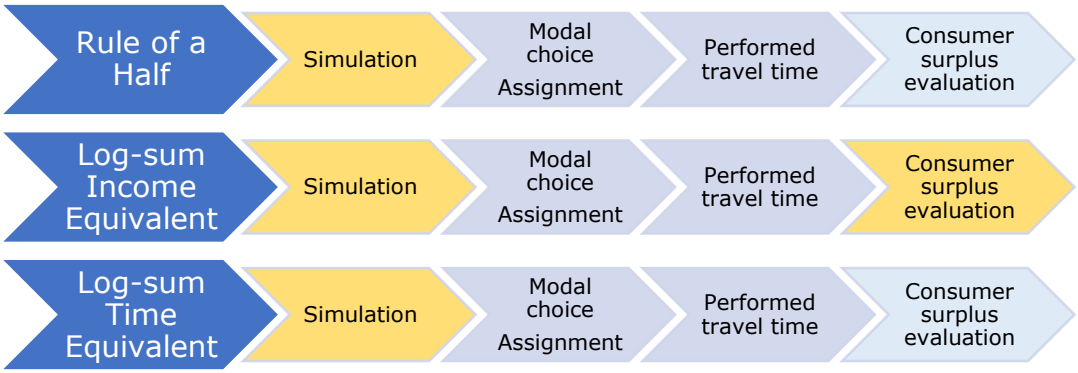

Figure 26. Uses of different values of time during the evaluation process
Caption:
Orange arrow: Use of behavioural value of time
Blue arrow: Use of equity value of time

Source: prepared by the authors

e) Conclusion

Both the RoH and the logsum are found to be pertinent consumer surplus variation evaluations (Table 8). For the logsum methodologies, the LTE is preferable to the LIE due to its ability to introduce equity VTTS. The RoH does not satisfactorily evaluate the introduction of a new mode of

transportation. Based on the results of this discussion, this thesis will base its consumer surplus evaluation process on the LTE evaluation process.

Methodologies	Capture welfare change due to transport project	Possibility to add new modes	Monetised welfare change	Equity consideration
Rule of a Half	Yes	No	Yes	Yes
Logsum - Income Equivalent	Yes	Yes	Yes	No
Logsum - Time Equivalent	Yes	Yes	Yes	Yes

Table 8. Consumer surplus estimation methodologies summary

Source: prepared by the author.

5) Equity vs Behavioral values

The value of time (VoT) is the opportunity cost related to time. The VoT has two main applications in transport economics:

It is used to analyse (in surveys) and simulate (in mobility models) the travel choices of users (e.g. route choice, mode choice, destination choice, etc.)

In economic appraisal, the VoT allows a comparison between gains or losses of time versus monetary expenses or profits.

However, for the evaluation, considering issues other than simple economic efficiency (e.g., equity between social classes or between territories) leads to a failure to consider other effects, in particular, the income effect (Wardman, Chintakayala, and de Jong 2016). The VoT definition raises some equity issues. Usually, the richer the people are, the higher their VoT in surveys.

For example, suppose two projects (Project A and Project B) compete for public funding, and both of them would save 1,000 h of travel per year, the exact same amount of time for their beneficiaries, and both of them would cost X, the same exact amount of euros. The beneficiaries from Project A have an estimated VoT of 20 euros/h, and the beneficiaries from Project B have an estimated VoT of 10 euros/h.

In this configuration, the economic assessment would advocate funding project A because the social surplus would be higher, as follows:

$$1000\ h\ \times 20\frac{euros}{h} - X > 1000\ h\ \times 10\frac{euros}{h} - X$$

This recommendation would then be based only on the VoT of the beneficiaries, as this relation could be simplified to:

$$20\frac{euros}{h} > 10\frac{euros}{h}$$

To limit situations in which public funding would be steered towards high VoT areas, the economic evaluation uses an equity VTTS (Börjesson and Eliasson 2019a) (sometimes called equity values) for the Value of Time (Quinet, 2013). The level of the VoT is then based on national or local (depending on the scope of the funding committee) averages to limit the influence of income in funding allocation.

Modes vs. distance vs. trip purpose

Three main methods are used to segment the VoT, even if some others can exist marginally (Börjesson and Eliasson 2019b). The values are estimated based on the transport mode, the trip distance and/or the trip purpose. The first level of segmentation aims to reflect the level of comfort of each mode. The more comfortable the mode is, the lower the VoT. The distance travelled operates similarly, as the longer the trips take, the greater the opportunity cost of time and the greater the VOT. Finally, the VoT often depends on the trip purpose (work, leisure, shopping, etc.), with typically greater values for commuting trips and even more so for business trips than for other purposes (E. Quinet 2013).

C. Scenario comparison

Scenarios will be compared on the basis of a traditional CBA, with additional insights.

The first basis for comparison is the social net present value, which is "*equal to the sum of the change in social surplus or the sum of changes in willingness to pay and changes in resources*" (de Rus et al. 2020, 28).

$$NPV_s = \sum_{t=0}^{T} \delta^t (B_t - C_t)$$

NPV_s*:* social Net Present Value
δ^t*:* Discount rate of period t

B_t: Aggregated Benefits from period t

C_t: Aggregated Costs from period t

The second basis for comparison is the NPV/I comparing the social effectiveness of the investment.

The third basis for comparison is at the agent level, with the agent surpluses, which indicates each category of agent wins or losses of the project and clarifies which category collects the respected gains and losses.

$$aS = \sum_{t=0}^{T} \delta^t (aB_t - aC_t)$$

aS: Agent Surplus

aB_t: Agent-level aggregated benefits from period t

aC_t: Agent-level aggregated costs from period t

Consumers are the most heterogeneous category of our selection of economic agents. The agent-based model MATSim allows us to produce an analysis based on the agent score. Three main indicators are used to indicate the surplus allocation of each agent.

- Winners versus losers: The proportion of agents that experience improvements from the baseline scenario, expressed as a percentage of the agent population.
- 10% measure: How much of the consumer surplus is captured by 10% of the agents that gain the most from the project implementation, expressed as a percentage of the aggregated positive consumer surplus.
- A Gini index based on the distribution of gains or losses for each agent.

The Figure 27 offers an overview of the comparison scenario KPIs.

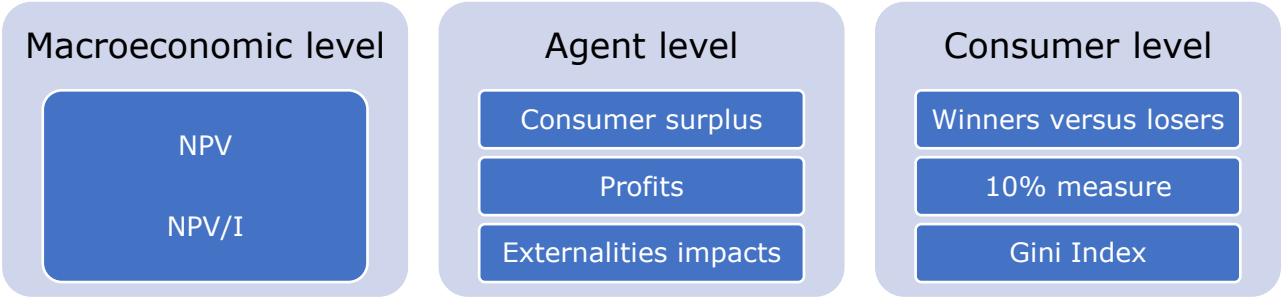

Figure 27. Scenario comparison methodology
Source: prepared by the author.

V. Cost benefit analysis adaptation for automated vehicle services evaluation

The goal of this section is to identify the expected impacts of mobility automation and provide a review of their inclusion in cost–benefit analysis.

A. Review of general mobility impacts

As reviews on the socioeconomic impacts of AV services have been common since the mid-2010s (Anderson et al. 2016; Clements and Kockelman 2017; Hyland and Mahmassani 2020; Narayan et al. 2020), this section reviews the identified economic impacts.

The Figure 28 classification is based on (Roukouni and Correia 2020), who worked on the impacts of shared mobility, and (Narayan et al. 2020), who focused on shared autonomous vehicles.

Figure 28. Automated Vehicle socioeconomic impacts
Source: prepared by the author.

a) Traffic and Safety

One of the most expected benefits of the development of automated vehicles is their improved driving capacities relative to human drivers. Vehicle-to-vehicle communication could allow vehicles to drive at safe distances and benefit from platooning effects (Arefizadeh and Talebpour 2018). They could increase road capacity thanks to a more coordinated flow. Computers are not subject to drowsiness, dizziness or other human issues, such as drug consumption. In 2018, 1637 French drivers died on roads (ONISR 2019). If Avs succeed in surpassing the average level of human driving ability, they could save lives and prevent injuries (Papadoulis, Quddus, and Imprialou 2019), congestion (J. Andersson et al. 2017) and costly vehicle and infrastructure repairs.

b) Travel Behaviour and Travel Demand

The main difference in travel behaviour between AVs and conventional private cars is the potential reduction in the VoT (Correia et al. 2019; Kolarova 2020; Kolarova, Steck, and Francisco J. 2019; Molin et al. 2020). Transitioning from being a car driver to a passenger would allow people to dedicate driving time to other activities (work, leisure, etc.) and increase their amount of available free time per day. Here, the time dedicated to driving a conventional car is not considered free time, as it is difficult to pursue other occupations while driving.

This reduction in VoT may push travellers towards the AV mode, causing a modal shift from public transit, bicycle and others.

This reduction in VoT can also be seen as a supply shock inducing more demand for transport. This induced demand may be characterised by an intensification in the time and distance of existing trips and the emergence of new trips allowed by the reduction of generalised costs (Carreyre et al. 2022). Moreover, automated vehicles would have the ability to drive without passengers, leading to more vehicles kilometres travelled and a vehicle occupancy of less than one person per vehicle on average.

Three main mechanisms could be the source of additional VKT:

- Induced demand:
    - More trips

The supply shock due to AV services can generate new trips that would not have been made if the service would not have been available. Similar conclusions have been found when new transport modes are introduced in existing markets (Cervero 2003).

    - Longer trips

The reduction in the generalised cost associated with the arrival of AVs could push consumers to commute further and longer (Carreyre et al. 2022). Furthermore, the empty trips realised by automated vehicles could increase the VKT.

- Modal share report from public transport, walk and ride

The commuters who previously used public transport, bicycle or walk may switch their modal choice towards the new attractive mode (Kamel et al. 2019);

Last but not least, the AV appearance may allow the operation of mobility services in either new form or to develop forms that were less popular before. These new forms would be more MaaS (Mobility-as-a-Service) oriented and would not require owning a car, especially in urban areas (Antonialli 2019; Stocker and Shaheen 2019; 2017). The most popular mobility services in the simulation literature are private and shared door-to-door automated taxis (Carreyre et al. 2022). By reducing the need for private cars, these new services could push people to renounce car ownership.

c) Transport Operators

The transport operators will be impacted in several ways by the automation of vehicles. First and foremost, it would require equipping both the vehicles and the infrastructure accordingly (H. Becker et al. 2020; Saeed 2019). Second, the services offered by companies may evolve towards new forms that have already started to appear with on-demand mobility (Földes and Csiszar 2018; 2016; Stocker and Shaheen 2019; 2017).

Infrastructure Investment

The automation of vehicles could require preparing the infrastructure for vehicles-to-infrastructure communication.

For AV-related infrastructure costs, the literature remains scarce (Saeed 2019). The infrastructure dedicated to conventional vehicles is evolving towards increasing connectivity. Between the rareness of the literature and the infrastructure evolution, crucial attention must be paid to the difference between the two situations (i.e., connected but conventional vehicles versus automated vehicles).

The AV infrastructure may need cameras, sensors and computers (Saeed, Alabi, and Labi 2021) and road markings (Najeh et al. 2020).

Fleet Investment

- Vehicle specification
  - Level of equipment

Automated vehicles would require a heavier vehicle investment than conventional mobility services (P. Andersson and Ivehammar 2019; Bösch et al. 2018; Tirachini and Antoniou 2020). The infrastructure necessities may be found again for the vehicles. The AV will have to be equipped with

cameras, sensors and computers. The use cases of AV may impact the level of equipment per vehicle (Khan and Khan 2015).

Two situations are identified:

- The AV ecosystem: the vehicles are expected to work on defined itineraries or territories and can interact with infrastructures and other vehicles.
- The standalone AV: the vehicles are equipped to be autonomous from infrastructure and other vehicles. These vehicles will be able to drive along any road.

If the vehicles are expected to be autonomous from infrastructure and other vehicle information to drive as stand-alone vehicles, the level of equipment needed per vehicle should be higher to attain redundancy levels. Excluding state-level decisions, the federal United States government does not legislate on the topic, leaving it up to industry to choose between the two methods (Pichereau 2021).

Financially, the equipment of infrastructures and other vehicles may be more important in the case of line-based services or high traffic areas. The costs could be distributed among users.

- Fleet size

On-demand mobility distinguishes itself from conventional private riding by sharing either a car (private ride hailing) or a ride (ridesharing). On-demand services require a smaller fleet to serve the same level of demand as conventional private driving (Balac, Hörl, and Axhausen 2020; Ben-Dor, Ben-Elia, and Benenson 2019; Bösch, Ciari, and Axhausen 2016; Farhan and Chen 2018).

Through shared mobility, the overall number of cars (or vehicles in a broader way) could be reduced if the demand remains unchanged. If AV services are more attractive than conventional private driving, this reduction in fleet size will need to be nuanced.

These reasons may lead to an increase in the demand for mobility, which mitigates the expected decrease in the fleet size.

Operating costs

- Wages – drivers/supervisors

The situation concerning the driving costs of the vehicle remains unclear. The heavy AV operation cost reduction is based on driver wage suppression. Most of the studies in the literature do not consider costs

associated with driving (H. Becker et al. 2020; Bösch et al. 2018; Tirachini and Antoniou 2020).

Abe (2019) considers the need for remote control by supervisors. He estimates the supervising cost at 3.4 JPY/km. The data are based on an article from ARK Invest, an investment fund, which states that AVs would cost 0.35$/km to consumers and 0.05$/km would be dedicated to remote operators and communication systems (Keeney 2018). The ARK Invest justifications of these assumptions are insufficient for scientific use.

- Fuel consumption

Three alternative motorisation modes are considered for AV propulsion. AVs may be electric, hydrogen or thermal.

AV driving abilities may reduce fuel consumption due to smoother driving (Stephens et al. 2016). This reduction would be proportional to its associated costs.

- Insurances

If AVs are on average safer than conventional vehicles, it would translate into fewer accidents per kilometre travelled, inducing fewer injuries, deaths and material damage.

Insurance fees can be proxied by calculating accident probabilities times their compensation. If the VA is safer, insurance fees should decrease.

However, if AV services induce more traffic, the societal level of accidents may not decrease as much as the AV driving ability.

d) Land Use

The relation between the mobility footprint in terms of land use and fleet size is important. The number of vehicles provides an indication of the space needed for roads and parking (Okeke 2020). Land being a scarce resource, the allocation of the space attributed to mobility is in competition with other activities such shopping or housing.

As mentioned in the previous section, new mobility services may arise from the automation of mobility. If on-demand mobility became increasingly popular, mostly in urban areas, during the previous decade, a decrease in marginal cost would help to promote these services even more.

Parking

- Fewer cars

The Operator fleet, the overall level of vehicles required should decrease with automation (Fagnant and Kockelman 2016; Farhan and Chen 2018; Gurumurthy, Kockelman, and Loeb 2019; Zhu and Kornhauser 2016). This reduction in the fleet size could allow us to reallocate some of the actual dedicated space from parking to other activities. Moreover, if the car activity ratio (use time/total time) increases through car sharing, it could reduce parking demand.

- Less need to use expensive city centre space

Today, whenever a car trip is completed in a city centre, the car must be park close to the trip destination. Automation can be used to park vehicles outside of the city centre, where the space is cheaper and less attractive for housing. This relocation of parking may generate more vehicle-kilometres travelled due to empty relocation trips (Harper Corey D., Hendrickson Chris T., and Samaras Constantine 2018; Okeke 2020).

Residential locations

If AVs supply a mobility service for a lesser generalised cost than do other solutions, it may be possible that the housing market will be impacted in the mid-to-long term (Boiteux-Orain and Huriot 2002; Zahavi and Talvitie 1980). A decrease in the generalised cost of transportation is often associated with a decrease in residential density and urban sprawl (Fujita and Ogawa 1982; Rosni and Noor 2016).

e) Environment

Mobility consumption usually has an effect on its environmental landscape (Delucchi 2000). These externalities may be global or local. The spatial localisation of carbon emissions does not intervene much in the economic calculation, but the magnitude of these must be known. Except when discussing life cycle analysis, the externalities are approached as direct marginal use externalities, i.e., the externalities due to the marginal use or consumption of mobility.

For AVs, we can identify three causes of externality variation.

Direct effects would be the effect directly due to automation. All things being equal, these variations could be found when conventional vehicles are replaced by their strictly AV-equivalent.

Concomitant effects or indirect effects are externalities due to changes originating from AV introduction. If the replacement of a bus line by an

automated taxi service implies a variation in pollutant emissions, this is considered a concomitant effect of automation.

As AV still remains under technical development, concurrent mobility effects may evolve. AVs are often conceived as electrical vehicles (Axsen and Sovacool 2019; Bauer, Greenblatt, and Gerke 2018; H. Becker et al. 2020; Farhan and Chen 2018; Loeb, Kockelman, and Liu 2018), but this propulsion evolution may have a distortive impact on cost–benefit analysis when comparing conventional thermic vehicles and automated electric vehicles.

Greenhouse gases

Automation may have benefits of smoother driving (F. Liu et al. 2019), a platooning effect or a reduction in vehicle weight (Taiebat et al. 2018), which have direct effects on the decarbonation of mobility. On the other hand, embedded computing systems may add significant weight and electrical consumption, diminishing the smoother driving effect (Annema 2020).

The nuanced effects for GHG emissions are mostly concomitant and concurrent effects (Thomopoulos and Givoni 2015). The service type change induced by AV introduction, such as the replacement of a low-level service bus line by on-demand mobility service, may have significant impacts on emissions.

Mobility electrification raises several questions. Is it interesting to compare conventional thermal vehicles to automated electrical vehicles? Emissions of GHGs by electricity production are highly dependent on a mix of energy production activities, but which one is the most influential?

(Annema 2020) shows that AV adoption could lead to a reduction in emissions per kilometer travelled, but the expected increase in VKT (Fagnant and Kockelman 2014) would offset this consumption performance improvement (F. Liu et al. 2019; Taiebat et al. 2018).

Local pollutants

The variation of local pollutants emissions such as NOx or particulate matters due to AV introduction has similarities with GHG variation.

Directs effects would be nuanced but concomitants and conjunctural effects are much clearer.

Noise

The noise externalities due to mobility may be impacted in similar ways as the emissions. The direct effect of smoother driving may reduce the noise externality.

The service type will surely impact the sound distribution (if different routes are used) and noise intensity (through vehicle type changes).

Motorisation is a major factor, and the concurrent effect of electrification may benefit the overall quality of life.

Lifecycle Assessment

The Life Cycle Analysis (LCA) is a "*quantitative analysis of environmental aspects of a product over all its life cycle stages*" (Kun-Mo 2004). Traditional transport CBA usually considers only marginal external costs, such as emissions directly emitted during transport service operations (Manzo and Salling 2016). An LCA benefits from a holistic view of the environmental effects of a project.

The additional production and alimentation of sensors, radars, LIDAR and computers require consideration of the vehicle's full lifetime emissions.

Although the goal of this work is not to compare electrical to thermal vehicles, the LCA also allows us to demonstrate differences on the topic.

B. How to implement Avs impacts in the CBA

The reviewed impacts of AV introduction in the mobility field will need to be introduced in the CBA. To integrate this variation into our Cost Benefit Analysis, the KPI will need two requisites:

- to have, or able to be translated to, a quantitative format.
- the ability to be monetised.

The following section discusses the impacts seen in the previous figure (Figure 28), except for the ones concerning the industry.

Traffic and safety	Quantitative format	Monetisation compatibility	Integration step	Integration	References
Deaths and injuries	Yes	Yes	Evaluation	Rate of accidents	(Papadoulis et al., 2019)
Congestion	Yes	Yes	Simulation & Evaluation	Simulations outputs	-
Property damage*	Yes	Yes	-	-	-

Table 9. Traffic and safety impacts

** Property damage refers to vehicles and infrastructure damages*
Source: prepared by the author.

From three impacts from Table 9, deaths and injuries can be integrated in the Externalities section through the Value of a Statistical Life (H. Andersson and Treich 2011).The congestion effect is captured during the simulation step. The Property damage are not integrated in this work.

Travel behaviour and travel demand	Quantita -tive format	Monetisation compatibility	Integration step	Integration	References
VoT variation	Yes	Yes	Simulation	Change in agents VoT	(Correia et al. 2019; Kolarova 2020; Kolarova, Steck, and Francisco J. 2019; Moreno et al. 2018)
Operating costs	Yes	Yes	Evaluation	Change in cost for travellers	(H. Becker et al. 2020)
Trips intensification	Yes	Yes	Simulation	Simulations outputs	(Carreyre et al. 2022)
Modal shift	Yes	No	Simulation	Simulations outputs	
Service changes	No	No	Simulation	Scenarios	(Antonialli 2019; Földes and Csiszar 2018; 2016)
Car ownership	Yes	Yes	Simulation	Simulations outputs	(Kim, Mokhtarian, and Circella 2020; 2020; Levin and Boyles 2015; Menon et al. 2019; Zhang, Guhathakurta, and Khalil 2018)

Table 10. Travel behaviour and travel demand impacts

Source: prepared by the author

The Table 10 offers an overview of the travel behaviour and travel demand impact and their integration steps. The VoT and trip intensification can be integrated into CBA through the monetisation of the time saved (or lost) and financial losses for the users. Operational costs are considered as a full section of the operator surplus section. The modal shift impact and transition from one service type to another are not valued for themselves

but based on variation of operational costs, fares and value of time. The car ownership variation can be valued in the private car financial section.

Land use	Quantitative format	Monetisation compatibility	Integration step	Integration	References
Parking spots	Yes	Yes	-	-	(Harper Corey D., Hendrickson Chris T., and Samaras Constantine 2018; Kolomatskiy et al. 2020; Okeke 2020)
Reallocation of parking spots	Yes	No	-	-	
Residential location	Yes	Yes	-	-	(Carrese et al. 2019; Kim, Mokhtarian, and Circella 2020; Krueger, Rashidi, and Dixit 2019)

Table 11. Land use impacts

Source: prepared by the author.

Table 11 discusses the land use impacts, which are discussed in this thesis but mostly not included in the CBA framework. Parking spot costs can be interpreted as a part of operational costs and therefore be integrated into the operator surplus section. The residential location effect of the introduction of AVs would require specific work on the topic; however, the VTTS can provide insight into trends in impacts on residential locations.

Transport supply	Quantitative format	Monetisation compatibility	Integration step	Integration	References
Infrastructure investment	Yes	Yes	Evaluation	Change in infrastructure cost	(Saeed 2019)
Fleet investment	Yes	Yes	Evaluation	Change in vehicle cost	(H. Becker et al. 2020; Bösch et al. 2018; Ongel et al. 2019; Tirachini and Antoniou 2020)
Operating costs	Yes	Yes	Evaluation	Change in cost for the operator	(H. Becker et al. 2020; Bösch et al. 2018; Ongel et al. 2019; Tirachini and Antoniou 2020)

Table 12. ***Operator profits***

Source: prepared by the author.

Infrastructure investment, fleet investment and operating costs (**Erreur ! Source du renvoi introuvable.**) are three components of operator surplus.

VI. French economic evaluation framework

A. Contextual parameters

The socioeconomic evaluation framework helps to understand distribution of the surplus among the stakeholders: First, the mobility consumers, second, the transport operators and third, the bearers of the externalities. If the mobility consumers also bear the externalities, our approach disaggregates the effects for mobility consumers and externality bearers.

In this methodology, two technical consumer surplus calculations are presented. Both provide different clarifications on equity. The Rule of the Half with reference values limits income distortion in the evaluation but does

not allow us to obtain the same level of detail offered by the Logsum methodology in regard to distinguishing winners and losers.

If the socioeconomic appraisal framework must be refined and refuelled by fresher data, the aim of this work is to remain as close as possible to what is recommended in (A. Quinet 2019; E. Quinet 2013). One of the main purposes of CBA is to respect a formal framework (Figure 29), allowing project comparison

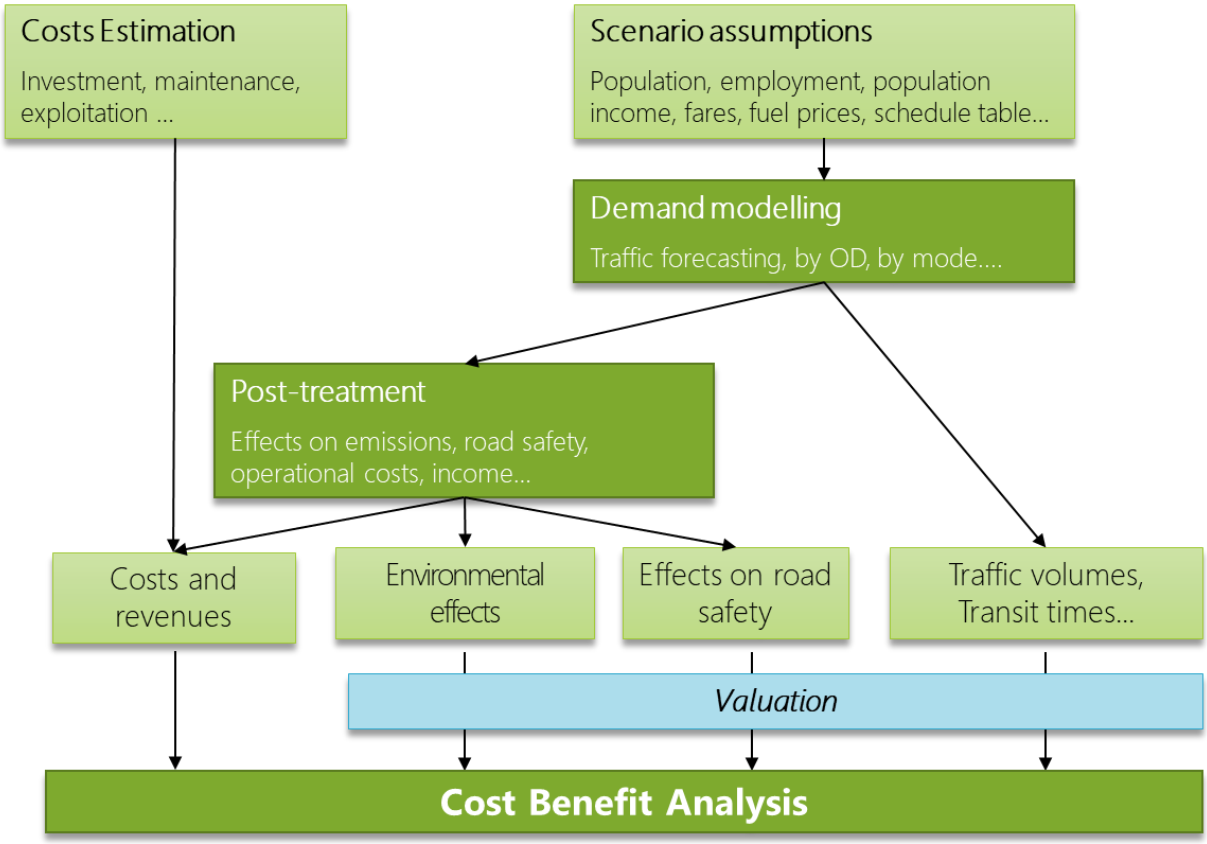

Figure 29. Cost Benefit Analysis appraisal flowchart
Source: (Eliasson 2014)

Discount

The discount rate (DR) is "*the opportunity cost of one unit of present consumption as consuming one unit today implies to give up 'one plus the discount rate' next year*" (de Rus et al. 2020, 29). This definition is based on the descriptive school of thinking.

(E. Quinet 2013) suggests using a 2.5% annual discount rate, which is close to the 3% recommended by the European Commission for most European countries (de Rus et al. 2020, 33). This value may be considered

low compared to the amount that may be attributed elsewhere (up to 15 or 18%), but (Mouter 2018) reviewed the discount practices in the Netherlands, United Kingdom, Norway, Sweden and Denmark, where discount rates were distributed between 1% and 4.5%. The discount rate is fixed at the European Commission level of 3%.

The DR is applied to the surpluses, as shown in (de Rus et al. 2020, 29):

$$NPV_S = \sum_{t=0}^{T} \delta^t \, (B_t - C_t)$$

$$\delta^t = \frac{1}{(1 + r_N)^t} \leq 1$$

B_t is the benefit attached to period t.

C_t is the cost attached to period t.

δ^t is the discount factor representing the weight of period t, based on the nominal discount rate r_N.

Inflation

The inflation rate in Europe has remained quite low over the last decade (2010-2020). In France, the inflation rate oscillated between 0.5% and 2% (Insee). The Russo-Ukrainian war has disturbed this trend by increasing the price of wheat and oil, for which the Ukraine and Russia are two major producers. The French inflation rate for 2022 is expected to hit the 5% threshold (Tripier and Aymeric 2022). However, in the long run, the European Bank mission to keep inflation below 2% per year supports a more conservative and less event-dependent inflation rate justification. A 1% level of inflation has been estimated.

Based on (de Rus et al. 2020), the inflation rate (φ) is applied at the same level as the discount rate, introducing the real discount rate instead (r_R) of the nominal discount rate:

$$r_R = \frac{r_N - \varphi}{(1 + \varphi)}$$

Growth

The GDP has mostly experienced many perturbations in the last few years due to COVID-19. This thesis does not aim to integrate the concurrent

COVID effects on mobility and the socioeconomic landscape. The per capita GDP is useful for forecasting the future value of time (VoT). Based on the recommendations of (E. Quinet 2013), the VoT evolves with the per capita GDP with an elasticity of 0.7 (i.e., For each 1% of GDP/capita growth, the VoT will increase by 0.7%).

An almost optimistic 1.5% GDP growth projection based on the 2000-2020 period in France has been ret ained, following the ("Cadrage Du Scénario de Référence" 2019). (E. Quinet 2013, 173) recommends to adjust the price of statistical life with the GDP per capita evolution which should evolve at a 1.2% rate ("Cadrage Du Scénario de Référence" 2019). It also recommends to adjust the LCA values by the GDP/capita evolution rate but as these values retained in (E. Quinet 2013) are a composition of externalities in CO_2 with global impact and local pollutant but the LCA in this work is based on CO2-eq emissions, we will make our LCA values evolves with the CO_2 values.

CO_2 emission and price variation in time

The evolution of CO_2 price is defined in (A. Quinet 2019, 124) at 250euros/t in 2030 and 500euros/t in 2040 giving an average annual growth rate of +7.18%. The CO_2 emissions/km for EV by ("Cadrage Du Scénario de Référence" 2019) is defined as 68kwh/100km in 2030 and 126 kwh/100km in 2050 giving an average annual growth rate of -1.43%.

	Discount rate	Inflation	GDP/capita	CO_2 emissions/km	CO_2 value
Average annual growth rate	+3%	+1%	+1,20%	-1,43%	+7,18%
Impacts	NPV	NPV	Air pollution Road safety	CO_2 emissions	CO_2 emissions LCA

Table 13. Contextual parameters

Source : prepared by the author.

B. Consumer Surplus Logsum

As seen in the Logsum introduction section, the expected variation of consumer surplus from the logsum methodology can be expressed as follows:

The monetary valuation of this score (here, only the best score is retained) can go through two equivalent methodologies. For equity-related questions, only the time equivalent method will be used.

$$\Delta m_j = \left(\frac{\Delta V_j}{\Delta t}\right)^{-1} \Delta V_j \times VTTS$$

$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1}$ is the inverse marginal utility of time

ΔV_j is the variation in utility between two states. It represents the utility gain or losses due to a policy implementation.

Δt_j is the number of hours required to counterbalance the policy implementation in agent utility.

Δm_j is the monetary compensation required to balance the policy implementation.

The value of time for automated vehicles has been a point of interest in the literature (Kolarova 2020; Kolarova, Steck, and Francisco J. 2019; Molin et al. 2020). The paper by (de Rus et al. 2020, 61) recommends using stated preference studies when dealing with hypothetical markets. As discussed in the preceding sections, behavioural VoT will be used for simulations. However, the section will only present the VoT estimated for evaluation purposes and then will only use reference value for equity reasons (which does not take into account the comfort of the mode).

In French national evaluation guidelines (E. Quinet 2013), several ways to segment VoT can be found:

- Mode
- Trip purpose
- Trips characteristics (length, time)
- Unproductivity factor for waiting time, egress/access time and connection time.

VTTS may also be based on other variables, such as user characteristics or occupation during travel (driver/passenger).

In France, trip purpose has been chosen to limit income distortion. However, this methodology assigns a higher importance to professional travel trips over commutes to work or all other trip purposes. The value of time is also higher if the evaluated project is based in Ile-de-France, the Parisian region. For that reason, we chose to adopt a single reference value

of travel time when the trip purpose, mode or trip characteristics were not specified. (Börjesson and Eliasson 2019b) advises to differentiate VTTS and advocates for the use of behavioural VTTS, but it relativizes the effect of the use of a single VTTS by explaining (citing (Börjesson, Eliasson, and Lundberg 2014)) that its few effect on projects ranking.

The specific value is 11,4 $€_{2015}$/h (E. Quinet 2019, 1), and the 2019 updated value is 10,7$€_{2010}$/h from (E. Quinet 2013, 147).

C. Profits

1) Infrastructure investments and maintenance

The AV infrastructure topic remains largely unexplored. The systematic review by (Y. Liu et al. 2019) references only 40 papers. As discussed below, cost variation estimations extensively differ.

Saeed (2019) indicated that the economic perspective on the infrastructure equipment may benefit from additions. The cost difference between the conventional infrastructure and automated vehicle-compatible infrastructure is based solely on pavement markings. An additional cost of 13 200 dollars per linear mile for three years has been estimated, but it did not include sensors, cameras and computers or even building costs. The cost estimated by (Xue 2022) to convert a conventional line to a high-occupancy lane for automated vehicles was 2,100,000 dollars per kilometer. This amount was based on a 1998 English experiment that paid £585,000 to convert a 1.2 kilometer conventional line to a high-occupancy line. Half a million to two million dollars seems excessive, which may be due to the experimental status. The methodology used to reach these results remains unclear, as no sensors, cameras or LIDAR were part of the investment.

There appears to be no consensus in the scientific community. As the marginal costs to equip the conventional infrastructure may be significant, a sensitivity study will need to be performed based on an arbitrary amount.

The cost estimated for the conversion of a conventional line to an AV compatible line will range between 50,000 euros^{2022} and 250,000 euros^{2022} up to an investment of 50,000 euros. The yearly maintenance, operational costs and replacement costs are based on a 10% fraction of the investment costs.

2) Rolling stock investment

The general consensus on the price tag of automated vehicles is that their price is marked up compared to conventional vehicles (H. Becker et al. 2020; P. Andersson and Ivehammar 2019; Tirachini and Antoniou 2020; Bauer, Greenblatt, and Gerke 2018; Ongel et al. 2019; Quarles and Kockelman 2018; Wadud 2017; Wadud and Mattioli 2021).

The most extensive study on light vehicles such as cars or shuttles can be found in Becker et al. (2020). Automation is supposed to add 5,000 US dollars to the vehicle price. A similar assumption can be found in Wadud and Mattioli (2021), who report that automation would cost 5,000 dollars or 3,000 dollars in the second-hand market. A study that builds on previous advances on the subject (Wadud 2017) indicated that automation would cost between 9,400 £ and 15,000 £ more per car. Tirachini and Antoniou's (2020) assumptions on automation costs are more pessimistic, as they proposed that automation would cost between 36% and 86% more, depending on the vehicle. The +36% to +86% markup estimates are consistent with the variation in absolute value found in (H. Becker et al. 2020; Wadud and Mattioli 2021) based on the 26,000 euro average selling price of a new car in France (Leroy 2021). The total markup estimated for AVs is 7,500 euros per vehicle.

For EVs, Bösch et al. (2018), on which the study by Becker et al. (2020) is based, do not consider any markup compared to thermal vehicles. Similar to Wadud and Mattioli (2021), the electric impact can be found in the operational, maintenance and insurance costs, but no purchase price variation seems to be applied. (Ongel et al. 2019) forecasted the purchase price of Internal Combustion Engine Vehicles (ICEVs), EVs and AVs for the year 2030 close to the shuttle format. They found that an ICEV should cost between 105,000 and 110,000 (2017 constant) dollars, the electric equivalent should be 20% more expensive and the automated and electric counterparts would be 28% more expensive. The estimated price for the AE shuttle is 128,000 euros with a 100,000 euro ICEV equivalent. For cars, (Mitropoulos, Prevedouros, and Kopelias 2017) found a 16% retail price difference between ICEVs (27,130 in 2015$) and EVs (31,590 in 2015$). This value is consistent with the +20% reported by (Ongel et al. 2019). Results of this discussion are presented in Table 14.

Automation impact vehicle price	Values	Automation impact factor
ICEV car	26,000 €	100%
Electrical car	31,200 €	100%
Automated ICEV Car	33,500 €	+ 29%
Automated Electrical car	38,700 €	+24%
ICEV Shuttle	100,000 €	100%
Automated electric Shuttle	128,000 €	+28%

Table 14. Automation impact factors based on the automation level and vehicle size.

Source: prepared by the author.

3) Operational costs

(H. Becker et al. 2020) have produced the most in-depth work on this topic. Considering multiple cities around the world, they provided simulation-backed results for several business models and a large amount of data on cost analysis for private cars, automated taxis and buses (see APPENDIX Figure 30). A shuttle cost structure can be found in (Bösch et al. 2018), a paper that also provides more insights into the influence of territory type on costs. (Abe 2019) produces a good overview of the influence of driver costs on the overall costs. The automation savings in operational costs are quite important, as drivers represent an important part of those costs. A total of 29% to 77% of the operational costs can be saved depending on the ratio of supervisors/vehicles required to monitor a taxi fleet (Abe 2019). However, (H. Becker et al. 2020) hold highly optimistic assumptions on the ability of AVs to drive themselves without supervisors. It seems reasonable that a supervision centre may be needed to regain control of autonomous vehicles that find themselves in situations where human intervention is needed. The supervisor topic has remained underexplored in the literature on AV cost analysis (Scoliege 2021). In the AV financial analysis field, (Nunes and Hernandez 2020) estimated that a supervisor should handle 50 vehicles at once to benefit from the economy of scale. This assumption may need additional discussion as it is not based on studies but rather one projection.

The effects of electrification are strongly dependent on local energy prices. Table B.12 from (H. Becker et al. 2020) (appendix Table 21) provides cost structures for automated and electrical taxis compared to conventional private cars.

For urban buses, full costs/km for the same use cases can be found in Table A.7 in Becker et al. (2020), see Table 22 in appendix. The effects of both automation and electrification have been identified. The shuttle cost structure is from (Bösch et al. 2018), Appendix D. However, no supervision costs are considered, which can be corrected by adding a +0.05 euro cost per VKT.

As the acquisition costs of AVs are already considered in the investment section for AVs and automated shuttles in (43; Fig. Table 2), the depreciation costs (0.054 CHF/km and 0.14 CHF/km) are deducted from the initial 0.48 CHF/km and 0.98 CHF/km operational costs considered in (43, p. 89). These operational costs were (OC) converted to euros and discounted. Supervision cost was not considered, which was corrected by adding a +e0.05 per vehicle kilometer traveled (VKT). Results of this discussion are presented in Table 15.

Mode	Invest Infra (per km)	Maintenance Infra Yearly Invest % cost	Vehicle Price	Operating costs (per km)
SAV (car)	50k-250k €	10%-50%	38 700 €	0,51 €
AV Shuttle	50k-250k €	10%-50%	128 000 €	0,90 €

Table 15. Operator(s) profits parameters

Source: prepared by the author.

NB: The Public Transit are not considered here as their level of service remains equivalent between scenarios. In this case, no differences could be found, whatever the financial parameters values.

4) Revenues

Revenues are tied to demand level and pricing strategies (Hardt and Bogenberger 2016). The demand side is supplied through the demand outputs and the pricing strategy depends on the scenario.

D. Externalities

1) CO^2 emissions

As for the CO^2 emissions, it needs to be evaluated through a combination of CO^2 price and total CO^2 emissions (which can be decomposed as Emission/km x Vehicle Kilometer Traveled).

For CO^2 emissions, (A. Quinet 2019) provides a monetary value for every tonne of CO^2 emitted for every year.

The political trend restricting thermal vehicle use in European cities (see the low emission zones in Italy, the UK or Paris) makes the development of AVs under thermal propulsion unlikely. Electric and hydrogen vehicles are good candidates, but the development of hydrogen vehicles does not benefit from the same support as that of EVs. AVs will then be considered electric.

For electric vehicles (EVs), general data need to be interpreted with caution. Electricity consumption is not a direct source of GHGs, but its production is often carbon-based. The mix of energy sources is heavily dependent on geographical political choices. Emissions for EVs or hybrid vehicles will need to be adapted for every use case with similar data to those in (E. Quinet 2013), (Buehler 2014), (Jochem, Babrowski, and Fichtner 2015), or (Jöhrens et al. 2020). The automation impact remains uncertain, as (F. Liu et al. 2019) point out. In the best-case scenario, a 13.28% reduction could be applied to the fuel consumption of EVs, in contrast with the worst-case scenario, which could increase the fuel consumption by 11.63%. However, Liu estimated that ten percentage points could be saved from the worst-case scenario by limiting speed limits alone. The difference between an automated car and a shuttle vehicle may have an impact on electricity consumption. (Jöhrens et al. 2020, 58) detailed electricity consumption levels based on vehicle size. Automated cars with four to five seats are assigned to the "Small Cars" category, with a consumption of 19.7 kWh/100 km, and automated shuttles are assigned to the "Large Cars" category with a 23,6 kWh/100 km consumption. A ratio of 1.19 based on the relative overconsumption of the shuttle is applied. A 5% fuel consumption is estimated for AVs compared to their strict equivalents, conventionally driven-EVs. Results of this discussion are presented in Table 16.

Automation impact on GHG emissions	Automation impact factor
Electric car	100%
Electric shuttle	+19%
Automated electric car	-5%
Automated electric shuttle	+13,05%

Table 16. GHG emissions Automation impact factors according to the automation level and vehicle size.

Source: prepared by the author.

2) Air pollution

The air pollution valuation in the CBA is an expression of the health impact. Usually, to consider such impacts, studies conducting mobility simulation, fleet composition, exposition to the emissions and impacts from the emissions are required (Martin et al. 2021). For CBA practice, less accurate measures are seen as acceptable. (E. Quinet 2013) provides a monetised valuation of air pollution from traffic data and territory type (based on population density).

For electrical vehicles, a 22.4 mg/VKT emission of PM2.5 was estimated by (Timmers and Achten 2016), but the ADEME found an emission of 14 mg/VKT (ADEME 2022). The ADEME value will be used in our appraisal, as it is more recent.

As both previous studies highlighted, the weight of a vehicle has a significant impact on its braking capacity and particle matter emissions. No data are available for shuttle vehicle sizes, but the ADEME found an almost proportional relation between weight and particle matter. As an empty Navya weighs 2.4 tons ("Navya Autonom Shuttle | Land Transport Guru" 2018) and a Toyota Prius weighs 1.53 tons, an increase of 57% emissions will be attributed to shuttles.

The automation may have a nuanced impact on particle matters marginal emissions. The automation compared to conventional EV) would have more equipment and would be heavier. On the other hand, AVs might be able to anticipate breaking phases more easily than human drivers. (J. Liu, Kockelman, and Nichols 2018) showed through different models that average PM2.5 emissions might be reduced by 19,1% thanks to the automation. Their paper also highlights that this marginal decrease of

emission per kilometers travelled might be offset by induced demand. A ratio of 0,809 will be applied on AV compared to their EV counterparts.

The valuation of this emission is not based on (E. Quinet 2013) because their estimated value is based on direct exhaust emissions, which are null for EVs. Exhaust emission could be attributed for electricity production, but they are not considered in this work. The estimated value originates from the HEATCO report (Bickel et al. 2002, S19) and is fixed at 430,000 $€_{2002}$ per ton of PM2.5 emitted. This translates to 0.78 euros (in $€_{2020}$) per VKT for a conventional EV. Results of this discussion are presented in Table 17.

Automation impact on local pollution	Values	Automation impact factor
Electric car	0,78 €	100%
Electric Shuttle	1,22 €	+57%
Automated Electrical car	0,63 €	-20,1%
Automated electric Shuttle	0,99 €	+27%

Table 17. Local pollution automation impact factors based on the automation level and vehicle size.

Source: prepared by the author.

3) Lifecycle impacts

As mentioned previously, lifecycle analysis is an appraisal methodology used to assess all environmental aspects of a product over its entire lifecycle. It can be performed as a standalone methodology, but its introduction in a Cost Benefit Analysis allow to get a broader scope of the impacts. (Manzo and Salling 2016) showed that the integration of LCA in a CBA could significantly impact the magnitude and surplus distribution in the results.

The LCA literature has followed the trend in publications on automated vehicles in the last five to ten years. Most of the papers on the topic have been published in the last five years. The most important papers on the topic were (Gawron et al. 2018; Kemp et al. 2020), which covered the main projected forms of automated vehicles.

In (Kemp et al. 2020), the materials and manufacturing (MM) phase represents 27% and the End-of-Life (EOL) phase represents 1% of the 42 ton of a the lifecycle carbon emissions of an EV. The Use phase, counting for 72% is not accounted in the lifecycle item as this work is already considering these emissions, the emissions due to the use part of the vehicle life will be subtracted from the lifecycle analysis. The automation sub-system is considered to add 1055 C02 kg. Previously mentioned studies did not include AV shuttles in their scope. (Held and Schücking 2017) introduced the topic. As such, a value of 20,000 kg was estimated for a shuttle ("BEV (minivan) RheinMobil, elec.-mix" (Figure 3), minus the "charging electricity" item, which is similar to the "Use phase" from (Kemp et al. 2020)). The same automation burden of 1055kg is added to the Shuttle system. All vehicle lifetime is estimated to be 300 000 kilometers, an assumption close to the 200 000 miles in (Kemp et al. 2020). The value of the CO2 ton is fixed at 250 euros, accordingly to the Quinet report for 2030. The retained values are close to the 0,9 euros value fixed by (E. Quinet 2013) for a private car. One could have expected a higher value as EV are known to have an heavier environmental impact during the MM phase. Note that for simplicity, only the carbon emissions of the lifeycle emissions have been considered. Results of this discussion are presented in Table 18.

Lifecycle analysis (per 100 km)	Values	Automation impact
Electric vehicle	0,95 €	-
Automated electric car	0,97 €	+2,5%
Automated electric shuttle	1,75 €	+85%

Table 18. Lifecycle automation impact factors based on the automation level and vehicle size.

Source: prepared by the author.

4) Noise

The automation and electrification of vehicles may decrease their noise impacts. Automated vehicles may have smoother driving, and electric vehicles are known to be less noisy than their thermal counterparts. These two effects can be treated separately.

(E. Quinet 2013) provides reference values based on either noise exposition or traffic data. This valuation is based on a real estate valuation. These values were updated in 2019. Reference values for noise externalities based on traffic of thermal vehicles can be found in (Quinet 2013, 183).

For conventional EVs, a 30% lower impact was found by (Verheijen and Jabben 2010). Our assumptions are based on more recent research (Taszka and Domergue 2017) that estimates a 50% reduction in impacts.

Except for (Patella, Aletta, and Mannini 2019), who simulated an introduction of a 100% autonomous fleet for the city of Rome, the topic remains unexplored. Even if AVs are good drivers, a conservative approach following the research of (Patella, Aletta, and Mannini 2019) is adopted, considering automation as a non-impacting factor. Results of this discussion are presented in Table 19.

Noise impact	Noise impact factor
Conventional vehicle	100%
Electric vehicle	50%
Automated electric vehicle	50%

Table 19. Noise impact factors based on the motorisation and automation levels.

Source: prepared by the author.

5) Safety

Safety has been one of the main selling points of AVs in the last decade. However, it is still difficult to determine the ability of AVs to drive safely.

(Papadoulis, Quddus, and Imprialou 2019) found that under a 100% market share of AV on motorways, conflicts can be reduced from 82% to 92%. Less optimistic, Kitajima et al. (2019) used an agent-based model to estimate human-based errors leading to crashes. They found an 18% reduction in collisions, but they warned of the need to consider their results with caution. Mahdinia et al. (2020) also found that automation would lead to a reduction in both driving volatility and time-to-collision, which would significantly affect accidents.

Tafidis et al. (2021) have performed the latest literature review on the topic to date. The fact that their review includes only 24 papers is due to

the novelty of the topic. No overall consensus can be found, but most of the papers highlight an improvement in road safety thanks to automation. These results are based on assumptions and may need to be evaluated as soon as field data become available.

A conservative approach was adopted, assuming a reduction of 20% of all crashes/VKT.

The value of a statistical life is set at 3 million $€_{2010}$ according to Quinet (2013). The type of territories and vehicles will be taken into account, as they have important roles. The rate of accidents/traffic should be available for each case; otherwise, the 2019 rate in France will be used as a reference (ONISR 2019, 18), with 5 deaths per billion vehicle kilometers travelled. Results of this discussion are presented in Table 20.

Road safety impact	Safety impact factor (deaths/VKT)
Conventional vehicle	100%
Electric vehicle	100%
Automated electric vehicle	80%

Table 20. Road safety impact factors based on motorisation and automation levels.

Source: prepared by the author.

VII. Conclusion

To conclude, the CBA has been chosen to lead an economic appraisal for its ability to rank transport projects and the easiness to pair it with mobility simulation. Autonomous vehicles may become a new mobility service in the near future, as such this chapter highlights the forthcomings challenges to address. The methodology has been adapted through the reference values used for the AV. Uncertainties concerning AV abilities and costs remains and must be updated in the future as these uncertainties would decrease with time. The AV introduction should impact the travel behavior, the travel demand, the road safety, the mobility supply and the environmental impact of mobility. The CBA framework developed in this chapter address most of these topics through the prism of three economic agents (the consumers/travelers, the supply side and the externalities). The CBA framework has been widely discussed for years, leading to exposure of

its limitations but also to refinements in its appraisal process. The aim of this section is to develop some aspects of CBA that have not been considered in the previous steps of the process. In 2022, automated vehicle experiments have been performed, but none had the commercial maturity to conduct an ex-post evaluation. If the DGITM appraisal methodology aims to propose an optimal introduction date, the technical immaturity of AVs places this work in a prospective and conceptual scope decorrelated from a launching date. The risk assessment will be conducted using sensitivity analysis as mentioned in Figure 22 "Cost Benefit Analysis steps". Wider economic impacts (WEI) from transport projects, which are the effects of transport on the level of unemployment, wages and overall productivity (Koopmans and Mouter 2020) due to the introduction of Avs, have not been taken into account. As an important supply shock is expected from the introduction of AVs to the vehicle market, a complementary approach including WEI would be an interesting contribution to the academic field. The wider WEI can be considered externalities (Rus 2021) at the same level that the environmental externalities are taken into account in our evaluation. Notably, the introduction of a transport service that generates a significant WEI would be at a disadvantage if evaluated by the previously-applied appraisal methodology. This appraisal project is fueled by the MATSim model, an agent-based mobility simulation. The module used does not allow the production of outputs on the land use variation. A land use model or a land use transport interaction model would be more appropriate for performing this analysis (de Rus et al., 2020). However, under certain conditions, consumer gains due to transport supply shocks are equivalent to the increase in land value due to mobility attractiveness. In the long term, landowners can expect to capture some of the transport gains in their real estate value (Smith and Gihring 2006). As mentioned earlier, infrastructure equipment may represent an important, and often forgotten, financial burden. However, in this work, we did not consider its environmental impact at any point.

VIII. References

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IX. Appendix

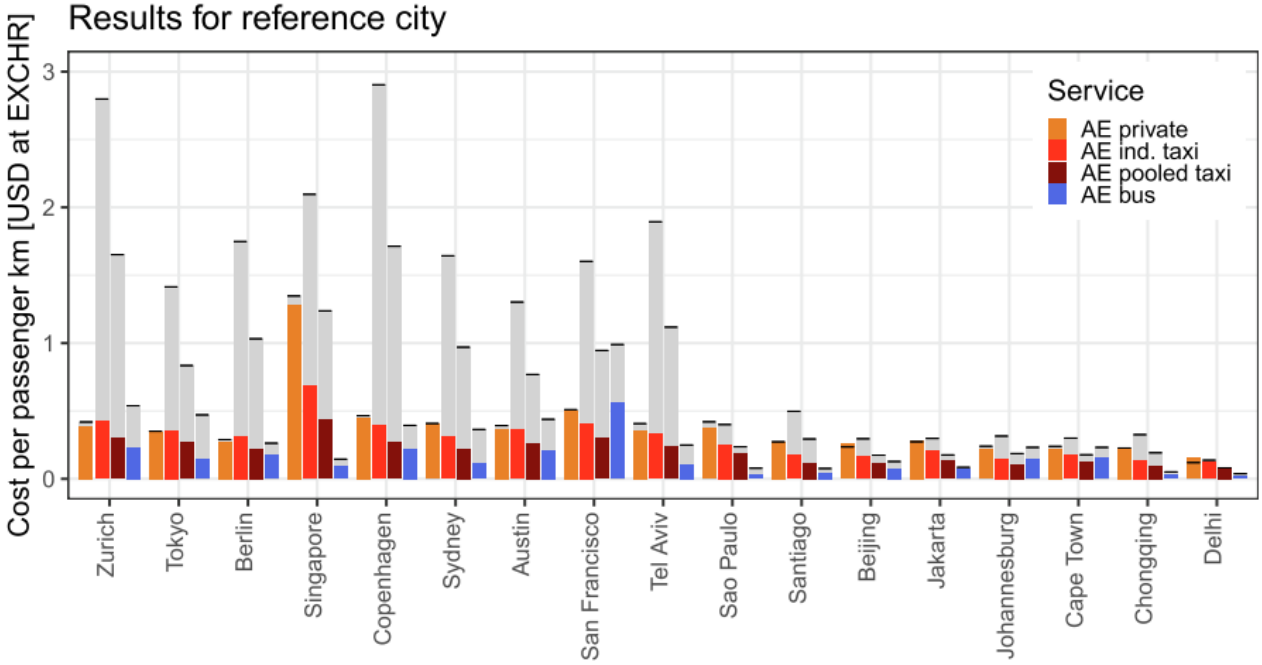

Figure 30. Comparison of costs for autonomous-electric services and conventional services.

NB: AE stands for "Automated and Electric", autonomous-electric services (colours), conventional services (light grey with black whiskers)

NB: assuming operational characteristics for Zurich (converted to US-$ at 2016 exchange rates)

Source: (H. Becker et al. 2020)

Service	variable	Zurich	Tokyo	Berlin	Singapore	Copen-hagen	Sydney	Austin	San Francisco	Tel Aviv	Sao Paulo	Santiago	Beijing	Jakarta	Johannesburg	Cape Town	Chongqing	Delhi
AE taxi	Overhead and vehicle operations	13.2	14.6	10.8	4.6	6.1	8.2	9.1	4.7	2.0	3.3	2.1	0.9	0.6	0.8	0.7	0.3	0.3
	Salaries	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Fuel	2.6	2.2	2.4	1.9	2.4	1.6	2.5	1.9	2.2	0.8	1.0	2.0	2.7	1.3	1.7	0.4	2.2
	Cleaning	11.7	14.2	4.0	2.4	4.1	4.0	10.0	5.4	10.0	5.3	2.5	1.2	0.7	0.8	1.1	1.7	0.8
	Parking and tolls	1.5	5.9	0.3	5.8	2.3	4.3	2.0	2.9	1.4	2.1	2.4	1.1	5.8	0.6	0.6	0.3	0.2
	Tax	0.0	0.0	0.0	11.6	2.6	0.3	0.0	0.2	0.0	0.7	0.3	0.0	0.6	0.0	0.0	0.0	0.0
	Insurance	0.2	0.4	0.3	0.3	0.1	0.1	1.1	0.4	0.2	0.6	0.2	0.3	0.2	0.2	0.2	0.1	0.1
	Depreciation	7.3	5.4	5.4	20.0	2.5	4.7	6.4	5.5	4.1	6.9	4.3	3.2	5.4	2.9	2.8	3.2	1.6
	Battery	2.3	2.5	2.1	1.8	1.5	2.0	2.9	2.2	1.4	2.3	2.1	1.4	2.2	1.7	1.6	1.4	1.3
	Maintenance and wear	3.6	1.2	2.5	2.2	2.4	1.5	5.8	1.7	2.6	1.3	1.7	0.7	0.6	0.6	0.6	0.7	0.2
Conv. taxi	Overhead and vehicle operations	13.2	14.6	10.8	4.6	6.1	8.2	9.1	4.7	2.0	3.3	2.1	0.9	0.6	0.8	0.7	0.3	0.3
	Salaries	240.9	208.6	151.5	116.3	138.5	129.6	113.2	74.5	70.4	24.9	28.9	23.2	11.9	11.9	9.6	9.8	4.2
	Fuel	5.8	4.3	5.3	5.9	4.3	4.5	3.7	3.5	4.1	6.1	4.1	2.5	4.6	4.5	4.1	2.5	2.8
	Cleaning	2.6	5.5	1.9	1.3	1.1	1.4	2.8	1.9	1.0	2.9	0.6	1.0	0.5	0.6	0.8	0.4	0.5
	Parking and tolls	1.5	5.9	0.3	5.8	2.3	4.3	2.0	2.9	1.5	2.1	2.4	1.1	5.8	0.6	0.6	0.3	0.2
	Tax	0.2	0.1	0.1	11.6	2.6	0.3	0.0	0.2	0.2	1.4	0.3	0.1	1.0	0.0	0.0	0.0	0.1
	Insurance	0.8	0.9	0.7	1.0	0.3	0.3	2.2	0.7	0.4	1.2	0.5	0.6	0.3	0.5	0.5	0.2	0.2
	Depreciation	6.4	4.4	4.6	19.3	1.9	3.9	5.2	4.5	3.6	5.7	3.4	2.6	4.4	2.1	2.0	2.6	1.0
	Battery	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Maintenance and wear	4.8	1.5	3.0	3.3	3.4	2.1	7.1	2.6	3.7	2.0	2.4	0.9	0.6	0.7	0.7	0.9	0.3

Table 21. Comparison of cost structures for taxi services (cost per 100 km in US-$ at EXCHR).

Source: (H. Becker et al. 2020), Table B.12

	Urban bus capacity	Urban bus full cost [US-$/km]	Urban bus effect of electrification	Urban bus effect of automation
Austin	60	5.90	−12%	−45%
Beijing	60	0.07	−16%	−29%
Berlin	94	5.53	−6%	−30%
Cape Town	60	3.12	−20%	−17%
Chongqing	60	1.01	−15%	−35%
Copenhagen	70	6.18	−6%	−40%
Delhi	60	0.51	−30%	−30%
Jakarta	100	1.90	−5%	−13%
Johannesburg	60	3.12	−24%	−17%
San Francisco	50	11.09	−6%	−40%
Santiago	90	1.54	−14%	−36%
São Paulo	99	1.75	−19%	−57%
Singapore	100	3.25	−6%	−32%
Sydney	60	4.89	−5%	−68%
Tel Aviv	70	3.91	−6%	−55%
Tokyo	72	7.61	−6%	−68%
Zurich	60	7.25	−6%	−55%

Table 22. Public transport parameters.

Source: (H. Becker et al. 2020) Table A.7

Chapter 3. Case studies

The aim of the thesis is to study the efficiency and relevance of autonomous vehicle (AV) services and how it varies depending on the type of territory. To do so, several case studies will be considered in this chapter in an attempt to explore both the diversity of territorial contexts, and the various forms that AV services could take. Then the cost-benefit analysis framework developed in the previous chapter will be applied to evaluate the selected AV services and help answer the research question.

In the first section the choice of the case studies and of the autonomous vehicle services that are simulated and evaluated in the three following sections are discussed. The services are defined by a feature-based methodology. The simulation model (including model parameters) and service parameters (such as the fleet size) are use case-specific, so that they are each discussed in their dedicated section. The three case studies are presented under article forms. The urban case study is published (Carreyre et al. 2023), the periurban case study has been accepted for presentation at the TRB conference and submitted for publication and the rural case study is in the process of being submitted. To make it possible to read each case study separately, a concise summary of the methodology is provided at the outset of each paper. The full methodology was presented in the previous chapter. Based on the results of the three case studies, the last section provides recommendations on the introduction of AV services, as well as for further research in order to better under their impacts and how to optimize their design.

I. Case studies definition

A. Introduction

This section aims to define which services will be evaluated for each case study. The introduction of automated vehicle (AV) services on specific territories requires a structured approach comprising three steps (Figure 31):

Define AV Services: the first steps entails a comprehensive definition of the various AV services under consideration.

Create a shortlist of services for implementation: subsequently, a shortlist of AV services will be crafted, tailoring them to the characteristics of each type of territory.

Define settings: the third step involves the specification of settings encompassing fleet size, vehicle type, capacity, level of service, and other relevant parameters. These settings will be presented in more detail in each case study section.

Figure 31. Scenario generation methodology steps
Source: prepared by the author.

This methodological sequence aims to ensure that the AV services considered in each case study are as well-suited as possible to the specific characteristics of each territory.

B. Definition of AV services

The definition of AV services has been developed thoroughly in the state-of-the-art section. Based on the literature, services are defined on a features-based nomenclature (Table 1 from (Carreyre et al. 2022)). The features are the ownership and usage mode, ridesharing setting, the service

availability, the vehicle type and the automation level. The services which have been identified are available in the Appendix (Table 24).

C. Shortlist of services

The purpose of the section is to define the type of scenario and their constitution. Similarly to Lucile Buisson, which offers methodological propositions on the design and evaluation of automated vehicles services (Buisson 2022), the scenario will be based on (Börjeson et al. 2006) methodology on scenario types and techniques.

Various scenario typologies have been suggested in attempts to make the field of futures studies easier to overview. Our typology is based on the scenario user's need to know what will happen, what can happen, and/or how a predefined target can be achieved. We discuss the applicability of various generating, integrating and consistency techniques for developing scenarios that provide the required knowledge. The paper is intended as a step towards a guide as to how scenarios can be developed and used. (Börjeson et al. 2006) define scenario categories according to the question they aim to answer "*What will happen?", "What may happen?" and "How can a specific target be reached?"* (Börjeson et al. 2006). In this thesis, the simulation-evaluation methodology corresponds to the first question "What will happen?" and puts our scenarios within the predictive category. This category is divided in two scenario types, the "Forecasts" ones and the "What-if" ones. Forecasts focuses on the most likely scenarios and what-if scenario look into the impacts of specific events. In this thesis, the primary focus is on the potential impact of level 5 autonomous vehicle services, but this thesis does not take position towards the feasibility of succeeding to reach level 5 autonomous vehicles. Instead, it exclusively examines scenarios where level 5 automated vehicles are assumed to be widely adopted, framing the analysis within a "What-if" context (see Figure 32).

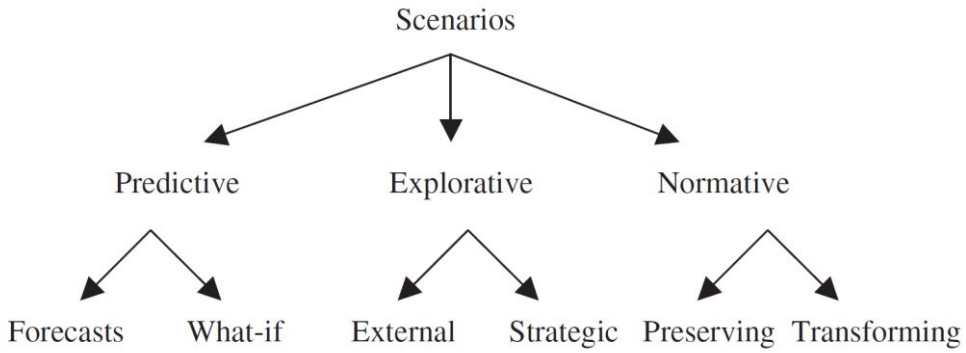

Figure 32. Scenario typology with three categories and six types
Source: Figure 1. from (Börjeson et al. 2006)

Predictive scenario generation is based on three techniques (surveys, workshops and delphi method, see Table 25). The selection of services will be based on the survey performed during the state-of-the-art chapter, including the meta-analysis which studies the performance of AV services with regard to Vehicle Kilometer Traveled (VKT), Travel Time (TT), Fleet Size (FS) and Total Cost (TC). Based on 48 documents modelling AV services either compared with conventional vehicles services or with other AV services, this state of the art provides indications on the focus of the literature and the performance of AV services, predominantly in urban territories.

The objective is to select the most promising AV services as well as to address gaps in the existing literature. Two primary approaches are employed to identify these services:

- Literature Focus: The first approach involves examining the services that have received significant attention in the existing literature. By analyzing the services that have been extensively simulated and studied, researchers can identify common trends and areas of interest. This process helps in understanding which services have been well-covered and may not require further evaluation, and which services have been underrepresented or overlooked, potentially warranting deeper investigation.
- Transferability from High Density to Low Density Areas: In cases where the literature lacks substantial information on a specific topic, such as the simulation of on-demand AV services in rural areas, researchers can draw insights from high-density area implementations and explore how similar services could be adapted and introduced in low-density areas. This approach involves

considering the unique challenges and requirements of low-density regions, such as the predominance of private car use and the need for cost-effective solutions. Researchers can leverage the lessons learned from high-density areas to devise strategies for introducing and optimizing AV services in low-density settings, aiming to bridge the gap in the literature and advance scientific understanding in this domain.

By combining these two approaches, it allows to identify services that are both well-researched and those that require further exploration across various types of territories.

First, the most simulated service in the literature are the shared automated taxis providing D2D service, the solo-ride automated taxis providing D2D service and the private AV (Figure 33) in urban territories.

Services	Occurrences
SAV	34
AV	16
Private AV	10
Stop Based SAV	7
Stop Based Shuttle	4
Door-to-Door Shuttle	4
Stop Based AV	2
Line Based Shuttle	2
Aut. Bus	1
Total général	**80**

Figure 33. Occurrences of the simulated services in the literature
Source: Carreyre et al. (2022)

The reviewed KPI of the meta-analysis are not enough to produce recommendations for the introduction of AVs, but they do provide insights into the likely performances of AV services.

Shared and solo automated taxis operating in door-to-door service, two of the most popular services in the literature, would raise VKT if they were to replace private cars. Furthermore, it seems that alternative routing (stop based/line based) and heavier vehicles would help to reduce VKT and the fleet size (FS) in densely populated areas. The reduction of VKT and decrease of the FS are two desirable objectives. The services proposed in urban areas will need to be heavy enough to absorb the demand without generating more VKT or increasing the FS. This increase in VKT when comparing Private Car with privately-owned (PO) AV, AV and SAV needs to

be reduced at its minimum. As PO AV, AV and SAV provide similar services, only the least impacting service will be retained. Note that the state of the art found a majority of urban and periurban scenarios, and conversely a lack of rural studies.

The service will need to be adapted towards lighter and more flexible services in low-to-medium density areas. The most flexible service can be represented by the automated taxis providing a private ride in door-to-door service and in the other and the less flexible one can be represented by a traditional line-based service of buses.

In line with the strong emphasis of the literature on on-demand services, this thesis will focus on this category of services. The subsequent subsections will introduce eligible scenarios tailored to each territory type: urban, periurban, and rural. These scenarios must adhere to two key principles:

1) consistency between the service flexibility and the expected density of demand. The more important is the demand density, the less a service would need to be flexible as the trips are more easily mutualized (see Figure 34**).**

2) the starting point on the flexibility/density ratio is the solo ride D2D AV (excluding the PO AV).

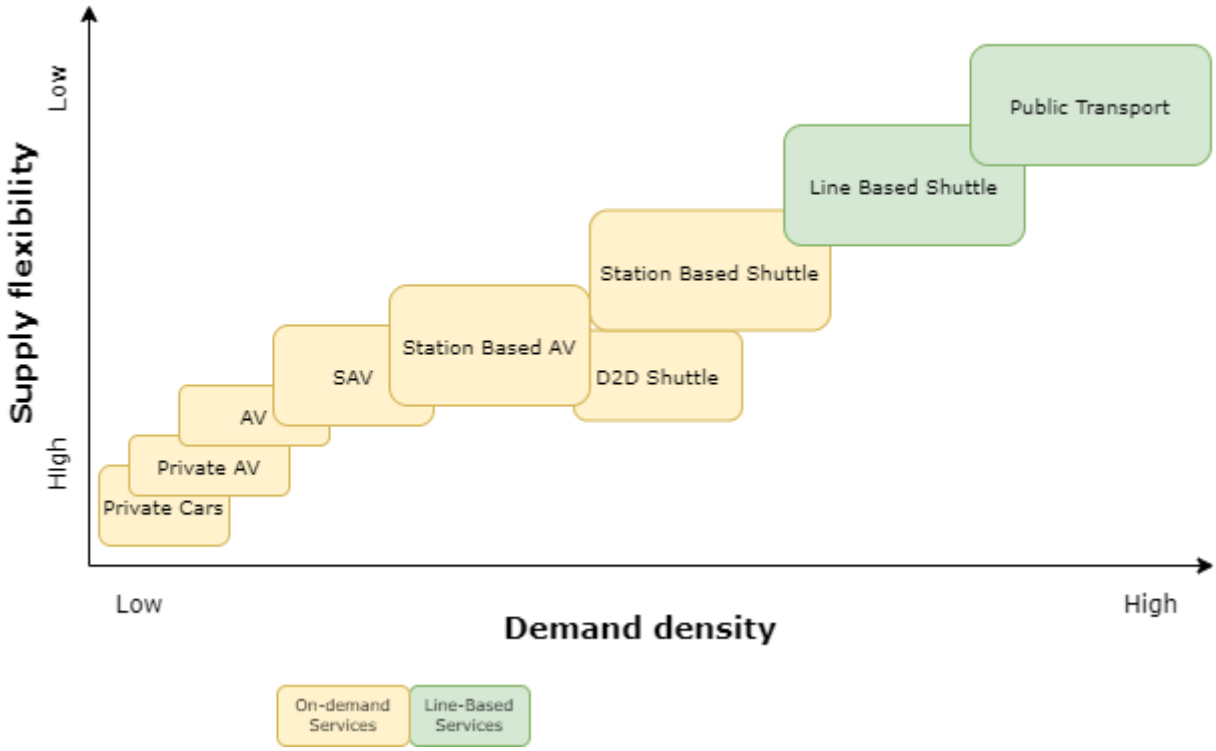

Figure 34. Service positioning regarding demand density
Source: prepared by the author.

The territories are divided in categories based on the Insee nomenclature of urban to rural territories ("Une Nouvelle Définition Du Rural Pour Mieux Rendre Compte Des Réalités Des Territoires et de Leurs Transformations – La France et Ses Territoires | Insee" n.d.).

1) Urban

The first case study will take place in the urban territory of Berlin. The literature has already produced a substantial number of simulations of private automated cars, automated taxis and shared automated taxis. The first results have shown that the replacement of conventional car trips by these three modes would result in higher VKT and Travel Time but smaller Fleet Size (Carreyre et al. 2022). If the fleet size reduction is attractive, it has no direct effect on the traffic level, and more indirectly on congestion and emissions (except when rides are shared). The Stop Based scenarios (taxis and shuttles) would lessen the externalities due to the service than a D2D scenario but will provide a more flexible way of transportation than conventional public transit. The implementation of stop-based services should not require a more important fleet than their door-to-door equivalent. Furthermore, the PO AV has significantly less interest than its

shared counterpart in urban environment where it does not allow to massify flows. As such, it will be excluded from the urban case study.

The following services will be tested:

- 1st scenario: SAV providing Door-to-Door services
- 2nd scenario: SAV providing Stop-Based services
- 3rd scenario: Shuttles providing Door-to-Door services
- 4th scenario: Shuttles providing Stop-Based services

2) Periurban

The second use will take place in the periurban area of the Communauté d'agglomération Paris Saclay, a county (*intercommunalité*) south of Paris. This case study has the particularity to link AVs service with conventional public transit in order to provide a feeder service. This intermodality module has been made available by IRT SystemX during our collaboration on this chapter. The intermodality may allow to take advantage of the strong interactions of the periurban rail stations with city centers.

The use of shared vehicles would allow to benefit of economies of scale due to the demand density (allowed by the large flows of arrivals at train stations). Moreover, the savings of the driver's wage could allow to operate more vehicles and provide a better level of service (in space and time) than the current bus lines services. The D2D and SB could provide better accessibility in the non-served places. The shuttle vehicle size would allow the economies of scale of conventional public transit, but would limit the detours due to the smaller size (compared to a full-size bus). Similarly with the urban case study PO AV has significantly less interest than its shared counterpart when used for first-and-last mile trips to train stations where massive arrivals of commuters could be expected. As such, it will be excluded from the periurban case study.

The following services will be tested:

- 1st scenario: SAV providing Door-to-Door services
- 2nd scenario: SAV providing Stop-Based services
- 3rd scenario: Shuttles providing Door-to-Door services
- 4th scenario: Shuttles providing Stop-Based services

NB: all AVs service in this case study work as a feeder service with public transit. The origin or the destination of the AV needs to be a public transit station. The Door-to-Door scenarios are then semi-Stop-Based.

3) Rural

The third case study takes place in the rural region of Dourdan and its vicinity, located approximately 30 kilometers south of Paris within the Ile-de-France region. This rural setting presents unique challenges as it is the least explored type of territory in the simulation literature. Additionally, rural areas predominantly rely on private car use, making it challenging for on-demand AV services to compete, given their inherent drawbacks of waiting times and higher marginal financial costs. Furthermore, rural areas are characterized by low population density, which poses a challenge for on-demand Shared AVs (SAVs). These SAVs would suffer from longer detours and increased waiting times (assuming an equal fleet size). While Stop-Based routing strategies have proven effective in mitigating congestion in urban and periurban areas, their applicability in rural regions may not yield the same advantages. In rural areas, such routing may result in significant access and egress times for commuters, which can profoundly impact both simulation and evaluation processes. As such, this chapter can focus on the differences between shared and solo-ride services in Door-to-Door configuration.

The following services will be tested:

- 1st scenario: SAV providing Door-to-Door services
- 2nd scenario: AV providing Stop-Based services

D. Conclusion

As presented above, the three case studies were selected in accordance with the results from the literature, while aiming to fill the gap regarding 1) rural studies which are much less frequent, and 2) the lack of economic appraisal for on-demand services. The scope of services which are considered in this thesis ranges from door-to-door solo-ride AV to stop-based shuttle services. Furthermore, this thesis seeks to contribute to the literature by considering the less treated case of low-density areas. Table 23 provides an overview of the scenarios simulated for each case study, categorizing them based on the features discussed, including ridesharing, intermodality, vehicle size, and routing.

Parameters	Berlin	Saclay	Dourdan
Ridesharing	Yes	Yes	No
Intermodality	No	Strictly with trains	No
Vehicle size	Cars/Shuttles	Cars/Shuttles	Cars
Routing	D2D/SB	D2D/SB	D2D

Table 23. Service considered for each case studies.

Source: prepared by the author.

E. References

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F. Appendix

Service features					Service Name
PO*	No RS*	D2D*	Car	Conv.	**Private car**
PO	No RS	D2D	Car	Aut.	**Private AV**
Public	RS	D2D	Car	Conv.	**Shared Taxi**
Public	No RS	D2D	Car	Aut.	**AV**
Public	RS	D2D	Car	Aut.	**SAV**
Public	RS	SB*	Car	Aut.	**Stop Based AV**
Public	RS	D2D	Shuttle	Aut.	**Door-to-Door Shuttle**
Public	RS	SB	Shuttle	Aut.	**Stop Based Shuttle**
Public	RS	Line Based Schedule based	Bus or rail	Conv.	**Conventional Public Transit**
Public	RS	Line Based Schedule based	Shuttle	Aut.	**Line Based Shuttle**

** PO stands for "Private Ownership ; RS stands for "Ride-sharing" ; D2D stands for Door-to-door ; SB stands for Stop Based*

Table 24. Mobility Services

Source: Table 4 from (Carreyre et al. 2022)

Scenario types	Techniques		
	Generating	Integrating	Consistency
Predictive			
Forecasts	• Surveys • Workshops • Original Delphi method	• Time series analysis • Explanatory modelling • Optimising modeling	
What-if	• Surveys • Workshops • Delphi methods	• Explanatory modelling • Optimising modeling	
Explorative			
External	• Surveys • Workshops • Delphi modified	• Explanatory modelling • Optimising modeling	• Morphological field analysis • Cross impact
Strategic	• Surveys • Workshops • Delphi methods	• Explanatory modelling • Optimising modeling	• Morphological field analysis
Normative			
Preserving	• Surveys • Workshops	• Optimising modeling	• Morphological field analysis
Transforming	• Surveys • Workshops • Backcasting Delphi		• Morphological field analysis

All techniques can be used in several phases but only their main contribution is mentioned in this table.

Table 25. Contribution of techniques in the phases of scenario development

Source: Table 1 from (Börjeson et al. 2006)

II. On-demand Autonomous Vehicles in Berlin: a Cost Benefit Analysis

Abstract

The autonomous vehicles (AV) technological development presents the challenge to their economic relevancy. Are AV worth it? We adapt the cost-benefit analysis framework to the case of AV services. The appraisal methodology is applied to the introduction of an on-demand AV services in Berlin, simulated through MATSim, an agent-based model. The introduction of AV in a dense urban environment would generate more pressure on the road network. This would cause private cars' users to suffer from longer travel times, resulting in a loss in terms of consumer surplus that would not offset the new AV users' benefits. In this configuration, a Stop-Based routing service appears to generate less externalities (congestion, emissions, accidents) and would be cheaper to operate than a Door-to-Door routing. Another configuration assumes that private cars are banned. In that case, the consumer surplus will significantly decrease, the AV services will not be able to absorb the whole demand and the modal shares of other modes will increase. Conversely, the externalities are strongly reduced. Finally, in an urban environment where on-demand AVs would be added to the available modes, the social impact would be negative for all economic agents, with heterogeneity on the different externality impacts. This would benefit some travelers but would also involve additional congestion. In that case, a Stop-Based routing seems less impacting (but still negative) than a Door-to-Door one. Further works discussing AVs' introduction into the urban environment should focus on online-based options such as automated bus services.

Keywords: Autonomous vehicles, mobility simulation, economic evaluation, transport, cost benefit analysis

A. Introduction

The previous chapter introduced an economic appraisal methodology aligned with the French national guidelines, and the preceding section delineated the services earmarked for evaluation. This section plays a pivotal role in addressing the overarching research questions posed by this thesis: "What is the performance of AV-based services when considering the perspectives of key stakeholders, and how does this performance vary across different types of territories? Which configuration or operating model of AV-based services proves most effective for deployment in each type of territory?". The primary objective of this section is to deepen our comprehension of the impending impact of on-demand AV-based services in urban territories. The literature review has revealed a prevailing trend wherein autonomous vehicles are predominantly envisioned to function within on-demand service frameworks in urban areas. By evaluating these services, this section aims to contribute significant insights towards addressing the central research inquiries, thereby advancing our understanding of how AV-based services perform and how their performance is influenced by different types of territories, particularly within urban settings. However, as it is a futuristic mode of transportation, the impact of AV services remains an open question. Mobility simulation studies suggest that distances travelled and travel times might increase, at different levels of intensity depending on the decrease of the generalized cost of travel. The overall fleet of vehicles (which can be cars or shuttles) required to serve the same level of demand could be reduced if the AVs were to be operated as ridesharing or carsharing services (Balac, Hörl, and Axhausen 2020; Bösch, Ciari, and Axhausen 2016; Ben-Dor, Ben-Elia, and Benenson 2019; Carreyre et al. 2022).

While simulation models allow forecasting operational trends, they lack a comprehensive scope to include the perspectives of main economic agents. (Ahmed et al. 2020) used a logsum-based method to measure the consumer surplus variation of employment accessibility amongst different socio-demographics clusters, but do not consider impacts on others agents. (Kockelman et al. 2017) developed a Cost Benefit Analysis (CBA) to assess the social value of the replacement of private cars by private AV but do not introduce on-demand services, which are an important incentive of AV development for investors (“40+ Corporations Working On Autonomous Vehicles” 2020). (Kaddoura, Bischoff, and Nagel 2020) introduced AVs in Berlin in order to propose an external pricing cost of their externalities with a simulation methodology close to the one developed in this article. Their evaluation only investigates consumer and operator surplus, but do not

study environmental impacts. Their consumer surplus might benefit from a better understanding of repartition of the AV contribution amongst travelers. The introduced service is a door-to-door service which should also be compared with other types of services, such as stop-based services or line-based services. (Andersson and Ivehammar 2019) considered the fact that the infrastructure would need to be equipped but the uncertainty of the impact (either positive or negative) prompted them to affect a neutral impact in their quantitative analysis. The uncertainty of some effects and the overall impact allow questioning AVs' social desirability. What are the economic impacts of AVs on agents in an densely populated area? What would be the most efficient AV services? As AVs remain at a technical development step but are considered to be the future of Mobility-as-a-Service with on-demand services (McKinsey Center for Future Mobility 2020; Berrada 2019; Mira Bonnardel, Antonialli, and Attias 2020), traveler behaviors cannot be empirically studied. To forecast traveler behavior variation and to provide inputs for the economic assessment, agent-based simulations will be used. This type of simulation models are favored by the academic community to work with on-demand services (Carreyre et al. 2022) and this article will focus on on-demand AVs services (or Demand Responsive Transport, i.e. DRT). The economic assessment benefits from a well-established methodology with the Cost Benefit Analysis (de Rus et al. 2020; de Rus 2021; Koopmans and Mouter 2020) which have been adopted in many countries as the reference method to evaluate projects (Koopmans and Mouter 2020, 27). This article contributes to the existing literature with methodological and empirical contributions. The appraisal method integrates a broader spectrum of impacts than the literature, such as infrastructure and supervision costs or externalities impact (noise, road safety, GHG emissions and lifecycle analysis) into a Cost Benefit Analysis framework. This economic evaluation is supplemented by an equity analysis, allowing a better understanding of the AVs impact repartition on travelers. The empirical contribution is the application of the appraisal framework to assess the economic relevancy of AV services in an urban environment. The systematic comparison of door-to-door (D2D) and stop-based (SB) routing services enriches the literature on the topic.

B. Method

The methodology relies on a two-step simulation-to-evaluation pipeline. Simulation is carried out using the MATSim agent-based mobility model, which allows to derive traffic and operational forecasts for the introduction of AV services. These forecasts are then used to carry out the

economic evaluation based on the Cost Benefit Analysis (CBA) methodology, which we adapt to the case of AV services.

1) Model

a) MATSim

MATSim is an agent-based mobility simulation framework (Horni et al. 2016). The use of an agent-based model allows to have a good representation of on-demand services as every traveler and vehicle is considered individually (Carreyre et al. 2022). It allows to simulate various mobility systems in large geographical areas. MATSim is activity-based, it relies on a fine-grained description of a population of agents that comprises a set of activities with location and time attributes that the agents need to perform. They consequently perform trips between the different activities at the relevant times. The road network as well as the mobility systems being capacitated, congestion effects are reproduced and a competition for resources takes place. By performing many iterations of the simulation and replanning the agents decision between each two iteration (mainly the departure times and used transportation modes), the agents' plans evolve over time until they stabilize in an equilibrium. This allows MATSim to provide meaningful outputs at the end of the process that reflect the impact of design choices on the users' decisions.

b) Demand Responsive Transport (DRT)

MATSim allows to simulate and study Mobility-on-Demand systems through the DRT Module (Maciejewski and Nagel 2013). The use of DRT will be now referring only to the simulation module and its parameters. The latter provides the implementation of an on-demand fleet from which users can request trips in an online manner. A vehicle assignment strategy is then used to select a vehicle to perform the submitted request. The strategy implemented by default tries to find the best way to insert the request in a vehicle's plan. The insertions are evaluated given the expected arrival time for the passenger and constrained by the vehicles' capacities as well as service level requirements: maximum waiting and travel time as well as a detour factor in case of a shared trip (difference between unshared and shared distances) which allows to consider the cost of ridesharing. The DRT module also defines a pricing scheme for the service. This scheme can be parametrized to consider a cost per kilometer, per time, and a minimum fare per trip. Note that the cost per kilometer is applied to the estimated unshared distance and the cost per time to the estimated unshared travel time, which means that the price doesn't increase if the trip is shared in

comparison to the trip being unshared. However it also means that the price of a shared trip is not less than an unshared trip. All the parameters used in the following will follow the default parameters (for fare, speed, vehicle size or dispatching strategies) from the DRT module, available in open-source (Bischoff and Maciejewski 2016).

2) Cost Benefit Analysis

The Cost Benefit Analysis (CBA) is a systematic and quantitative method to evaluate transport projects. It attempts to quantify "*the change in the well-being of the individuals living in the society, and this involves calculating, in monetary terms, the magnitude of the potential […] gains compared with the opportunity costs of the resources."*. The theorical background is well covered (de Rus et al. 2020; Boadway 1974; Boardman et al. 2017; OECD 2018). Several criticism and works had risen the last several decades (Asplund and Eliasson 2016; Börjesson and Eliasson 2019; Beria, Maltese, and Mariotti 2012) which led to incorporate topics such as equity in the process. The replicability of the method and its capability to understand the impact of public funds attribution convinced governments to seize this appraisal tool since its introduction in the USA (Flood Control Act, 1936) (Congress 2018). Governments have since published methodological guides (E. Quinet 2013; "Document: Cost Benefit Analysis Guidelines" n.d.; "Cost Benefit Analysis Guidance" 2014) and provided reference values which are regularly updated.

In this paper, we use the French CBA guidelines (E. Quinet 2013), which we adapt by providing a new way to compute the consumer surplus and by providing new reference values for AVs. This conceptual framework is intended to be used in three different case studies, an urban environment, a suburban territory and a rural territory. As this article is the urban territory, and even though it takes places in Germany, the two following case studies will be located in France. As such, the French guidelines have been selected rather than the German ones. If the parameters value may vary between French and German guidelines, they share a very similar structure (see (E. Quinet 2013; Gühnemann 2013)) and methodologies. For example, both French and Germans use the trip purpose to differentiate travel time savings.

For the three categories, it originates from de Rus et al. 2020 (Methodology for the cost-benefit analysis of transport projects and policies.) which identify five categories of economic agents (consumer, producers, workers, taxpayers and externalities or "rest of the world"). Our

conceptual framework does not include the workers and the taxpayers, it may be a welcome addition to further works. The structure is divided into the three categories (Consumer Surplus, Operator profits and Externalities Impacts), each based on an economic agent and their sub-components (Figure 35).

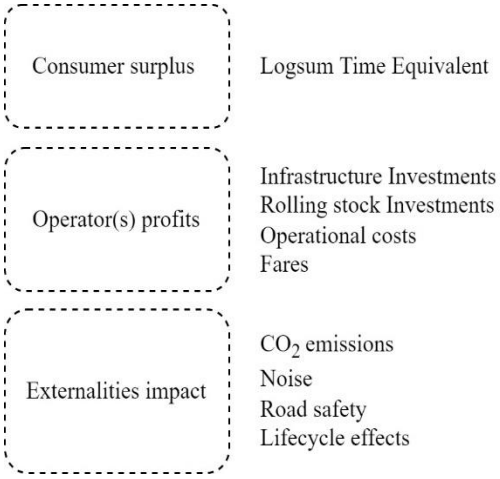

Figure 35. Cost Benefit Analysis sub-components
Source: prepared by the author.

a) Consumer surplus

The Consumer surplus is defined as the monetized value of the utility gains or losses of the mobility consumers. It is based on the logsum methodology, a welfare measure defined as "*the log of the denominator of a logit choice probability, divided by the marginal utility of income, plus arbitrary constants.*" (de Jong et al. 2007). The utility is based on the MATSim plans score according to the methodology developed by (Kickhöfer, Nagel, and Nagel 2016; Kickhöfer 2014). For each agent, the best score is selected and converted into an equivalent monetary term using the marginal utility of income. As all agents do not necessarily have the same value of time and marginal utility of income, a time equivalent approach is used. Based on (Kickhöfer 2014, 54, 55) the overall Consumer Surplus change, with individuals j = 1..J, is:

$$\Delta CS = \sum_{j=1}^{J} \Delta m_j \quad (1)$$

ΔCS is the overall Consumer Surplus change

Δm_j is the monetary compensation required to balance the policy implementation, i.e. the expression of the difference in consumer welfare between both states.

The Logsum expression in Time Equivalent (LTE) can be expressed as follows:

$$\Delta m_j = \Delta t_j \times VTTS_j \quad (2)$$

Δt_j is the number of hours required to counterbalance the policy implementation in agents utility

$VTTS_j$ is the Value of Travel Time Savings (EURO/h).

$$\Delta t_j = \left(\frac{\Delta V_j}{\Delta t}\right)^{-1} \Delta V_j \quad (3)$$

$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1}$ is the inverse marginal utility of time

ΔV_j is the variation of utility between two states, i.e., before and after a policy implementation.

b) Operator profits

The operator(s) profit (π) is the difference between costs, including infrastructure investment and maintenance, rolling stock investment and operating costs, and revenues generated by usage fees, sponsoring, advertising and subsidizing.

There is not yet a consensus regarding the investment and maintenance costs of AV infrastructure. The cost to upgrade the infrastructure to accommodate AVs varies from 3 000 dollars (Saeed 2019) per year and per kilometer to more than two millions dollars (Xue 2022, 10). Similarly, maintenance and replacement costs should be based on

feedbacks of previous deployments and are thus only roughly estimated as for now. Consequently, these costs will be analyzed in this paper through a sensitivity analysis assuming that the investment cost (I_{infra}) varies from 50,000 to 250,000 EUR/km and that maintenance and replacement costs (M_{Infra}) are based on a yearly replacement rate of 10 to 50% of the investment cost to 50% (i.e., 50% means that the infrastructure will be fully replaced every two years). The infrastructure length is noted as Km_{Infra}.

The general consensus on the price tag of automated vehicles is that their price is marked up compared to conventional vehicles (Andersson and Ivehammar 2019; Bauer, Greenblatt, and Gerke 2018; Becker et al. 2020; Ongel et al. 2019; Quarles and Kockelman 2018; Tirachini and Antoniou 2020; Wadud 2017; Wadud and Mattioli 2021). The most extensive study on light vehicles such as cars or shuttles can be found in (Becker et al. 2020). Automation is supposed to add 5,000 US dollars to the vehicle price. A similar assumption can be found in (Wadud 2017), who report that automation would cost 5,000 dollars or 3,000 dollars in the second-hand market. A more recent study that builds on previous advances on the subject (Wadud and Mattioli 2021) indicated that automation would cost between 9,400 £ and 15,000 £ more per car. (Tirachini and Antoniou 2020) assumptions on automation costs are more pessimistic, as they proposed that automation would cost between 36% and 86% more, depending on the vehicle. The +36% to +86% markup estimates are consistent with the variation in absolute value found in (Becker et al. 2020; Wadud and Mattioli 2021) based on the 26,000 euro average selling price of a new car in France (Leroy 2021). The total markup estimated for AVs is 7,500 euros per vehicle.

For EVs, (Bösch et al. 2018), on which the study by (Becker et al. 2020) is based, do not consider any markup compared to thermal vehicles. Similar to (Wadud and Mattioli 2021), the electric impact can be found in the operational, maintenance and insurance costs, but no purchase price variation seems to be applied. (Ongel et al. 2019) forecasted the purchase price of Internal Combustion Engine Vehicles (ICEVs), EVs and AVs for the year 2030 close to the shuttle format. They found that an ICEV should cost between 105,000 and 110,000 (2017 constant) dollars, the electric equivalent should be 20% more expensive and the automated and electric counterparts would be 28% more expensive. The estimated price for the AE shuttle is 128,000 euros with a 100,000 euro ICEV equivalent. For cars, (Mitropoulos, Prevedouros, and Kopelias 2017) found a 16% retail price

difference between ICEVs (27,130 in 2015$) and EVs (31,590 in 2015$). This value is consistent with the +20% reported by (Ongel et al. 2019). All the aforementioned parameters value can be found in Table 26.

Automation impact vehicle price	Values	Automation impact factor
ICEV car	26,000 €	100%
Electrical car	31,200 €	100%
Automated ICEV Car	33,500 €	+ 29%
Automated Electrical car	38,700 €	+24%
ICEV Shuttle	100,000 €	100%
Automated electric Shuttle	128,000 €	+28%

Table 26. Automation impact factors based on the automation level and vehicle size.

Source: prepared by the author.

The initial rolling stock investment is based on the number of vehicles required (NB_{Veh}) to serve the demand, and the replacement investment on a 300,000 km distance-lifetime of vehicle. The price of an AV is noted as P_{veh}.

(Becker et al. 2020) have produced the most in-depth work on AV operating cost. Considering multiple cities around the world, they provided simulation-backed results for several business models and a large amount of data on cost analysis for private cars, automated taxis and buses. A shuttle cost structure can be found in (Bösch et al. 2018), a paper that also provides more insights into the influence of territory type on costs. (Abe 2019) produces a good overview of the influence of driver costs on the overall costs. The automation savings in operational costs are quite important, as drivers represent an important part of those costs. A total of 29% to 77% of the operational costs can be saved depending on the ratio of supervisors/vehicles required to monitor a taxi fleet (Abe 2019). However, (Becker et al. 2020) hold highly optimistic assumptions on the ability of AVs to drive themselves without supervisors. It seems reasonable that a supervision centre may be needed to regain control of autonomous vehicles that find themselves in situations where human intervention is needed. The supervisor topic has remained underexplored in the literature on AV cost analysis (Scoliege 2021). In the AV financial analysis field, (Nunes and Hernandez 2020) estimated that a supervisor should handle 50

vehicles at once to benefit from the economy of scale. This assumption may need additional discussion as it is not based on studies but rather one projection. As the acquisition costs of AVs are already considered in the investment section for AVs and Automated Shuttles in (Bösch et al. 2018, fig. Table 2), the depreciation costs (0,054 CHF/km and 0,14 CHF/km) are deducted from the initial 0,48CHF/km and 0,98CHF/km (Bösch et al. 2018, 89). These operational costs are converted to euros and discounted. No supervision cost is considered, which is corrected by adding a +0,05 EUR per Vehicle Kilometer Traveled (VKT). The revenues for the operator will be the results of the fare revenues (F) of the operations. All the aforementioned parameters value can be found in Table 27.

Mode	Invest Infra (per km)	Maintenance Infra Yearly Invest % cost	Vehicle Price	Operating costs (per km)
Private EV	-	-	-	Integrated in CS
Ride	-	-	-	Integrated in CS
SAV (car)	50k-250k €	10%-50%	38 700 €	0,45 €
AV Shuttle	50k-250k €	10%-50%	128 000 €	0,80 €

Table 27. Operator(s) profits parameters

Source: prepared by the author.

NB: The Public Transit are not considered here as their level of service remains equivalent between scenarios. In this case, no differences could be found, whatever the financial parameters values.

Finally, the profit could be expressed as:

$$\pi = F - \left(\begin{array}{c} \left(I_{infra} * Km_{Infra}\right) * \left(1 + M_{Infra}\right) + NB_{Veh} * P_{veh} \\ + \frac{VKT}{300000} * P_{veh} + VKT * OC \end{array} \right) \quad (4)$$

c) Externalities impacts

Externalities of AV (Ext) are divided into four sub-components, based on the segmentation by (E. Quinet 2013). Air pollution is not included as all AV vehicles are assumed to be electric.

The political trend restricting thermal vehicle use in European cities (see the low emission zones in Italy, the UK or Paris) makes the development of AVs under thermal propulsion unlikely. Electric and hydrogen vehicles are good candidates, but the development of hydrogen vehicles does not benefit from the same support as that of EVs. AVs will then be considered electric. For CO^2 emissions, (E. Quinet 2013) provides a monetary value for every ton of CO^2 emitted for every year. This value has been reviewed in (A. Quinet 2019) and fixed at 250 euros. For electric vehicles (EVs), general data need to be interpreted with caution. Electricity consumption is not a direct source of GHGs, but its production is often carbon-based. The mix of energy sources is heavily dependent on geographical political choices. Emissions for EVs or hybrid vehicles will need to be adapted for every use case with similar data to those in (E. Quinet 2013), (Buehler 2014), (Jochem, Babrowski, and Fichtner 2015), or (Jöhrens et al. 2020). The automation impact remains uncertain, as (Liu et al. 2019) point out. In the best-case scenario, a 13.28% reduction could be applied to the fuel consumption of EVs, in contrast with the worst-case scenario, which could increase the fuel consumption by 11.63%. However, Liu estimated that ten percentage points could be saved from the worst-case scenario by limiting speed limits alone. The difference between an automated car and a shuttle vehicle may have an impact on electricity consumption. (Jöhrens et al. 2020, 58) detailed electricity consumption levels based on vehicle size. Automated cars with four to five seats are assigned to the "Small Cars" category, with a consumption of 19.7 kWh/100 km, and automated shuttles are assigned to the "Large Cars" category with a 23,6 kWh/100 km consumption. A ratio of 1.19 based on the relative overconsumption of the shuttle is applied. A 5% fuel consumption is estimated for AVs compared to their strict equivalents, conventionally driven-EVs. The CO_2 emissions include the valuation of all CO_2-equivalent emissions from the use phase of the vehicle lifecycle (Em_{veh}). Private cars emissions are based on German emission for 2030 (Jochem, Babrowski, and Fichtner 2015).

The Lifecycle effects include the valuation of all CO_2-equivalent emissions made during the manufacturing and end-of-life phases, as the use phase is already covered.

In (Kemp et al. 2020), the materials and manufacturing (MM) phase represents 27% and the End-of-Life (EOL) phase represents 1% of the 42 ton of a the lifecycle emissions of an EV. The Use phase, counting for 72% is not accounted for in the lifecycle item as this work has already considered these emissions, the emissions due to the use part of the vehicle life will be

subtracted from the lifecycle analysis. The automation sub-system is considered to add 1055 CO_2eq kg. Previously mentioned studies did not include AV shuttles in their scope. (Held and Schücking 2017) introduced the topic. As such, a value of 20,000 kg was estimated for a shuttle ("BEV (minivan) RheinMobil, elec.-mix" (Figure 3), minus the "charging electricity" item, which is similar to the "Use phase" from (Kemp et al. 2020)). The same automation burden of 1055kg is added to the Shuttle system. All vehicle lifetime is estimated to be 300 000 kilometers, an assumption close to the 200 000 miles in (Kemp et al. 2020). The value of the CO_2eq ton is fixed at 250 euros, accordingly to the Quinet report for 2030. The retained values (V_{LCE}) (0,95 euros for EVs, 0,97 for AVS and 1,75 euros for autonomous shuttles) are close to the 0,9 euros value fixed by (E. Quinet 2013) for a private car. One could have expected a higher value as EV are known to have an heavier environmental impact during the MM phase.

The noise externality is taken into account as the inconvenience that the road traffic might cause (E. Quinet 2013). (Taszka and Domergue 2017) found a -50% effect of the noise externalities due to electrification. Automation was not considered as a lever to reduce noise impact (N_{Impact}) based on (Patella, Aletta, and Mannini 2019) recommendations. Lastly, road safety is considered as AV are also expected to decrease accidents rates. (Papadoulis, Quddus, and Imprialou 2019) found that under a 100% market share of AV on motorways, conflicts can be reduced from 82% to 92%. Less optimistic, Kitajima et al. (2019) used an agent-based model to estimate human-based errors leading to crashes. They found an 18% reduction in collisions, but they warned of the need to consider their results with caution. Mahdinia et al. (2020) also found that automation would lead to a reduction in both driving volatility and time-to-collision, which would significantly affect accidents. (Tafidis et al. 2021) have performed the latest literature review on the topic to date. The fact that their review includes only 24 papers is due to the novelty of the topic. No overall consensus can be found, but most of the papers highlight an improvement in road safety thanks to automation. These results are based on assumptions and may need to be evaluated as soon as field data become available. A conservative approach was adopted, assuming a reduction of 20% of all crashes/VKT. The value of a statistical life is set at 3 million $€_{2010}$ according to Quinet (2013). The type of territories and vehicles will be taken into account, as they have important roles. The rate of accidents/traffic should be available for each case; otherwise, the 2019 rate in France will be used as a reference (ONISR 2019, 18), with 5 deaths per billion vehicle kilometers travelled. All the aforementioned parameters value can be found in Table 28.

Externalities per 100km	Carbon cost	Air pollution	Vehicle Lifecycle	Noise impact	Road Safety
Private EV	1,45 €	0,78 €	0,95 €	0,0005 €	0,0134 €
SAV	1,38 €	0,63 €	0,97 €	0,0005 €	0,0107 €
Difference compared to EV	*-5%*	*-19%*	*+2,1%*	*-*	*-20%*
Aut. Shuttle	1,64 €	0,99 €	1,75 €	0,0005 €	0,0107 €
Difference compared to EV	*+13,05%*	*+27%*	*+84,2%*	*0%*	*-20%*

Table 28. Externalities impact parameters

Source: prepared by the author.

Consequently, the externalities could be calculated using:

$$Ext = Em_{veh} * VKT * P_{CO_2} + V_{LCE} * VKT + N_{Impact} * VKT + V_{SL} * AR_D * VKT \quad (5)$$

d) Indicators for scenarios comparison

The comparison of scenarios is performed on three different levels: the macroeconomic level, the economic agents' level and the consumer level (Figure 36).

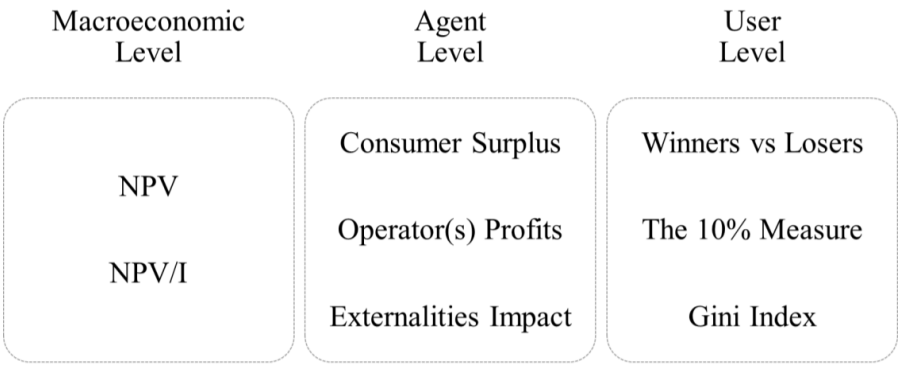

Figure 36. Scenario comparison methodology

Source: prepared by the author.

Comparison at the macroeconomic level is made using the social Net Present Value, "equal to the sum of the change in social surplus or the sum of changes in willingness to pay and changes in resources" (de Rus et al. 2020, 28). All cost and benefits considered in the NPV are not financial costs but also consumer surplus and externalities gain or loss.

$$NPV_s = \sum_{t=0}^{T} \delta^t (B_t - C_t) \quad (6)$$

NPV_s: social Net Present Value

δ^t: Nominal discount rate of period t

B_t: Aggregated Benefits from period t

C_t: Aggregated Costs from period t

Based on (de Rus et al. 2020), the inflation rate (φ) is applied at the same level as the discount rate, introducing the real discount rate instead (r_R) of the nominal discount rate (δ^t):

$$r_R = \frac{r_N - \varphi}{(1+\varphi)} \quad (7)$$

An 1% inflation rate value based on the last decade of inflation rate in Europe has been retained. The Ukrainian war have increased to inflation rates to a higher level, but a more conservative and event-free approach is considered here. (E. Quinet 2013) suggests using a 2.5% annual discount rate, which is close to the 3% recommended by the European Commission for most European countries (de Rus et al. 2020, 33). This value may be considered low compared to the amount that may be attributed elsewhere (up to 15 or 18%), but (Mouter 2018) reviewed the discount practices in the Netherlands, United Kingdom, Norway, Sweden and Denmark, where discount rates were distributed between 1% and 4.5%. The discount rate is fixed at the European Commission level of 3%. Further research could explore the difference in price evolution between autonomous vehicles and autonomous vehicle infrastructure, as well as the overall level of prices. (E. Quinet 2013, 173) recommends to adjust the price of statistical life with the GDP per capita evolution which should evolve at a 1.2% rate ("Cadrage Du Scénario de Référence" 2019). It also recommends to adjust the LCA values by the GDP/capita evolution rate but as these values retained in (E. Quinet 2013) are a composition of externalities in CO_2 with global impact and local

pollutant but the LCA in this work is based on CO_2eq emissions, we will make our LCA values evolves with the CO_2 values.

The evolution of CO_2 price is defined in (A. Quinet 2019, 124) at 250euros/t in 2030 and 500euros/t in 2040 giving an average annual growth rate (AGR) of +7.18%. The CO_2 emissions/km for EV by ("Cadrage Du Scénario de Référence" 2019) is defined as 68kwh/100km in 2030 and 126 kwh/100km in 2050 giving an AGR of -1.43%. All the aforementioned parameters value can be found in Table 29.

	Discount rate	Inflation	GDP/capita	CO_2 emissions/km	CO_2 value
AGR	+3%	+1%	+1,20%	-1,43%	+7,18%
Impacts	NPV	NPV	Air pollution	CO2 emissions	CO2 emissions
			Road safety		LCA

Table 29. Contextual parameters

Source: prepared by the author.

The second base of comparison is the NPV/Investment which evaluates the social profitability of the investment.

At the agent level, the comparison is performed through the Agents Surpluses, which indicate the transactions between all agents in terms of gains and losses due to the service production

$$aS = \sum_{t=0}^{T} \delta^t (aB_t - aC_t) \quad (8)$$

aS: Agent Surplus

aB_t: Agent level aggregated benefits from period t

aC_t: Agent level aggregated costs from period t

Finally, "Consumers" is the most heterogenous category of our selection of economic agents. The agent-based model MATSim provides an analysis based on the agents score. Three main indicators are used to give indications on the surplus allocation of each agent.

- Winners versus losers: Repartition of agents with a better situation (winners), a worst situation (losers) or the exact same situation (indifferent) than in the baseline scenario, expressed as a percentage of the agents' population.
- The 10% measure: estimates how much of the consumer surplus due to the project implementation is being captured by the 10% of the agents winning the most, expressed as a percentage of the aggregated positive consumer surplus.
- A Gini Index based on the distribution of gain or loss for each agent.

C. Case study

The appraisal methodology is applied to Berlin, Germany. The choice of Berlin as an urban case study follows two criteria. First, most simulations have taken place in urban environments (Carreyre et al. 2022), where the mobility market is more important and models are more easily available. As it is a territory where the impacts could be the highest for the consumer but also for the externalities an economic evaluation is in order. Secondly, the MATSim Berlin model is available to the public in open-access (Ziemke, Kaddoura, and Nagel 2019), which allows to easily replicate the tested scenarios.

1) Territory

The German capital is the country most populated city with more than 3,5 million inhabitants living in less than 900km^2 (2015 data from Federal Statistical Office of Germany). The main modes of transportation available to travelers are private cars, public transit, and active modes (biking, walking). The public transit is composed of rail, metro, tram, bus and ferry services.

2) MATSim Berlin

Ziemke et al. opened access to a new MATSim Berlin model (Ziemke, Kaddoura, and Nagel 2019) in 2016. The synthetic population is based on the 2011 Zensus, excluding all children. CEMDAP, an activity model, has been used to assigned activity chains to every agents on a daily basis. The calibration is based on the CaDyTS model, which compares agents plans with real-world data (traffic counts) and adjusts plans accordingly. Utility functions, mode speeds and scoring parameters used for this work are from

the 5.5.x version. The model parameters will be discussed in the following scenario section.

3) Scenarios

The implementation of AVs services in Berlin requires to define AV services, and define scenario configuration for each service. As the evaluation step comes after the simulation step, the evaluation scenarios set will be a subset of the simulation scenarios set.

The comprehensive literature review (Carreyre et al. 2022) identifies ten operating schemes from the literature. Private AV (a privately-owned autonomous car), the AV (autonomous taxis offering D2D non-shared trips) and the SAV (autonomous taxis offering D2D non-shared trips) are the three services which were the most extensively investigated in previous works. Moreover, the worldwide benchmark performed by (Mira Bonnardel, Antonialli, and Attias 2020, 29) points out that AVs are mostly considered as Mobility-as-a-Service. For example, Waymo, which is known to be the most advanced company working on the AV development ("Here's Why Waymo Is Leading the Self-Driving Car Race," n.d.), has launch a robo-taxi service in Phoenix (Evans and Walker 2022). This work will focus on on-demand services and thus the Private AV will not be retained for this work. The meta-analysis performed in (Carreyre et al. 2022) showed that SAV would have higher performances than AV based on the total travel time, the distance traveled per vehicle and the fleet size. For these reasons only shared autonomous vehicles would be tested in this article. A service feature which draws attention from the academic community in the last few years (Marczuk et al. 2015; Heilig et al. 2017; Javanshour, Dia, and Duncan 2019; Gurumurthy and Kockelman 2022), is the Stop-Based (SB) routing where boarding/alighting is only permitted at stations. When the vehicle is shared, the SB routing could allow to limit detours and thus reducing shared rides in-vehicle traveled time for passengers and VKT at the cost of a more important egress and access time.

As mentioned in the DRT section, all parameters used will be the default parameters of the DRT module. Note that these parameters have an influence on the results. For example, each time a traveler request a DRT ride, the DRT module has to send a vehicle with a maximum waiting time of 1200 seconds or 10 minutes for the customer, otherwise, the request is rejected. One could choose to decrease this maximum waiting time which may lead to a decrease of waiting time for the customer but an increase of the fleet size (Carreyre et al. 2022), and thus the operators costs. In the

other hand, a shorter expected waiting time for the customer could also increase the demand for DRT service and their potential revenues. This is a political and a service design decision (Sebastian Hörl, Becker, and Axhausen 2021).

The simulation scenarios set will be composed of height scenarios where AV would be implemented and a basecase scenario without any AV and with default Berlin parameters (Table 30). The following scenarios will explore AV impacts if SAV taxis were to be introduced in Berlin with supply variations, such as lower fares or/and increased capacity (AV: 4 seats; Shuttle: 8 seats) or/and modal competition reduction[7]. In a second step, the CBA scenarios set will be composed of four AV scenarios and the basecase (can be found in the Table 30, "CBA scenario" column). AV scenarios can be found in-between "forecasts" and "what-if" scenario" (Börjeson et al. 2006). The two leading scenarios introduce free SAV taxis operating in D2D and SB (in two distinct scenario). We used public transit stops as AV stops. The two following scenarios operate similarly with distinct D2D and SB shuttles (height-seats vehicles) but go further and offer an exploratory scenario of private cars ban. The reduction of space allocated to private cars in the European metropolis (Paris, London or Amsterdam) prompts to investigate impacts of such a measure paired with a SAV introduction. Except for the AV scoring function, which has been fixed at the public transit level, the Berlin model parameters and the DRT module parameters were used, except when announced change has been performed. By example, in the Free D2D SAV scenario, no fares are applied to the use of a SAV.

[7] The uncertainty around AV abilities led to introduce sensibility analysis on fares and utility functions but these scenario will not be discussed for concision reasons.

Scenario	Description	Justification	CBA scenario
BC	Basecase scenario, no on-demand service	Basecase	*
D2D AV	Door-to-door SAV	Consequences of a simple AVs introduction	
SB AV	Stop-Based SAV	Consequences of a simple AVs introduction	
F-D2D AV	Free Door-to-door SAV	Maximum demand for an AVs service	*
F-SB AV	Free Stop-Based SAV	Maximum demand for an AVs service	*
F-D2D Shuttles	Free D2D Aut. Shuttles	Does shuttles do better than cars?	
F-SB Shuttles	Free SB Aut. Shuttles	Does shuttles do better than cars?	
D2D & Car ban	Free D2D Aut. Shuttles / Private cars ban	The AVs in a car-free environment	*
SB & Car ban	Free SB Aut. Shuttles / Private cars ban	The AVs in a car-free environment	*

Table 30. Simulations and evaluation sets

Source: prepared by the author.

D. Results

1) Simulations Results and Discussion

a) General Results

The most significant result is that, except for car ban scenarios, AV will attract passengers from all other modes (Figure 37) and contribute to road congestion. Car drivers, even if they travel less distance overall (Figure 38), spend more time travelling due to the increase in congestion (Figure 37). The additional AV's VKT, originating both from modal shift and empty kilometers traveled, are responsible for the decrease of private cars' performances. It has a direct, and counter-intuitive, effect on agents scores (Appendix Figure 47). Whereas a new mode of transportation has been added to travelers' modal alternatives, the aggregated scores decrease. It shows that AV travelers gains are offset by the travel time losses of private car users. The overall increase of road VKT and travel times are consistent with the findings from the literature (Carreyre et al. 2022).

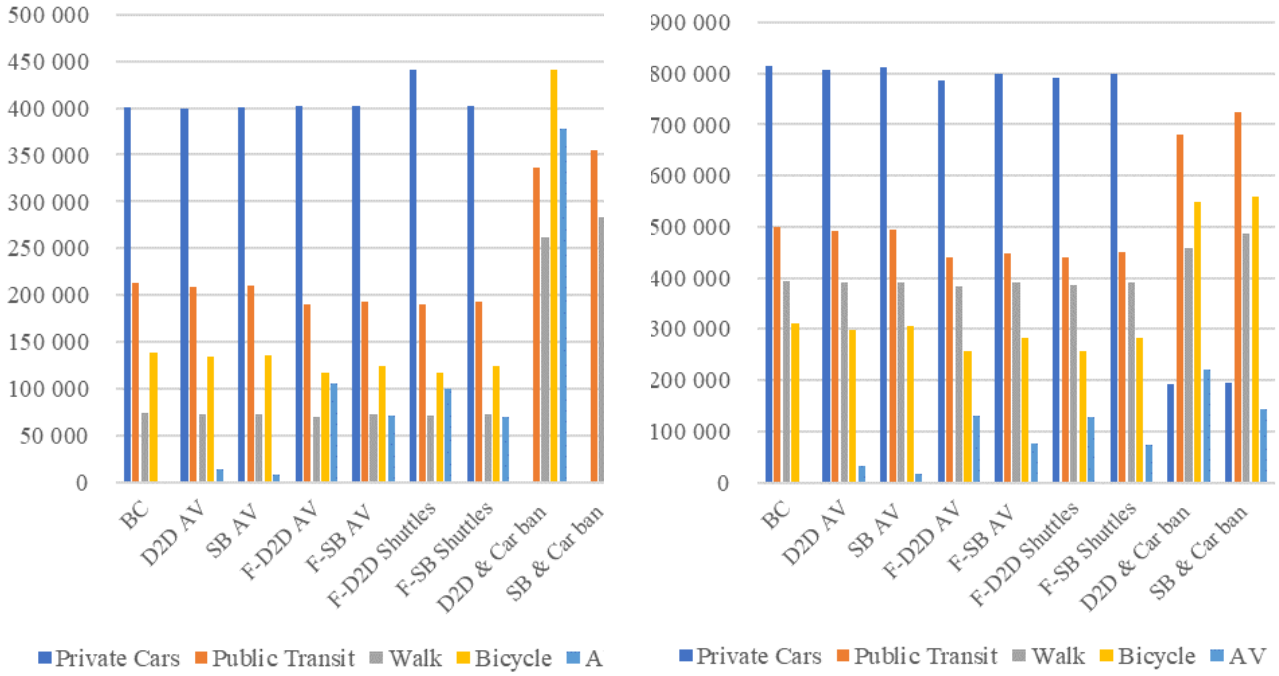

Figure 37. Trips per day (left) and Travel Time (right)
Source: prepared by the author.

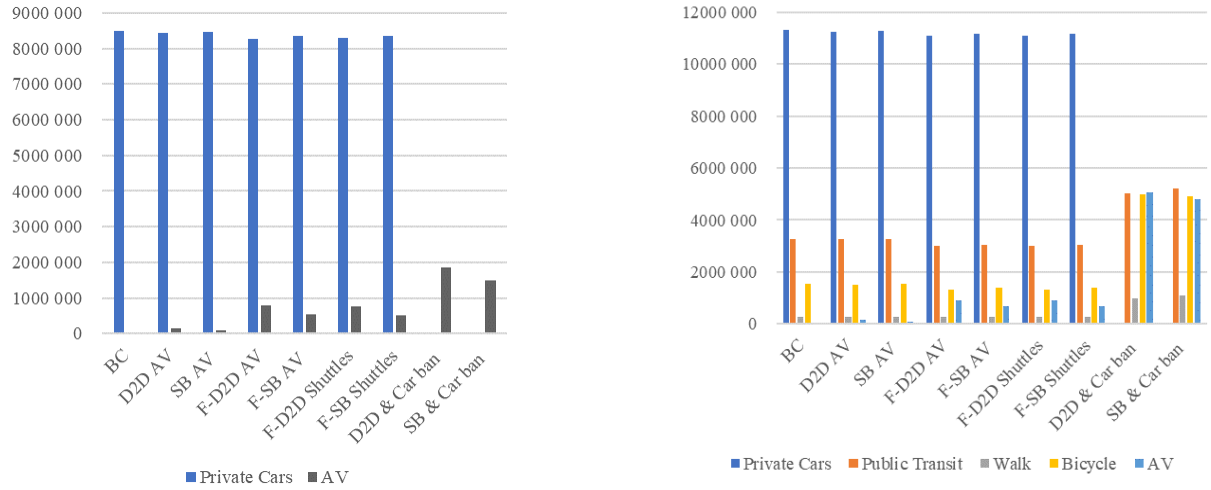

Figure 38. Vehicle Kilometer Traveled (left), Distance Traveled (in pass.km, right)
Source: prepared by the author.

For the car ban scenarios, the most important result is the increase of aggregated Total Time Traveled (TTT = waiting time+access/egress time+in-vehicle time) by roughly 50% for both scenarios. This result can be explained by the short-term temporary horizon of the model which does

not allow agents to adapt their home location strategy and fixed demand for trips. However, AVs do not absorb the full private cars demand even though the full available fleet was not used. AVs are not a perfect substitute for private car, even when fares are no longer asked. This result is quite surprising as AVs could be considered as the most efficient alternative to private cars. The increase of bike and walk travel times might express the fact that agent prefer to process a longer walk or ride but not to spent too much time waiting. Rail and AV have a more important average travel distance per trip than bike, as a result of their greater speed. In real life situation, such an increase would be unlikely in the long-term, if we consider Marchetti's constant observations. Agents would rather change their residence, job and leisure locations.

b) AVs Focus

AVs performances are sensitive to the routing proposed, the fare level and the modal competition. The comparison of D2D and SB routing shows that 1) D2D is more attractive than SB (Figure 39), probably due to a better level of service (Figure 40) 2) D2D is more resource consuming (Figure 41) due to a more important demand. The D2D consistently presents a lower average vehicle occupancy rate (AVO) which can be caused by the routing which generates higher detours than SB, thereby pushing away agents from AV ridesharing. Furthermore, SB routing consistently presents a higher travel speed than D2D services, even though considering their higher average vehicle occupancy, which implies more stops. An additional interpretation, which would be difficult to validate with simulation results, is the fact that SB vehicles could more easily avoid entering low-capacity streets and remain on the main streets. All our results are consistent with the existing literature comparing D2D and SB services (Heilig et al. 2017; Marczuk et al. 2015; Javanshour, Dia, and Duncan 2019; Gurumurthy and Kockelman 2022).

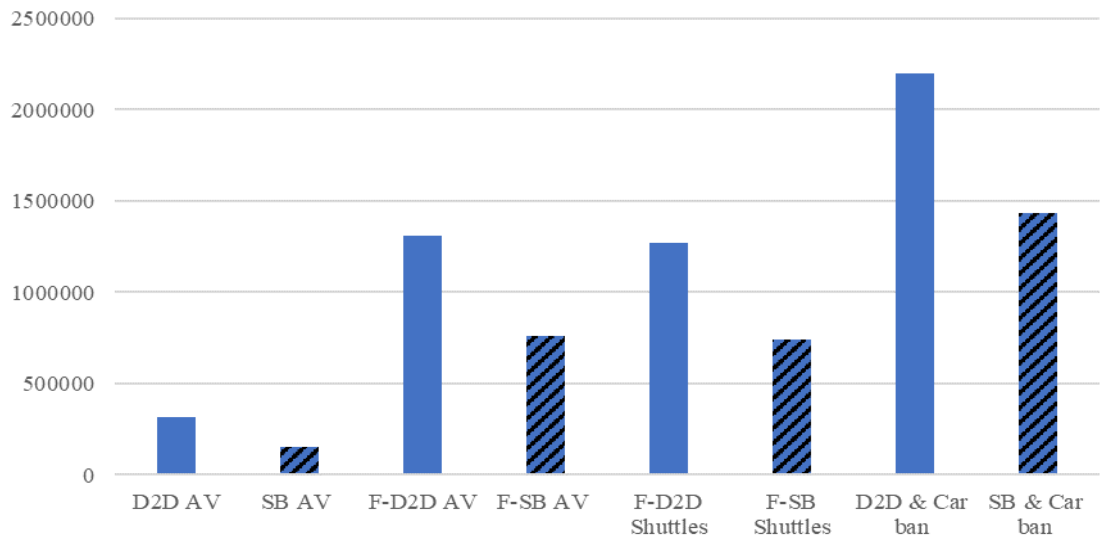

Figure 39. AV Trips per day
Source: prepared by the author.

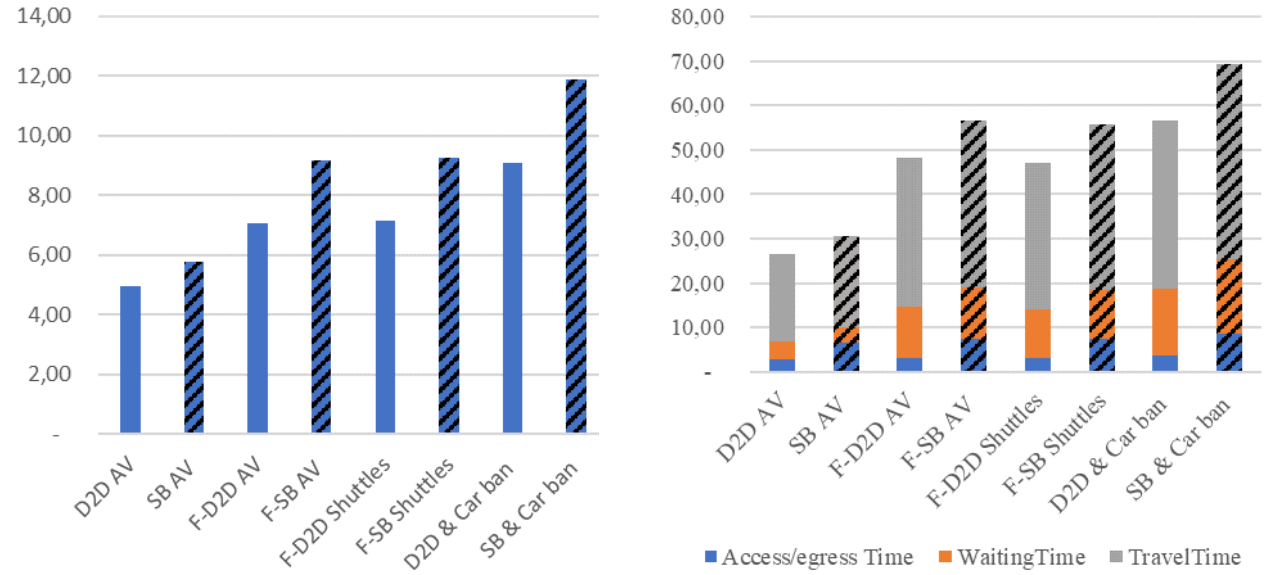

Figure 40. Average Distance Traveled per trip (km, left) and Average Total Traveled Time (min, right)
Source: prepared by the author.

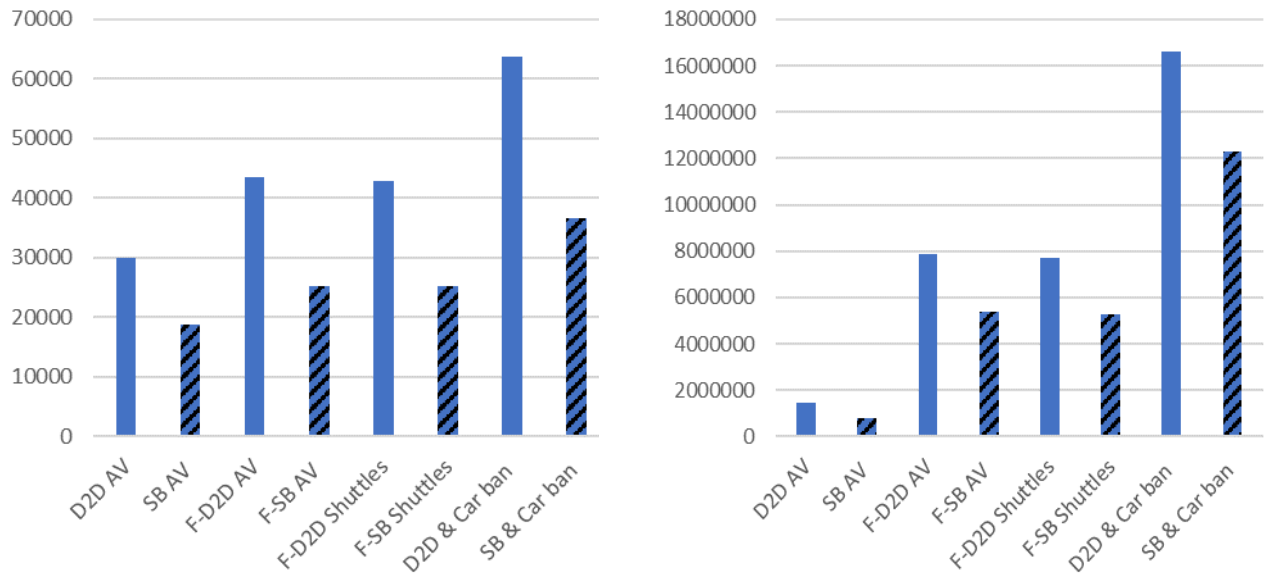

Figure 41. AV Fleet Size (left) and AV Vehicle Kilometers Traveled (right)

Source: prepared by the author.

NB: D2D routing service are the plain columns and the SB services are the stripes columns.

2) Cost Benefit Analysis Results and Discussion

a) Consumer Surplus (CS)

The CS for all four CBA scenarios presents a negative value, with important heterogeneity between scenarios.

The decrease of CS for the introduction of AVs taxis could surprise as when a new mode is added to the consumer choice set, the overall utility should theoretically increase if its offers, for a least one trip a lower cost than the other best alternative. However, as mentioned in the previous section, when AV are introduced, the users come from all modes. The ridesharing effect does not offset the additional demand for road transport, which generates externalities. As private car users are the most important group of users, even if the load on the road network remains light, the loss of time from private car users causes an overall decrease of the consumer surplus (Figure 42). Paradoxically, even if the SB routing has a less efficient level of service than D2D routing, the decrease of consumer surplus is lower, due to a lesser amount of AV trips and congestion.

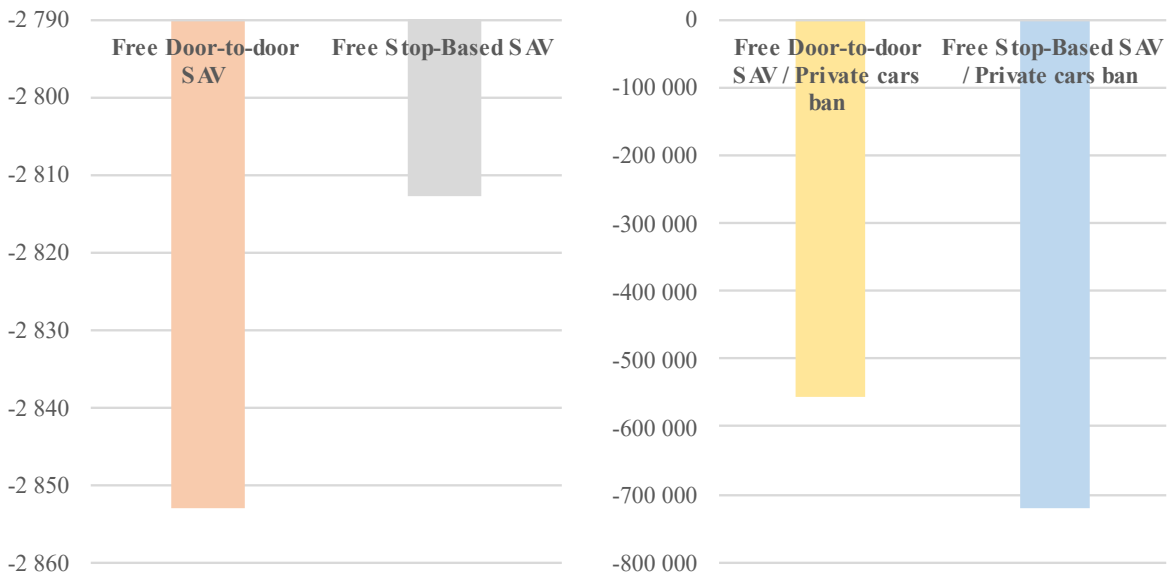

Figure 42. Consumer surplus

Caption: 10 years term, millions € differences with basecase

NB: for scale reasons, the variation of consumer surplus are represented in two figures.

Source: prepared by the author.

The CS loss found for the two car ban scenarios is 200 times larger than for the first two scenarios (Figure 42). The loss in itself is expected, as the car ban withdraws one of the most efficient modal alternatives. The magnitude of the loss can be found in the substantial loss of time due to the use of slow modes (walk and bike, see Figure 37) for an important share of the trips.

In this comparison, the decrease in CS is more substantial for the SB routing than for the D2D. Without any road competition for AVs, their impact on congestion only affects only AV-users and not travelers of other modes. In a congestion-free scenario, the D2D efficiency has a better impact on CS than the SB.

These results go against the literature findings of (Kockelman et al. 2017; Andersson and Ivehammar 2019; Shatanawi and Mészáros 2022) in which an important gain can be found at the vehicle scale. The difference can be found in the parameters used to value the opportunity cost of time. (Andersson and Ivehammar 2019) chose to reduce the VoT from 75% to 93% which largely offsets the slight modal shift effect from trains to AVs. (Kockelman et al. 2017) reduced the VoT by 50% which counterbalance the

increase of VMT (+10%), congestion and travel time. (Shatanawi and Mészáros 2022) chose to reduce the VOT from 25% to 50%, found a reduction of 45% of the traffic volume (in VKT), an average speed increase and an increase of Consumer Surplus. On the other hand, (Xue 2022) found that AVs traffic flow improvement would result in overall positive consumer gain, despite an assumed 2% yearly traffic growth and no VoT reduction for AVs passengers. (Kaddoura, Bischoff, and Nagel 2020) also found an increase in traffic. However, by considering only AVs passengers they found a gain for users, which is consistent with the following equity analysis where specific users see their utility increase despite an overall loss.

The equity KPIs (Figure 43) show that the losers' share for the first two scenarios is similar to the private car modal shares. However, it reveals that the CS loss conceals a surplus gain for 25 to 27% of the agents after the AV introduction. The decrease of the winners' share after the car ban might be due to the model's ridesharing parameters. The AVs' average TTT increases after the car ban, probably associated to the increase of the AVO and of detours for existing AV users. Amongst the winners, the gains are concentrated around the 10% of the agents winning the most in the four scenarios. On the other hand, for all scenarios, the Gini index remains close to 0, indicating a flat repartition of consumer utilities variation.

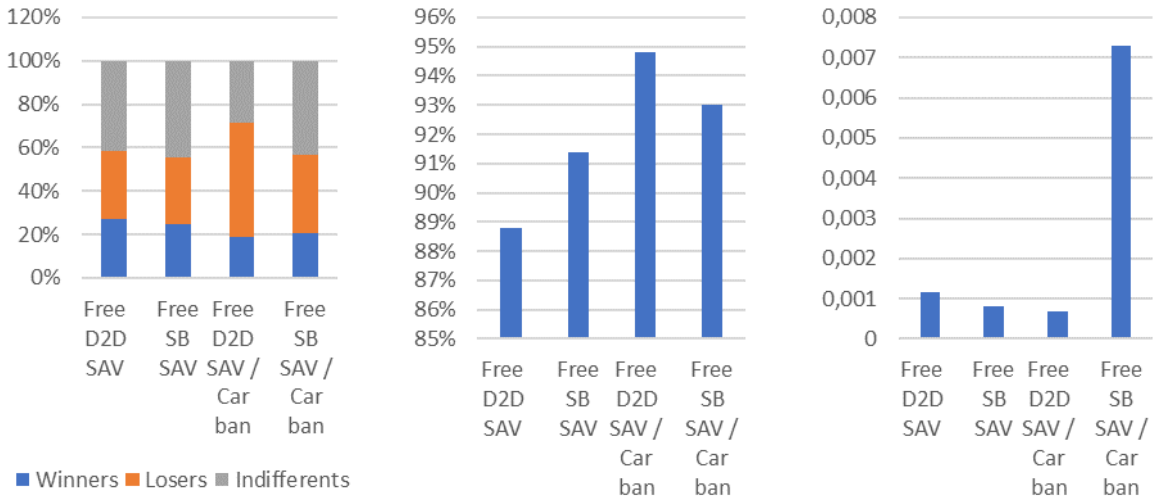

Figure 43. Equity KPIs Winners versus Losers (left), the 10% measure (middle) and Gini index (right)
Source: prepared by the author.

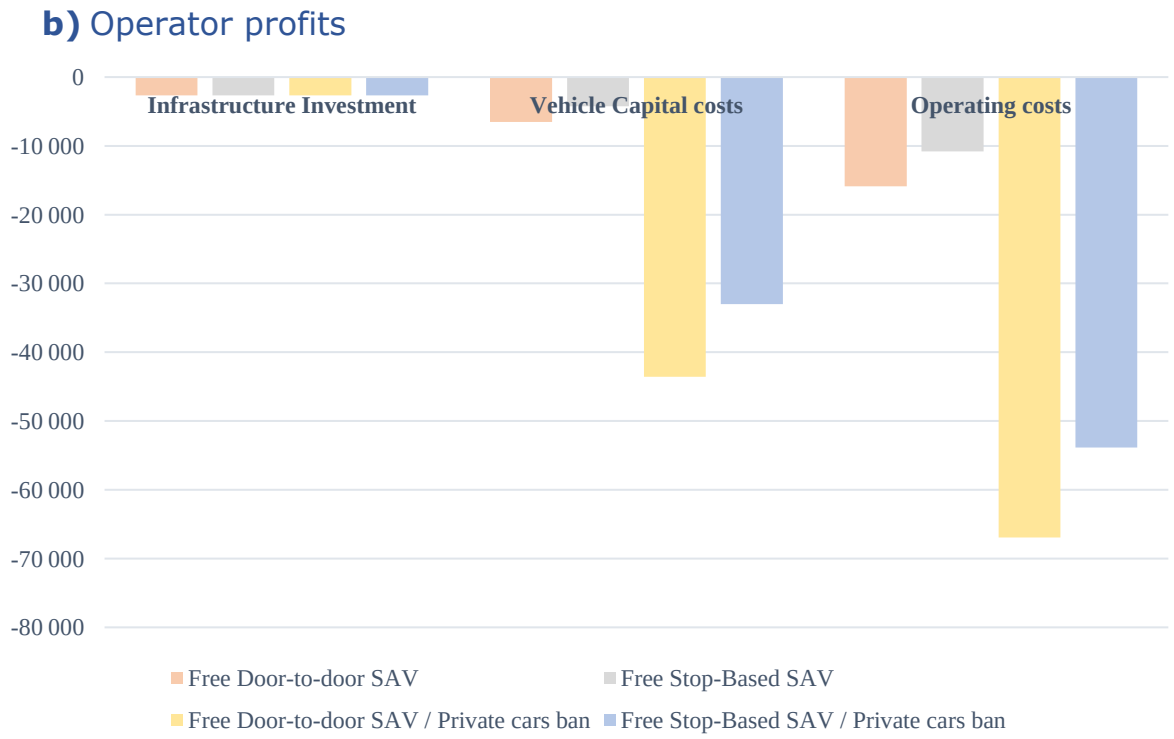

Figure 44. Financial surplus

Caption: 10 years term, millions € differences with basecase

Source: prepared by the author.

The costs of the operator(s) are mainly composed of the capital vehicle costs and the operational costs. The infrastructure's investments remain of a lower magnitude than the two previous items. The rolling stock investment and replacement of vehicles are highly sensible to the distance traveled. Vehicles drive an average of 181, 213, 260, 336 km/day depending on the scenario. Even if SB routing vehicles drive more per day, the smaller fleet size required allows to get smaller replacement costs and operating cost (Figure 44). The infrastructure costs are one of the most uncertain items. In our situation, parameters may substantially vary. The sensitivity analysis considers a 1 to 15 ratio (Appendix. Table 31). This sensitivity analysis is based on an average cost per kilometer, but for more accuracy, future research should focus on a composite cost based on the infrastructure length as well as the number of intersections for the investment and the use of the infrastructure for its maintenance and replacement rate. The comparison with the existing literature is difficult as the study of infrastructure costs remain relatively unexplored. However, these first estimations show that it may represent an non-negligeable share of the financial costs of AV introduction.

c) Externalities

The introduction of AVs lead to an increase in overall VKT and vehicles used. This increase in resources consumed lead to an overall increase of the externalities impact (Figure 45). The AV efficiency (less emissions and less accident per kilometers) do not compensate. (Narayanan, Chaniotakis, and Antoniou 2020) had identified this rebound effect and recommended to counter-balance by introducing a "congestion *pricing to curb induced demand*". The increase of externalities negative impact goes against the findings of the (Le Hong and Zimmerman 2021) in their Motor city scenario which sees a slight reduction of 6% of GHG emissions but most of the trips that AVs would replace would have been made in Gasoline or diesel based vehicle (83% of the fleet).

On the other hand, the implementation of car ban scenarios has been shown to be effective in reducing road traffic, and encouraging travelers to opt for less impactful modes of transportation such as AVs, public transit (which remains unchanged), and active modes. This approach has a positive impact on all externalities, particularly when combined with the deployment of AVs. Three key factors contribute to this effect. Firstly, the efficiency of AVs helps to reduce the social impact of each vehicle kilometers traveled (VKT) when compared to conventional cars. Secondly, compared to conventional cars, the AV business model enables ride-sharing, which further reduces the number of vehicles on the road. Finally, the car ban policy encourages people to choose more sustainable modes of transportation than AVs, resulting in a further reduction in the overall social and environmental impact.

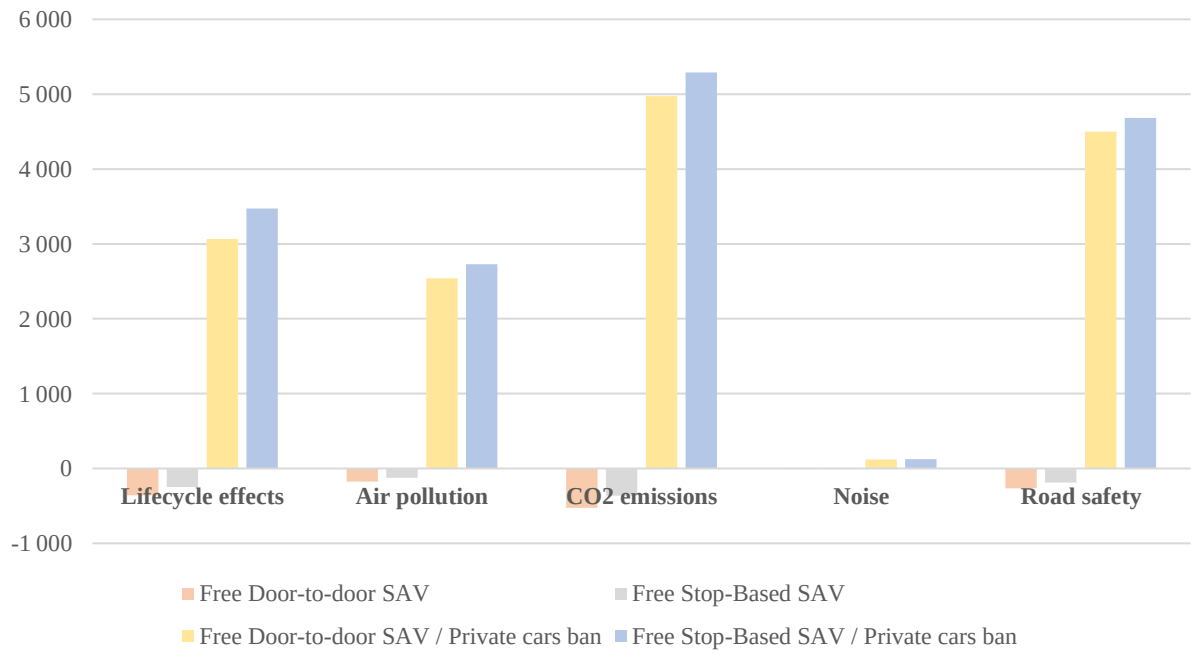

Figure 45. Externalities impact

Caption: 10 years term, millions € differences with basecase

Source: prepared by the author.

These results are consistent with the literature (Kockelman et al. 2017; Andersson and Ivehammar 2019; Xue 2022) in which externalities can also be found to decrease with the AVs introduction. (Kaddoura, Bischoff, and Nagel 2020), which used a more advanced impact diffusion model on noise and air pollution, worked on the external cost pricing of AVs in Berlin and found similar results to ours, even though the vehicle propulsion scenarios are different. (Xue 2022) found that externalities would decrease, and that half of the externalities' lesser impacts could be related to safety benefits, which are slightly more important than in our car ban scenarios, and differs from our AVs introduction scenarios.

d) Net Present Value

The introduction of AVs showed that, except for some heterogeneity amongst the consumers, every agent would lose compared to the base case scenario (Figure 46). These results are consistent with (Berrada and Poulhès 2021). The gain for few users does not trade off the loss on each agent surplus. However, in the case of the introduction of a new mode of transportation in an urban area, the SB routing has less negative impacts than the D2D, both at the agent level and at the overall level. The SB routing

also has a better (but still negative) investment social efficiency (-3,36 euros per euro invested) compared to a D2D service (-3,49 euros per euro invested). In case of negative NPV/I, it might be misleading to follow similar rules as we commonly do with positive NPV/I. Here, the two scenarios presents a very similar NPV/I values (-3,36 and -3,49 euros), which may imply that both are equally undesirable but the D2D scenario requires more investments than the SB scenario (27 691 million euros against 23 144 million euros) for a greater negative NPV (-6 905 million euros against -9 178 million euros). The cost of the car ban and the AV introduction presents more important costs but more heterogeneous than the simple AV introduction. Even if the simulation results need to be taken with cautious, especially on the consumer surplus side, the car ban would result in an important loss of accessibility. On the other hand, externalities impacts might decrease due to the use of less emitting modes (AVs, but also bike and walk).

If the D2D routing helps to reduce the consumer surplus loss, it also induces more important costs and externalities emissions. The tradeoff of the investment social efficiency leans towards the D2D side (-15,58 euros per euro invested) compared to the SB routing (-22,41 euros per euro invested).

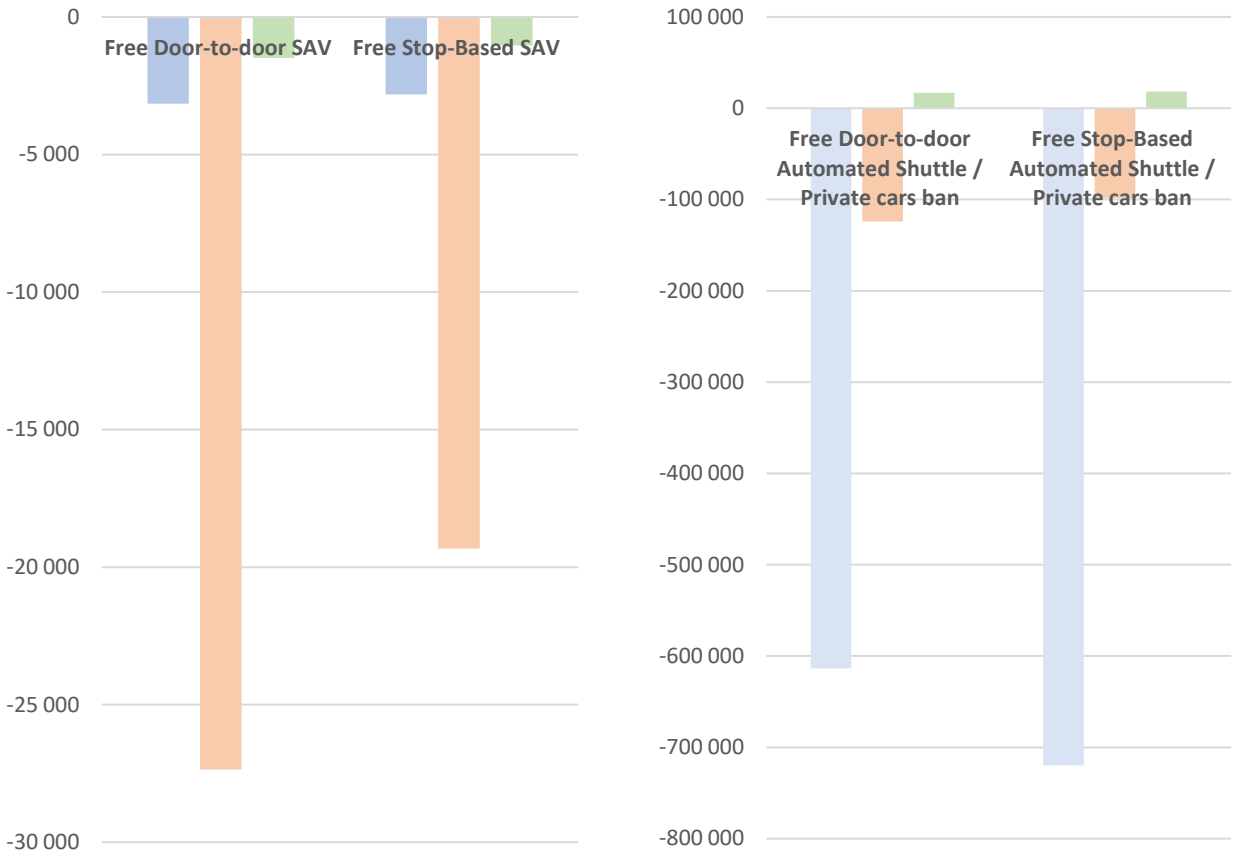

Figure 46. Net Present Value

Caption: 10 years term, millions € differences with basecase

Source: prepared by the author.

To conclude these results section, the consumer surplus and financial results are mostly inconsistent with the literature which may be summarized as followed. The consumer surplus losses is due to the reduced values of time considered by (Kockelman et al. 2017; Andersson and Ivehammar 2019; Shatanawi and Mészáros 2022). The difference of items considered in others financial evaluation of AVs which did not include infrastructure costs or supervision costs (Kaddoura, Bischoff, and Nagel 2020). In the other hand, the externalities results seems to be consistent with the literature. As mentioned in (Annema 2020), which explores the literature on environmental AVs impacts, "*the net energy and CO2 balance for AVs seems at its best neutral but is probably negative*".

E. Conclusions

The introduction of Autonomous Vehicles (AV) in an urban territory generates additional VKT and congestion, leading to an overall decrease of the consumer surplus. The new service benefits to some users, but the congestion effect offsets these utility gains. If this introduction is coupled with a car ban, the consumer surplus decrease is much more important (as an efficient mode is withdrawn from the pool of available modes). The financial costs represent an important part of the social costs and the cost burden will certainly have an important impact on the agents surplus, whether it be private operators or the public authority. The impact on externalities is uncertain, as AVs abilities to decrease marginal externalities might not offset the additional demand for mobility. The results show that Door-to-door (D2D) services are more attractive but more resources intensive than Stop-Based (SB) services. SB services should be favored (based on the NPV) in densely populated areas with the purpose to limit externalities but D2D would become increasingly interesting as the mobility demand decreases or if the modal competition from car decreased as such as in the two car ban scenarios. However, the general negative results from the introduction of on-demand service should push decision-maker towards solutions such as pricing regulation or the research of other mode of transportation. Modes such as the metro have already taken advantage of the development of driver-less train technology.

This article offers a comprehensive economic appraisal methodology of on-demand AVs services paired with an agent-based simulation. This methodology has the particularity to include equity analysis, AV infrastructure and supervision costs and consider externalities impacts. The Berlin case study allows to evaluate the AV introduction in an urban territory, which was an important focus of the simulation community but still lacked economic assessment. Finally, this paper contributes to the comparison between the Door-to-Door and the Stop-Based routing systems.

For the simulations limits, a new dispatching algorithm might help to enhance AVs performances. (S. Hörl et al. 2019) shown that this type of study are strongly dependent on the dispatching strategy and the parameters used. Moreover, in this work, the demand for on-demand AVs is constant across scenarios and does not depend on the performance of each variation of the system. This is due to the lack of feedback between the observed performance of AV trips and the user choices. Additionally, investigating the economic impact of AVs used in intermodality with public transport will be an important step for the literature. These challenges will

be addressed in future work. For the evaluation limits, we opened some topic such as the infrastructure and supervision costs or the vehicle lifecycle, but our analysis still lacks understanding on the environmental impact of the infrastructure through its lifecycle or the supervision environmental cost. Finally, the evaluation as electric vehicles whereas no charging behavior has been incorporated into the simulation should also be considered. Furthermore, economic agents such as workers or taxpayers may be included in the analysis to broaden the scope of the assessment.

As observed in this chapter, population density had a major impact in shaping the social performance of AV-based services. Moving forward with the economic evaluation of AVs, the logical progression would involve introducing AVs in less densely populated areas, such as suburban territories. In this context, the operational scheme would shift towards a feeder service model, aligning with train stations to aggregate and streamline passenger flows with shared origins or destinations. This strategic shift acknowledges the characteristics and transportation needs of suburban areas, aiming to optimize the use of AVs to enhance mobility and accessibility in these specific settings.

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G. Appendix

Total 10 years cost		Maintenance and replacement cost per year				
		10%	20%	30%	40%	50%
Infrastructure Equipment cost	50 000	100 000 €	150 000 €	200 000 €	250 000 €	300 000 €
	100 000	200 000 €	300 000 €	400 000 €	500 000 €	600 000 €
	150 000	300 000 €	450 000 €	600 000 €	750 000 €	900 000 €
	200 000	400 000 €	600 000 €	800 000 €	1 000 000 €	1 200 000 €
	250 000	500 000 €	750 000 €	1 000 000 €	1 250 000 €	1 500 000 €

Table 31. Infrastructure Cost Sensibility Analysis

Source: prepared by the author.

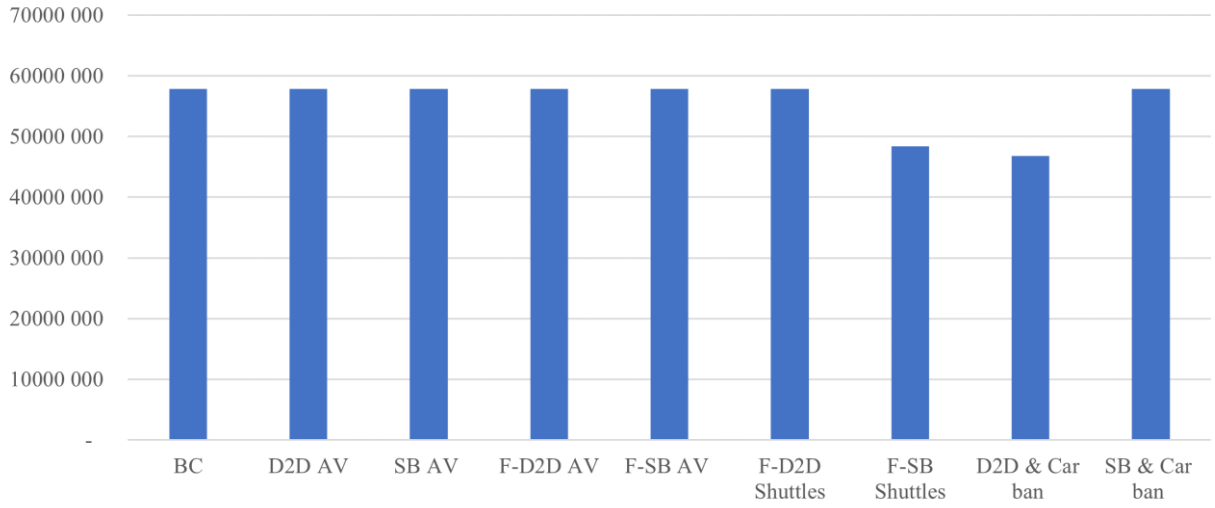

Figure 47. Agents aggregated scores
Source: prepared by the author.

III. On-demand Autonomous Vehicles in periurban territory: a Cost Benefit Analysis

Abstract

The appraisal methodology is applied to the introduction of AV services in Paris-Saclay, an intercommunity, south of Paris, simulated through MATSim, an agent-based model. AVs would be implemented as a feeder service, working as a last-mile, last-mile service to public transit. The introduction of AV in a periurban environment would generate more pressure on the road network but would improve travelers utilities. Some private cars' users suffers from longer travel times, resulting in a loss in terms of consumer surplus that could offset the new AV users' benefits, depending on the consumer surplus estimation method. In this configuration, a Stop-Based routing service have a greater ability to benefit from economies of scale than a Door-to-Door routing.

Finally, in an periurban environment where on-demand AVs would be added to reduce the access and egress cost of public transit, the social impact would be nuanced for travelers, but externality would increase. This would benefit some travelers but would also involve additional congestion. In that case, a Stop-Based routing seems less impacting than a Door-to-Door one and it could allow to equip a downsized network.

Keywords: Autonomous vehicles, mobility simulation, economic evaluation, transport, cost benefit analysis

A. Introduction

As mentioned in the state-of-the-art chapter, the impact of autonomous vehicles may have heterogenous impacts depending on the type of territories in which they are introduced. In urban areas, the demand is concentrated and the space is scarce. As seen in the Berlin case study, the introduction of on-demand services will have negative impact due to congestion effect. This phenomena should diminish provided that the demand decreases and the space become more available. Such exclusive territory types as defined by the INSEE (the French National Institute of Statistics) may lack finetuning but they provide a good overview of demand density. Periurban territories are structured by several matters such as the predominance of the private cars and public transport attractiveness. The AV challenge in such a territory is not to add traffic on the road but rather to massify flows and offers a complementary service to the public transit. In this chapter, a first and last mile use case of AVs is presented. If the periurban territories have been covered in the literature (Berrada 2019; Berrada and Poulhès 2021; Bösch, Ciari, and Axhausen 2018; Merlin 2017), the contribution of this chapter is the presentation of a feeder service evaluated through the prism of the Cost Benefit Analysis. The feeder service remains relatively ignored in the simulation literature, in (Carreyre et al. 2022) on almost a hundred articles reviewed only five (Berrada 2019; Sieber et al. 2020; Gurumurthy, Kockelman, and Zuniga-Garcia 2020; Huang et al. 2020; Lee et al. 2019) addressed a feeder service use case. Amongst the five (Berrada 2019) is the only one to provide an economic analysis. This work may be pursued further using a Cost Benefit Analysis for the economic assessment. This chapter basecase is based on (Chouaki, Hörl, and Puchinger 2023) which introduces AV taxis in the periurban area of the "*Communauté d'agglomération Paris Saclay*" (inter-township of Saclay, a Paris suburbs).

B. Method

The methodology relies on a two-step simulation-to-evaluation pipeline. Simulation is carried out using the MATSim agent-based mobility model, which allows to derive traffic and operational forecasts for the introduction of AV services. These forecasts are then used to carry out the economic evaluation based on the Cost Benefit Analysis (CBA) methodology, which we adapt to the case of AV services.

1) Model

a) MATSim

MATSim is an agent-based mobility simulation framework (Horni et al. 2016). The use of an agent-based model allows to have a good representation of on-demand services (Carreyre et al. 2022). It allows to simulate various mobility systems in large geographical areas. MATSim is activity-based, it relies on a fine-grained description of a population of agents that comprises a set of activities with location and time attributes that the agents need to perform. They consequently perform trips between the different activities at the relevant times. The road network as well as the mobility systems being capacitated, congestion effects are reproduced and a competition for resources takes place.

b) Eqasim

Eqasim is a discrete mode-choice extension of MATSim which replaces the discrete mode choice model instead of the MATSim co-evolutionary algorithm. Based on utility functions and previous iterations travel outputs (travel time, waiting time…), agents may change modes until an equilibrium is found. Compared to MATSim, this mode choice system has the benefit to be based on multinomial logit model, which has been developed in 1974 (McFadden 1974). The academic community has worked on the topic ever since (Ben-Akiva et al. 1985; Train 2002; "Discrete Choice Models" n.d.). (Hörl, Balac, and Axhausen 2018; Hörl 2021) have conceived bridges between the discrete choice models and modal choice model and implemented them in MATSim, an agent-based model. This discrete mode choice also allows to run simulations faster as impossible alternatives are ruled out before they are tried in the simulation (Hörl, Balac, and Axhausen 2019).

The mode choice is based on utility functions and constraints. Based on the utility function, the mode choice can either follow a multinomial model (Hörl, Balac, and Axhausen 2019) or a MaximumUtility model.

For the multinomial model, if the tour (i.e. the sum of daily trips) respects the constraints, the probability to use the modal alternative i for each trips is based on the following formula:

$$P(i) = \frac{\exp(\hat{u}_i)}{\sum_{i'} \exp(\hat{u}_{i'})} \quad (1)$$

$P(i)$: probability to chose to alternative i

$\hat{u}_i$: estimated utility of alternative i

$\sum_{i'} (\hat{u}_{i'})$: estimated utilities of all i alternatives

As for the MaximumUtility mode choice, the chosen tour is the one presenting the best utility. A random parameter trips based on the SHA-512 algorithm is attributed to each alternative for every trips. As the seed remains the same, the parameter value remains identical between iterations but also between scenarios. The distribution of the random parameters follows a Gumble distribution. It is important to note that the scenarios were initially simulated using the multinomial mode choice model, which resulted in a counterintuitive loss in overall utility when introducing a new mode of transportation. We first looked into a congestion effect but the agent did not seem to see their travel time increase. Even more, the average speed for car users had increased but we cannot say confidently that it was due to a decrease in congestion or a structural diminution of the car trips driving on low-speed limit links. Further research is needed to explore the implications of AVs on travel behavior and traffic congestion, and to improve the routing algorithms to limit congestion effects around train stations.

The tour must respect the following constraints:

- Vehicle continuity: vehicles are located and must be used at their final known location
- Person-based attributes: car ownership or driving license

The utility functions used originate from (Hörl, Balac, and Axhausen 2019) and can be found in Appendix Table 39.

c) DRT

In this chapter, DRT vehicle will be used only as a feeder service. No trips could be done only in DRT but with only within a public transit trips with the access and/or the egress travel operated through with a DRT. The feeder service system will be based as a semi-stop-based routing with either starting or destination point based on a rail station service (rail, subway and tram lines).

MATSim allows to simulate and study Mobility-on-Demand systems through the DRT Module (Maciejewski and Nagel 2013). The latter provides the implementation of an on-demand fleet from which users can request trips in an online manner. A vehicle assignment strategy is then used to select a vehicle to perform the submitted request. The strategy implemented by default tries to find the best way to insert he request in a vehicle's plan. The insertions are evaluated given the expected arrival time for the passenger and constrained by the vehicles' capacities as well as service level requirements: maximum waiting and travel time as well as a detour factor in case of a shared trip (difference between unshared and shared distances) which allows to consider the cost of ridesharing. The DRT module also defines a pricing scheme for the service. This scheme can be parametrized to consider a cost per kilometer, per time, and a minimum fare per trip. Note that the cost per kilometer is applied to the estimated unshared distance and the cost per time to the estimated unshared travel time, which means that the price doesn't increase if the trip is shared in comparison to the trip being unshared. However it also means that the price of a shared trip is not less than an unshared trip. All the parameters used in the following will follow the default parameters (for fare, speed, vehicle size or dispatching strategies) from the DRT module, available in open-source.

2) Cost Benefit Analysis

The Cost Benefit Analysis (CBA) is a systematic and quantitative method to evaluate transport projects. It attempts to quantify "*the change in the well-being of the individuals living in the society, and this involves calculating, in monetary terms, the magnitude of the potential […] gains compared with the opportunity costs of the resources."*. The theorical background is well covered (de Rus et al. 2020; Boadway 1974; Boardman et al. 2017; OECD 2018). Several criticism and works had risen the last several decades (Asplund and Eliasson 2016; Börjesson and Eliasson 2019; Beria, Maltese, and Mariotti 2012) which led to incorporate topics such as equity in the process. The replicability of the method and its capability to understand the impact of public funds attribution convinced governments to seize this appraisal tool since its introduction in the USA (Flood Control Act, 1936) (Congress 2018). Governments have since published methodological guides (E. Quinet 2013; "Document: Cost Benefit Analysis Guidelines" n.d.; "Cost Benefit Analysis Guidance" 2014) and provided reference values which are regularly updated.

In this paper, we use the French CBA guidelines (E. Quinet 2013), which we adapt by providing a new way to compute the consumer surplus and by providing new reference values for AVs. The structure is divided into three categories (Consumer Surplus, Operator profits and Externalities Impacts), each based on an economic agent and their sub-components (Figure 48).

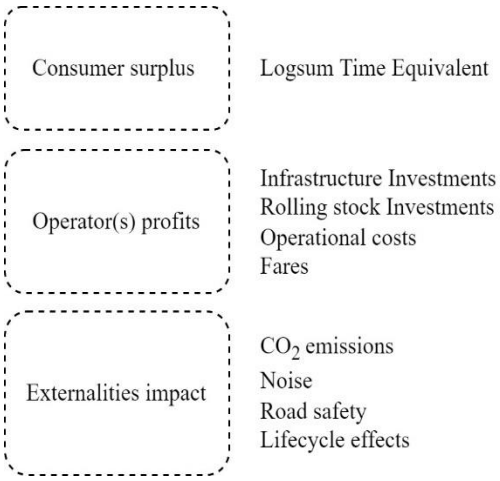

Figure 48. Cost Benefit Analysis sub-components
Source: prepared by the author.

a) Consumer surplus

The Consumer surplus is defined as the monetized value of the utility gains or losses of the mobility consumers. It is based on the logsum methodology, a welfare measure defined as "*the log of the denominator of a logit choice probability, divided by the marginal utility of income, plus arbitrary constants.*" (de Jong et al. 2007). The utility is based on the MATSim plans score according to the methodology developed by (Kickhöfer, Nagel, and Nagel 2016; Kickhöfer 2014). For each agent, the best score is selected and converted into an equivalent monetary term using the marginal utility of income. As all agents do not necessarily have the same value of time and marginal utility of income, a time equivalent approach is used. Based on (Kickhöfer 2014, 54, 55) the overall Consumer Surplus change, with individuals j = 1..J, is:

$$\Delta CS = \sum_{j=1}^{J} \Delta m_j \quad (1)$$

ΔCS is the overall Consumer Surplus change

Δm_j is the monetary compensation required to balance the policy implementation, i.e. the expression of the difference in consumer welfare between both states.

The Logsum expression in Time Equivalent (LTE) can be expressed as follows:

$$\Delta m_j = \Delta t_j \times VTTS_j \quad (2)$$

Δt_j is the number of hours required to counterbalance the policy implementation in agents utility

$VTTS_j$ is the Value of Travel Time Savings (EURO/h)

$$\Delta t_j = \left(\frac{\Delta V_j}{\Delta t}\right)^{-1} \Delta V_j \quad (3)$$

$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1}$ is the inverse marginal utility of time

ΔV_j is the variation of utility between two states, i.e., before and after a policy implementation.

Eqasim has a specific marginal utility of travel time per mode, as such Δt_j is not obtainable. To implement an equity VTTS, the utility from the total travel times (U_{TT}), access/egress/transfer and waiting time included, is obtained from the travel times. It is similar with the 2.15 equation from (Kickhöfer 2014, 55), except that Kickhöfer compensated the difference of consumer surplus between two scenarios with an amount of hours based on the marginal utility of time to reintroduce an equity value of travel time savings. In this work, the equity VTTS is introduced before to compare the utility based on the total travel time, following the same philosophy that *"one could argue that one hour of life time of any individual is equally important for society, and, thus, use some average VTTS for monetization"* (Kickhöfer 2014, 55).

$$U_{B_{TT}} = \sum_{j=1}^{J} \beta_{travel\ time_{mode\ i}} . x_{travel\ time_{mode\ i}} + \beta_{waiting\ time_{mode\ i}} . x_{waiting\ time_{mode\ i}} + \beta_{AET\ time_{mode\ i}} . x_{AET\ time_{mode\ i}} \quad (4)$$

$U_{B_{TT}}$ Total travel time utility based on behavioral VTTS

$\beta_{travel\ time_{mode\ i}}$ marginal utility of travel time for the mode i

$\beta_{waiting\ time_{mode\ i}}$ marginal utility of waiting time for the mode i

$\beta_{AET\ time_{mode\ i}}$ marginal utility of access, egress and transfer time for the mode i

$$U_{B_{TT}} = U_B - U_\Delta \quad (5)$$

U_B: Utility based on behavioral VTTS

U_Δ: difference between the Utility and Utility from total travel time

$$U_{VTTS_{TT}} = \sum_{i=1}^{J} VTTS.x_{travel\ time_{mode\ i}} + VTTS.x_{waiting\ time_{mode\ i}}.WT\ factor + VTTS.x_{AET\ time_{mode\ i}}.WT\ factor \quad (6)$$

$U_{VTTS_{TT}}$: Total travel time corrected Utility based on equity VTTS

$WT\ factor$: correction of the VTTS value to integrate the waiting discomfort

$AET\ factor$: correction of the VTTS value to integrate the access/egress and transfer discomfort

$$U_{VTTS} = U_{VTTS_{TT}} + U_\Delta \quad (7)$$

U_{VTTS}= Utility based on equity VTTS

This operation allows to not only integrate an equity value for the valuation of time but also to bear this translation only on the travel time and not on the utility difference between scenarios as it is defined in (Kickhöfer 2014). This utility difference between scenario integrates items such as the number of transfers or financial costs (U_Δ) which have no justification to be included in the process of introducing equity VTTS. The VTTS parameter is based on the 11,74 euros (2030 euros) (E. Quinet 2013), adjusted each year by a 0.7 elasticity with the GDP per capita rate. Compared to the

behavioral value of time for all mode, this equity value decreases the value of time of the private cars (19,43 euros/h), the walk (26,21 euros/h) and the bicycle (43,69 euros/h) and increases the one from public transit (4,95 euros/h).

b) Operator profits

The operator(s) profit (π) is the difference between costs, including infrastructure investment and maintenance, rolling stock investment and operating costs, and revenues generated by usage fees, sponsoring, advertising and subsidizing.

There is not yet a consensus regarding the investment and maintenance costs of AV infrastructure. The cost to upgrade the infrastructure to accommodate AVs varies from 3 000 dollars (Saeed 2019) per year and per kilometer to more than two millions dollars (Xue 2022, 10). Similarly, maintenance and replacement costs should be based on feedbacks of previous deployments and are thus only roughly estimated as for now. Consequently, these costs will be analyzed in this paper through a sensitivity analysis assuming that the investment cost (I_{infra}) varies from 50,000 to 250,000 EUR/km and that maintenance and replacement costs (M_{Infra}) are based on a yearly replacement rate of 10 to 50% of the investment cost to 50% (i.e., 50% means that the infrastructure will be fully replaced every two years). The infrastructure length is noted as Km_{Infra}.

The general consensus on the price tag of automated vehicles is that their price is marked up compared to conventional vehicles (Andersson and Ivehammar 2019; Bauer, Greenblatt, and Gerke 2018; Becker et al. 2020; Ongel et al. 2019; Quarles and Kockelman 2018; Tirachini and Antoniou 2020; Wadud 2017; Wadud and Mattioli 2021). The most extensive study on light vehicles such as cars or shuttles can be found in (Becker et al. 2020). Automation is supposed to add 5,000 US dollars to the vehicle price. A similar assumption can be found in (Wadud 2017), who report that automation would cost 5,000 dollars or 3,000 dollars in the second-hand market. A more recent study that builds on previous advances on the subject (Wadud and Mattioli 2021) indicated that automation would cost between 9,400 £ and 15,000 £ more per car. (Tirachini and Antoniou 2020) assumptions on automation costs are more pessimistic, as they proposed

that automation would cost between 36% and 86% more, depending on the vehicle. The +36% to +86% markup estimates are consistent with the variation in absolute value found in (Becker et al. 2020; Wadud and Mattioli 2021) based on the 26,000 euro average selling price of a new car in France (Leroy 2021). The total markup estimated for AVs is 7,500 euros per vehicle.

For EVs, (Bösch et al. 2018), on which the study by (Becker et al. 2020) is based, do not consider any markup compared to thermal vehicles. Similar to (Wadud and Mattioli 2021), the electric impact can be found in the operational, maintenance and insurance costs, but no purchase price variation seems to be applied. (Ongel et al. 2019) forecasted the purchase price of Internal Combustion Engine Vehicles (ICEVs), EVs and AVs for the year 2030 close to the shuttle format. They found that an ICEV should cost between 105,000 and 110,000 (2017 constant) dollars, the electric equivalent should be 20% more expensive and the automated and electric counterparts would be 28% more expensive. The estimated price for the AE shuttle is 128,000 euros with a 100,000 euro ICEV equivalent. For cars, (Mitropoulos, Prevedouros, and Kopelias 2017) found a 16% retail price difference between ICEVs (27,130 in 2015$) and EVs (31,590 in 2015$). This value is consistent with the +20% reported by (Ongel et al. 2019). All the aforementioned parameters value can be found in Table 32.

Automation impact vehicle price	Values	Automation impact factor
ICEV car	26,000 €	100%
Electrical car	31,200 €	100%
Automated ICEV Car	33,500 €	+ 29%
Automated Electrical car	38,700 €	+24%
ICEV Shuttle	100,000 €	100%
Automated electric Shuttle	128,000 €	+28%

Table 32. Automation impact factors based on the automation level and vehicle size.

Source: prepared by the author.

The initial rolling stock investment is based on the number of vehicles required (NB_{Veh}) to serve the demand, and the replacement investment on a 300,000 km distance-lifetime of vehicle. The price of an AV is noted as P_{veh}.

(Becker et al. 2020) have produced the most in-depth work on AV operating cost. Considering multiple cities around the world, they provided simulation-backed results for several business models and a large amount of data on cost analysis for private cars, automated taxis and buses. A shuttle cost structure can be found in (Bösch et al. 2018), a paper that also provides more insights into the influence of territory type on costs. (Abe 2019) produces a good overview of the influence of driver costs on the overall costs. The automation savings in operational costs are quite important, as drivers represent an important part of those costs. A total of 29% to 77% of the operational costs can be saved depending on the ratio of supervisors/vehicles required to monitor a taxi fleet (Abe 2019). However, (Becker et al. 2020) hold highly optimistic assumptions on the ability of AVs to drive themselves without supervisors. It seems reasonable that a supervision centre may be needed to regain control of autonomous vehicles that find themselves in situations where human intervention is needed. The supervisor topic has remained underexplored in the literature on AV cost analysis (Scoliege 2021). In the AV financial analysis field, (Nunes and Hernandez 2020) estimated that a supervisor should handle 50 vehicles at once to benefit from the economy of scale. This assumption may need additional discussion as it is not based on studies but rather one projection. As the acquisition costs of AVs are already considered in the investment section for AVs and Automated Shuttles in (Bösch et al. 2018, fig. Table 2), the depreciation costs (0,054 CHF/km and 0,14 CHF/km) are deducted from the initial 0,48CHF/km and 0,98CHF/km (Bösch et al. 2018, 89). These operational costs are converted to euros and discounted. No supervision cost is considered, which is corrected by adding a +0,05 EUR per Vehicle Kilometer Traveled (VKT). The revenues for the operator will be the results of the fare revenues (F) of the operations. All the aforementioned parameters value can be found in Table 33.

Mode	Invest Infra (per km)	Maintenance Infra Yearly Invest % cost	Vehicle Price	Operating costs (per km)
Private EV	-	-	-	Integrated in CS
Ride	-	-	-	Integrated in CS
SAV (car)	50k-250k €	10%-50%	38 700 €	0,45 €
AV Shuttle	50k-250k €	10%-50%	128 000 €	0,80 €

Table 33. Operator(s) profits parameters

Source: prepared by the author.

NB: The Public Transit are not considered here as their level of service remains equivalent between scenarios. In this case, no differences could be found, whatever the financial parameters values.

Finally, the profit could be expressed as:

$$\pi = F - \left(\left(I_{infra} * Km_{Infra}\right) * \left(1 + M_{Infra}\right) + NB_{Veh} * P_{veh} \; + \frac{VKT}{300000} * P_{veh} + \right) \quad (8)$$
$$VKT * OC$$

c) Externalities impacts

Externalities of AV (Ext) are divided into four sub-components, based on the segmentation by (E. Quinet 2013). Air pollution is not included as all AV vehicles are assumed to be electric.

The political trend restricting thermal vehicle use in European cities (see the low emission zones in Italy, the UK or Paris) makes the development of AVs under thermal propulsion unlikely. Electric and hydrogen vehicles are good candidates, but the development of hydrogen vehicles does not benefit from the same support as that of EVs. AVs will then be considered electric. For CO^2 emissions, (E. Quinet 2013) provides a monetary value for every ton of CO^2 emitted for every year. This value has been reviewed in (A. Quinet 2019) and fixed at 250 euros. For electric vehicles (EVs), general data need to be interpreted with caution. Electricity consumption is not a direct source of GHGs, but its production is often carbon-based. The mix of energy sources is heavily dependent on geographical political choices. Emissions for EVs or hybrid vehicles will need to be adapted for every use case with similar data to those in (E. Quinet

2013), (Buehler 2014), (Jochem, Babrowski, and Fichtner 2015), or (Jöhrens et al. 2020). The automation impact remains uncertain, as (Liu et al. 2019) point out. In the best-case scenario, a 13.28% reduction could be applied to the fuel consumption of EVs, in contrast with the worst-case scenario, which could increase the fuel consumption by 11.63%. However, Liu estimated that ten percentage points could be saved from the worst-case scenario by limiting speed limits alone. The difference between an automated car and a shuttle vehicle may have an impact on electricity consumption. (Jöhrens et al. 2020, 58) detailed electricity consumption levels based on vehicle size. Automated cars with four to five seats are assigned to the "Small Cars" category, with a consumption of 19.7 kWh/100 km, and automated shuttles are assigned to the "Large Cars" category with a 23,6 kWh/100 km consumption. A ratio of 1.19 based on the relative overconsumption of the shuttle is applied. A 5% fuel consumption is estimated for AVs compared to their strict equivalents, conventionally driven-EVs. The CO_2 emissions include the valuation of all CO_2-equivalent emissions from the use phase of the vehicle lifecycle (Em_{veh}). Private cars emissions are based on German emission for 2030 (Jochem, Babrowski, and Fichtner 2015).

The Lifecycle effects include the valuation of all CO_2-equivalent emissions made during the manufacturing and end-of-life phases, as the use phase is already covered.

In (Kemp et al. 2020), the materials and manufacturing (MM) phase represents 27% and the End-of-Life (EOL) phase represents 1% of the 42 ton of a the lifecycle emissions of an EV. The Use phase, counting for 72% is not accounted for in the lifecycle item as this work has already considered these emissions, the emissions due to the use part of the vehicle life will be subtracted from the lifecycle analysis. The automation sub-system is considered to add 1055 CO_2eq kg. Previously mentioned studies did not include AV shuttles in their scope. (Held and Schücking 2017) introduced the topic. As such, a value of 20,000 kg was estimated for a shuttle ("BEV (minivan) RheinMobil, elec.-mix" (Figure 3), minus the "charging electricity" item, which is similar to the "Use phase" from (Kemp et al. 2020)). The same automation burden of 1055kg is added to the Shuttle system. All vehicle lifetime is estimated to be 300 000 kilometers, an assumption close to the 200 000 miles in (Kemp et al. 2020). The value of the CO_2eq ton is fixed at 250 euros, accordingly to the Quinet report for 2030. The retained values (V_{LCE}) (0,95 euros for EVs, 0,97 for AVS and 1,75 euros for autonomous shuttles) are close to the 0,9 euros value fixed by (E. Quinet

2013) for a private car. One could have expected a higher value as EV are known to have an heavier environmental impact during the MM phase.

The noise externality is taken into account as the inconvenience that the road traffic might cause (E. Quinet 2013). (Taszka and Domergue 2017) found a -50% effect of the noise externalities due to electrification. Automation was not considered as a lever to reduce noise impact (N_{Impact}) based on (Patella, Aletta, and Mannini 2019) recommendations. Lastly, road safety is considered as AV are also expected to decrease accidents rates. (Papadoulis, Quddus, and Imprialou 2019) found that under a 100% market share of AV on motorways, conflicts can be reduced from 82% to 92%. Less optimistic, Kitajima et al. (2019) used an agent-based model to estimate human-based errors leading to crashes. They found an 18% reduction in collisions, but they warned of the need to consider their results with caution. Mahdinia et al. (2020) also found that automation would lead to a reduction in both driving volatility and time-to-collision, which would significantly affect accidents. (Tafidis et al. 2021) have performed the latest literature review on the topic to date. The fact that their review includes only 24 papers is due to the novelty of the topic. No overall consensus can be found, but most of the papers highlight an improvement in road safety thanks to automation. These results are based on assumptions and may need to be evaluated as soon as field data become available. A conservative approach was adopted, assuming a reduction of 20% of all crashes/VKT. The value of a statistical life is set at 3 million $€_{2010}$ according to Quinet (2013). The type of territories and vehicles will be taken into account, as they have important roles. The rate of accidents/traffic should be available for each case; otherwise, the 2019 rate in France will be used as a reference (ONISR 2019, 18), with 5 deaths per billion vehicle kilometers travelled. All the aforementioned parameters value can be found in Table 34.

Externalities per 100km	Carbon cost	Air pollution	Vehicle Lifecycle	Noise impact	Road Safety
Private EV	1,45 €	0,78 €	0,95 €	0,0005 €	0,0134 €
SAV	1,38 €	0,63 €	0,97 €	0,0005 €	0,0107 €
Difference compared to EV	*-5%*	*-19%*	*+2,1%*	-	*-20%*
Aut. Shuttle	1,64 €	0,99 €	1,75 €	0,0005 €	0,0107 €
Difference compared to EV	*+13,05%*	*+27%*	*+84,2%*	*0%*	*-20%*

Table 34. Externalities impact parameters

Source: prepared by the author.

Consequently, the externalities could be calculated using:

$$Ext = Em_{veh} * VKT * P_{CO_2} + V_{LCE} * VKT + N_{Impact} * VKT + V_{SL} * AR_D * VKT \quad (9)$$

d) Indicators for scenarios comparison

The comparison of scenarios is performed on three different levels: the macroeconomic level, the economic agents' level and the consumer level (Figure 49).

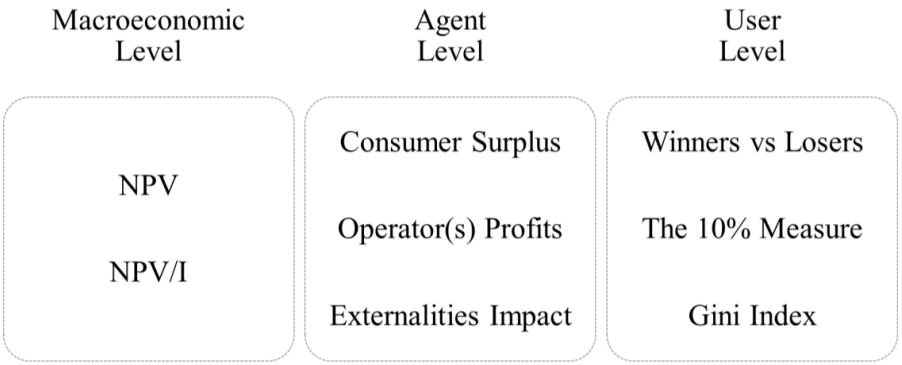

Figure 49. Scenario comparison methodology

Source: prepared by the author.

Comparison at the macroeconomic level is made using the social Net Present Value, "equal to the sum of the change in social surplus or the sum of changes in willingness to pay and changes in resources" ((de Rus et al.

2020, 28)). All cost and benefits considered in the NPV are not financial costs but also consumer surplus and externalities gain or loss.

$$NPV_s = \sum_{t=0}^{T} \delta^t (B_t - C_t) \quad (10)$$

NPV_s: social Net Present Value

δ^t: Nominal discount rate of period t

B_t: Aggregated Benefits from period t

C_t: Aggregated Costs from period t

Based on (de Rus et al. 2020), the inflation rate (φ) is applied at the same level as the discount rate, introducing the real discount rate instead (r_R) of the nominal discount rate (δ^t):

$$r_R = \frac{r_N - \varphi}{(1+\varphi)} \quad (11)$$

An 1% inflation rate value based on the last decade of inflation rate in Europe has been retained. The Ukrainian war have increased to inflation rates to a higher level, but a more conservative and event-free approach is considered here. (E. Quinet 2013) suggests using a 2.5% annual discount rate, which is close to the 3% recommended by the European Commission for most European countries (de Rus et al. 2020, 33). This value may be considered low compared to the amount that may be attributed elsewhere (up to 15 or 18%), but (Mouter 2018) reviewed the discount practices in the Netherlands, United Kingdom, Norway, Sweden and Denmark, where discount rates were distributed between 1% and 4.5%. The discount rate is fixed at the European Commission level of 3%. Further research could explore the difference in price evolution between autonomous vehicles and autonomous vehicle infrastructure, as well as the overall level of prices. (E. Quinet 2013, 173) recommends to adjust the price of statistical life with the GDP per capita evolution which should evolve at a 1.2% rate ("Cadrage Du Scénario de Référence" 2019). It also recommends to adjust the LCA values by the GDP/capita evolution rate but as these values retained in (E. Quinet 2013) are a composition of externalities in CO_2 with global impact and local pollutant but the LCA in this work is based on CO_2eq emissions, we will make our LCA values evolves with the CO_2 values.

The evolution of CO_2 price is defined in (A. Quinet 2019, 124) at 250euros/t in 2030 and 500euros/t in 2040 giving an average annual growth rate (AGR) of +7.18%. The CO_2 emissions/km for EV by ("Cadrage Du Scénario de Référence" 2019) is defined as 68kwh/100km in 2030 and 126 kwh/100km in 2050 giving an AGR of -1.43%. All the aforementioned parameters value can be found in Table 35.

	Discount rate	Inflation	GDP/capita	CO_2 emissions/km	CO_2 value
AGR	+3%	+1%	+1,20%	-1,43%	+7,18%
Impacts	NPV	NPV	Air pollution	CO2 emissions	CO2 emissions
			Road safety		LCA

Table 35. Contextual parameters

Source: prepared by the author.

The second base of comparison is the NPV/Investment which evaluates the social profitability of the investment.

At the agent level, the comparison is performed through the Agents Surpluses, which indicate the transactions between all agents in terms of gains and losses due to the service production

$$aS = \sum_{t=0}^{T} \delta^t (aB_t - aC_t) \quad (12)$$

aS: Agent Surplus

aB_t:Agent level aggregated benefits from period t

aC_t: Agent level aggregated costs from period t

Finally, "Consumers" is the most heterogenous category of our selection of economic agents. The agent-based model MATSim provides an analysis based on the agents score. Three main indicators are used to give indications on the surplus allocation of each agent.

- Winners versus losers: Repartition of agents with a better situation (winners), a worst situation (losers) or the exact same situation

(indifferent) than in the baseline scenario, expressed as a percentage of the agents' population.

- The 10% measure: estimates how much of the consumer surplus due to the project implementation is being captured by the 10% of the agents winning the most, expressed as a percentage of the aggregated positive consumer surplus.

- A Gini Index based on the distribution of gain or loss for each agent.

C. Case study

This appraisal methodology has been applied to Berlin (Carreyre et al. 2023). The reasons behind the choice were 1. The use of MATSim, an open-access simulation model (allowing reproducible research) and 2. an application in an already covered territory. The following case study complies to the same criteria by using Eqasim, a widely available open-access model developed by (Hörl, Balac, and Axhausen 2019), based on a discrete choice module from MATSim. The territory in itself is also covered in other simulation works (Berrada 2019; Berrada and Poulhès 2021), even if the mode choice model used is different (Chouaki, Hörl, and Puchinger 2023).

1) Territory

The « *Communauté d'agglomération Paris-Saclay* » (CPS) is an inter-township administrative structure in the Île-de-France region, 20 kilometers south from Paris. It is home to over 450,000 people, making it one of the largest agglomerations in the Paris region.

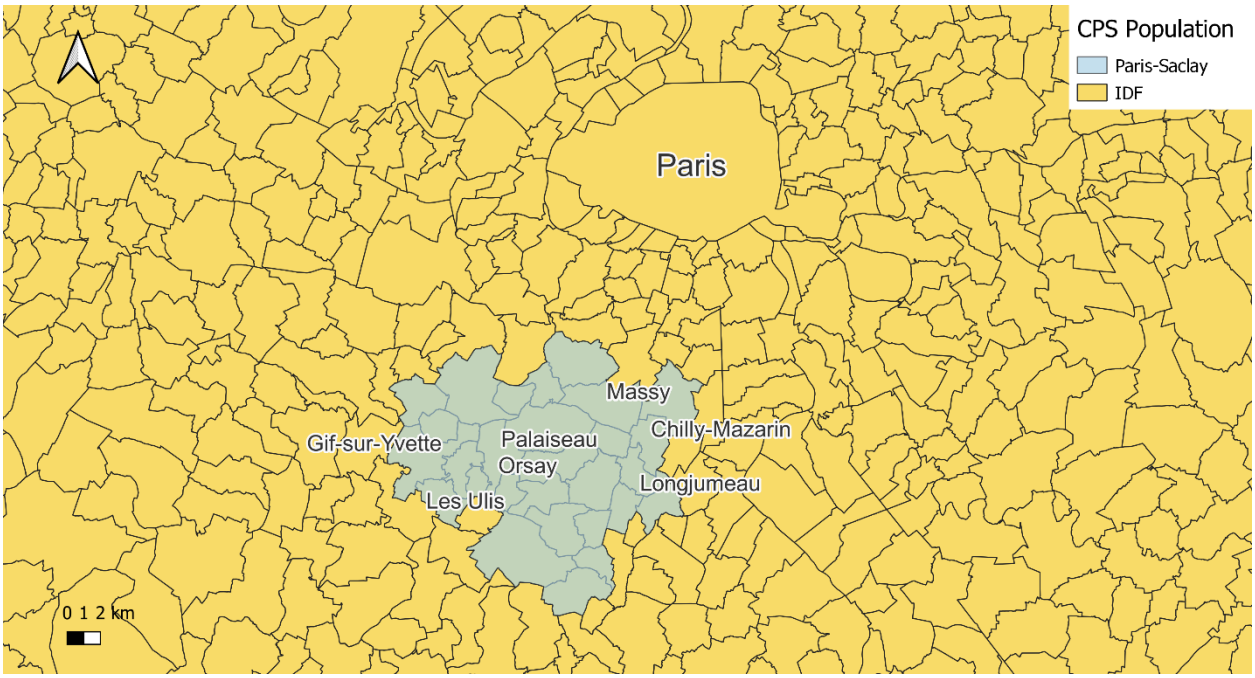

Figure 50. Communauté d'agglomération Paris Saclay (CPS) position in Île-de-France
Source: INSEE, made by the author.

Demographically, the CPS is home to a diverse population, with a mix of urban and suburban areas. The whole communauté might be defined as a periurban area for its position towards Paris (Figure 50). If some areas such as Massy and Palaiseau are densely inhabited and see a lot of activities territories south and north of Gif-sur-Yvette are developing themselves. Figure 51 shows that the CPS is a periurban territory in Île-de-France according to the INSEE definition.

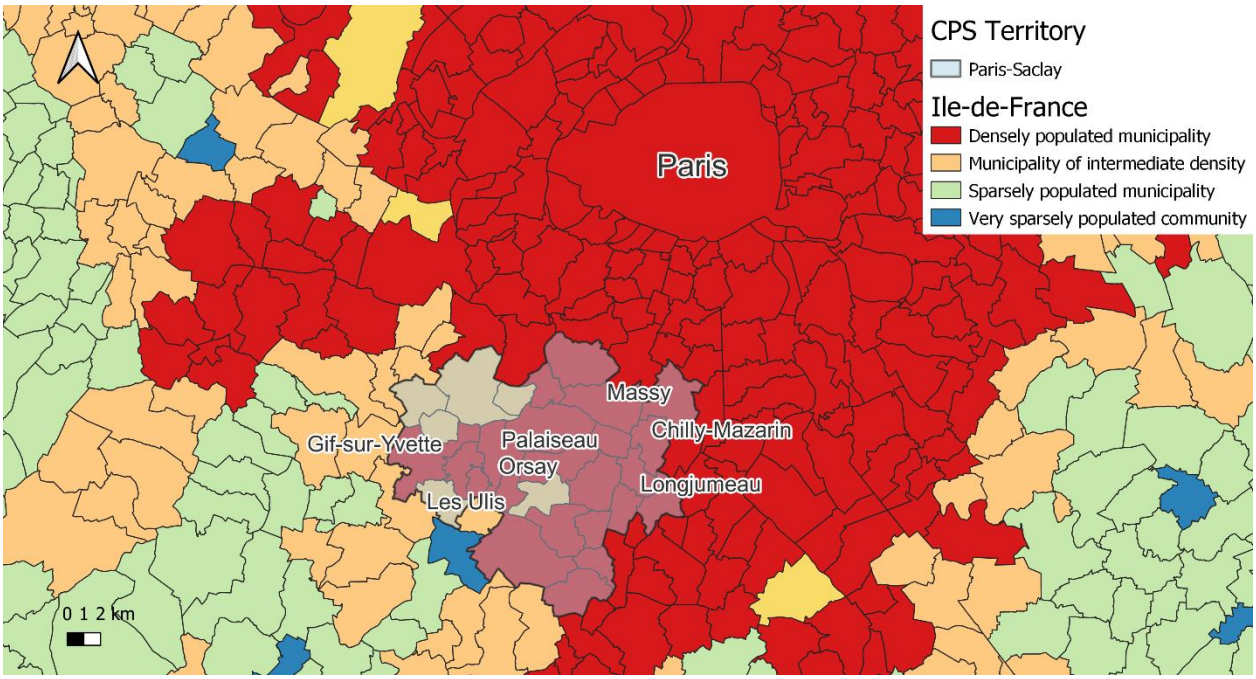

Figure 51. CPS communities following the INSEE (National French Institute of Statistics) nomenclature
Source: INSEE, made by the author.

The local economy is strong and diverse, with a range of industries represented, including technology, research and development, and services. The communauté is home to a number of major international companies, as well as many smaller businesses, concentrated around the axis Massy-Palaiseau-Orsay-Les Ulis (Figure 52)

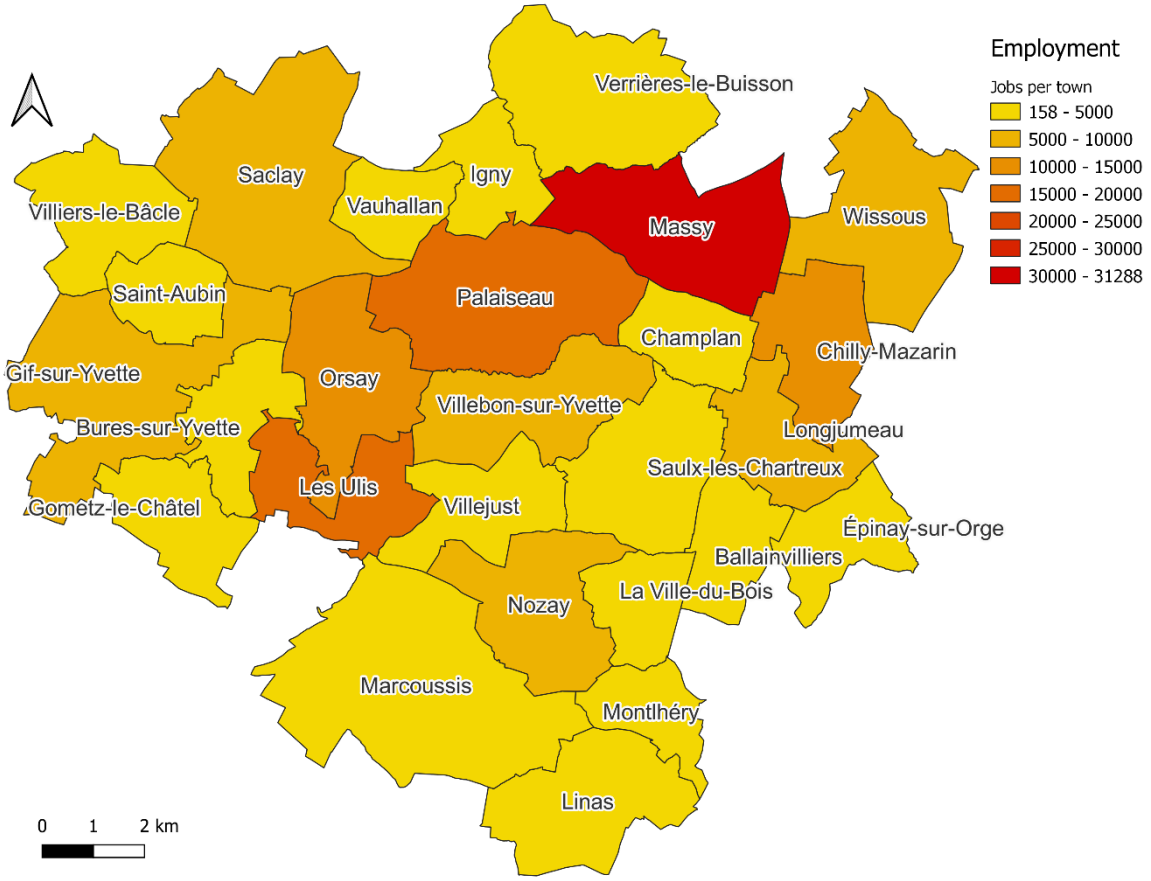

Figure 52. CPS employment
Source: INSEE, made by the author.

This jobs density also follows the RER B design, one of the major local train line in Île-de-France. Massy also benefits from being on the route of the RER C, one other major local train line. As it would be detailed below, in this work, additional public transport services were added to match the 2030 Grand Paris Express expectations.

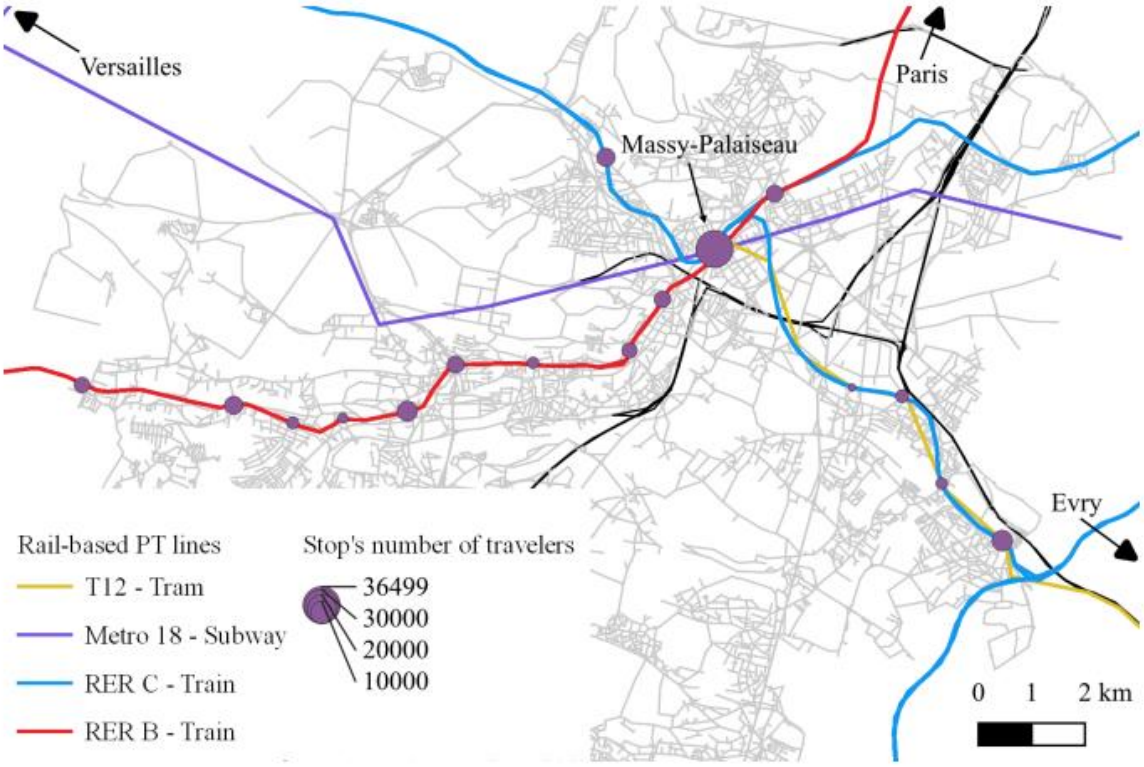

Figure 53. Existing and future rail-based transit lines - Focus on the CPS area

Source: (Chouaki, Hörl, and Puchinger 2023)

2) CPS Eqasim

(Chouaki, Hörl, and Puchinger 2023) developed a model specific for the CPS territory based on (Hörl, Balac, and Axhausen 2019). In addition, to the existing model, they added the expected new transit lines (subway line 18 and tram and tramway line 12, see Figure 53).

3) Scenarios

The implementation of AVs services in Saclay requires to define AV services, and define scenario configuration for each service. As the evaluation step comes after the simulation step, the evaluation scenarios set will be a subset of the simulation scenarios set. The aim of the scenarios set is to understand the AVs potential as a feeder service in a periurban area. The scenarios have been developed with the same methodology used to developed scenarios for (Carreyre et al. 2023), but with adaptations for the territory and use case. For (Carreyre et al. 2023), scenarios have been developed to comprehend the economic impact of on-demand autonomous

vehicles in an urban territory. The CPS is a periurban area with scarcer public transit supply. If train lines provides fast mode of transportation, mostly towards Paris center, the bus lines are known to be slow and overcrowded. If some parts of the discontent may be attributed to operational disorganization (Chevallier 2022), the 2017 Transport Scheme for the CPS points out the need to reinforce the buses frequency, especially during peak-hours (Agglomération Paris-Saclay, Parme Avocats, and SYSTRA 2017). On-demand autonomous vehicles could provide a more reliable, comfortable and faster way to access to the rail-based modes of transportation (trains, metro, subway). To test this assumption, a feeder service operated with on-demand autonomous vehicles service based on (Carreyre et al. 2022) nomenclature. AV taxis with varying capacities (4 seats or 8 seats) and different routings are introduced in the CPS territory. The routings will either be Stop-Based (working from a stations network) or Door-to-Door but both will link at least one of the segment point to a rail station (train, metro or subway) station. The stations of the Stop-Based network are based on the public transit stations of the CPS area. The agent traveling with the DRT service will need to either have used a public transit mode to access or leave the station. The agents cannot use the DRT service as a stand-alone service. The 400 vehicles fleet size is based on the first fleet size to reach a sub-five percent rejection rate for AV request with 100 vehicles steps. The parameters used for these simulations were the default ones. The ride must be done in a D2D scheme, with a 10 minutes waiting time constraint, a fare of 0,3 euros per kilometers traveled and ridesharing enabled. Results from this simulation might be found in the 0,3 D2D scenario. This method allows to remain around the 5% rejection rate threshold for the following simulations when the DRT service attractivity were to be altered. The scenarios set which freed the service from fares allows to assume a fare integration between the public transit fare policy and the AV service. As for the evaluation scenarios, we retained the four scenarios which have the most important impact on the mobility landscape, with the four scenarios with free AVs.

Name	Description	Ridesharing	Routing	Capacity	Fare (euros/km)	Fleet size	CBA
	Basecase scenario	N/A	N/A	N/A	N/A	N/A	*
SAV D2D	Door-to-door AV	Yes	D2D	4	0	400	*
SAV SB	Stop-Based AV	Yes	SB	4	0	400	*
0,3 D2D	Door-to-door AV	Yes	D2D	4	0,3	400	
0,3 SB	Stop-Based AV	Yes	SB	4	0,3	400	
0,6 D2D	Door-to-door AV	Yes	D2D	4	0,6	400	
0,6 SB	Stop-Based AV	Yes	SB	4	0,6	400	
D2D Shuttles	Door-to-door AV	Yes	D2D	8	0	400	*
SB Shuttles	Stop-Based AV	Yes	SB	8	0	400	*

Table 36. Simulations and evaluation sets

Source: prepared by the author.

D. Results

1) Simulations Results and Discussion

a) General Results

The purpose of this study was to simulate the potential impact of autonomous vehicles (AVs) on travel behavior and traffic congestion. Using a maximum utility mode choice model and the Eqasim simulation, we found that AVs are likely to attract passengers mostly from car travel and public transit modes, with a modal share of almost 2% in the most AV favorable scenario which is consistent with (Chouaki, Hörl, and Puchinger 2023). The overall decrease of public transit trips represented in the Figure 54 hides a result consistent with (Chouaki, Hörl, and Puchinger 2023), where bus trips decrease but trips in train or metro increase thanks to a better attractiveness.

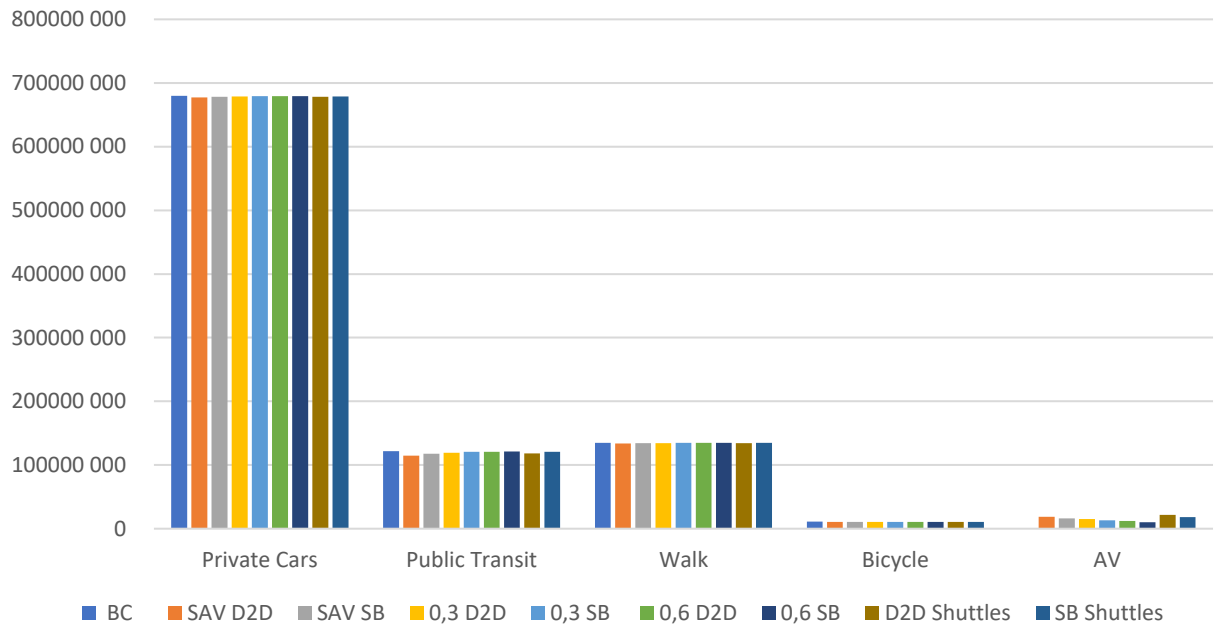

Figure 54. Trips
Source: prepared by the author.

Overall VKT (private cars VKT + AVs VKT, see Figure 56) increased between +0,8% and 1,7%, which is consistent with the literature (Carreyre et al. 2022) but at a lower rate. We also found that travel time for car users unexpectedly increased between 7% and 34% depending on the scenario. This increase is difficultly explained by the VKT increase or distance traveled increase (<1% for all scenarios, see Figure 55). This increase of travel time may be due to congestion effects around train stations, where links experienced significant delays and travel times were multiplied by up to 30 times their initial values. Despite this increase in travel time, the overall utility observed from the agent's plan improved after the AVs introduction as we will see in the Consumer Surplus section. The travel time increase is consistent with the literature (Carreyre et al. 2022) but the congestion increase might found three explanations. First, Eqasim is calibrated based on modal share and congestion has not been calibrated yet. The congestion is modelled based on the MATSim queue effect between links and the congestion function based on (Vickrey 1969) inside the links. Secondly, the MaximumUtility function makes every agent choose the modal alternative with the sum of the highest deterministic utility plus a random parameter. This parameters is based on a hash function which simulates a random parameters by giving an attribute to each modal alternative for each trips. It allow to simulate a random attribution but with the ability to give the

same parameters to each alternative between iterations but also simulations.

	Hash function	
seed	input	output
1234	b1	y1
1235	b2	y2
1236	b3	y3
1237	b4	y4
1238	b5	y5
…	…	…

Table 37. Seed and hash function

trips	Cars	Walk	Public Transit
a_1	y1	y2	y3
a_2	y4	y5	y6
a_n	…	…	…

trips	Cars	Walk	Public Transit	AVs
a_1	y1	y2	y3	y4
a_2	y5	y6	y7	y8
a_n	…	…	…	

Table 38. Initial random parameters attribution (left) and after the introduction of a new mode (right)

Source: prepared by the author.

It also may be at the origin of the additional congestion that we observed with the AVs introduction. This random attribution may be disturbed (i.e. the same random parameter may not be attributed to the same alternative) if a new mode if introduced (see Table 37 and Table 38). We tested our reference scenario with different seeds and observed similar impacts on congestion. The congestion is also impacted by random parameters influenced by the hash function.

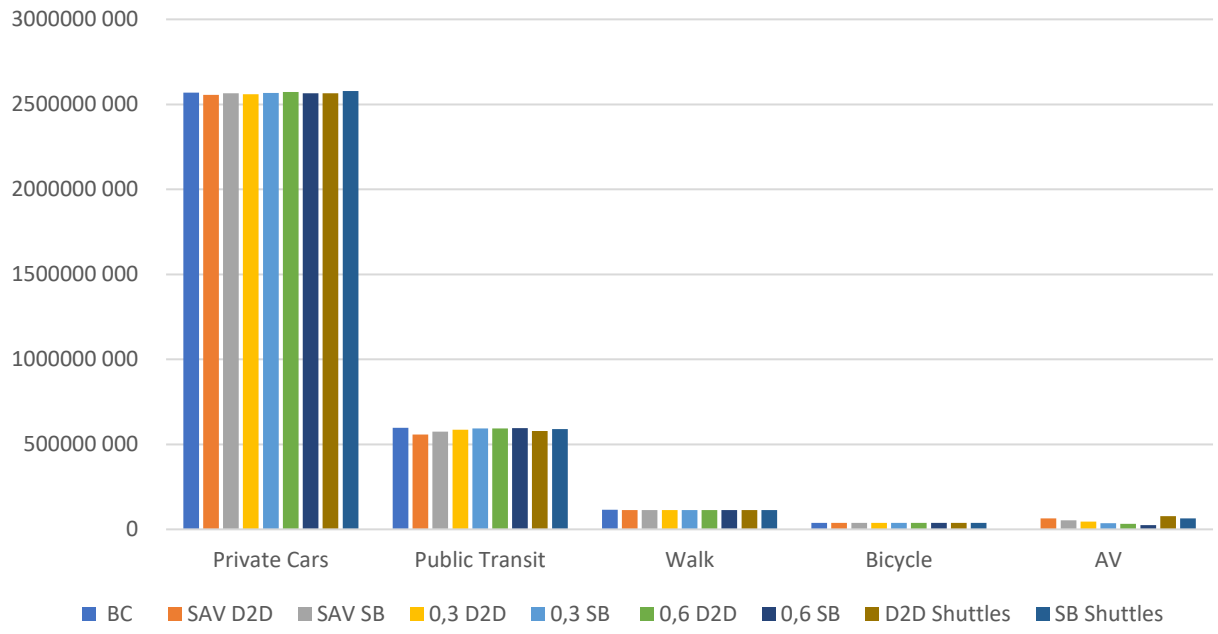

Figure 55. Distance travelled (in pass.km)
Source: prepared by the author.

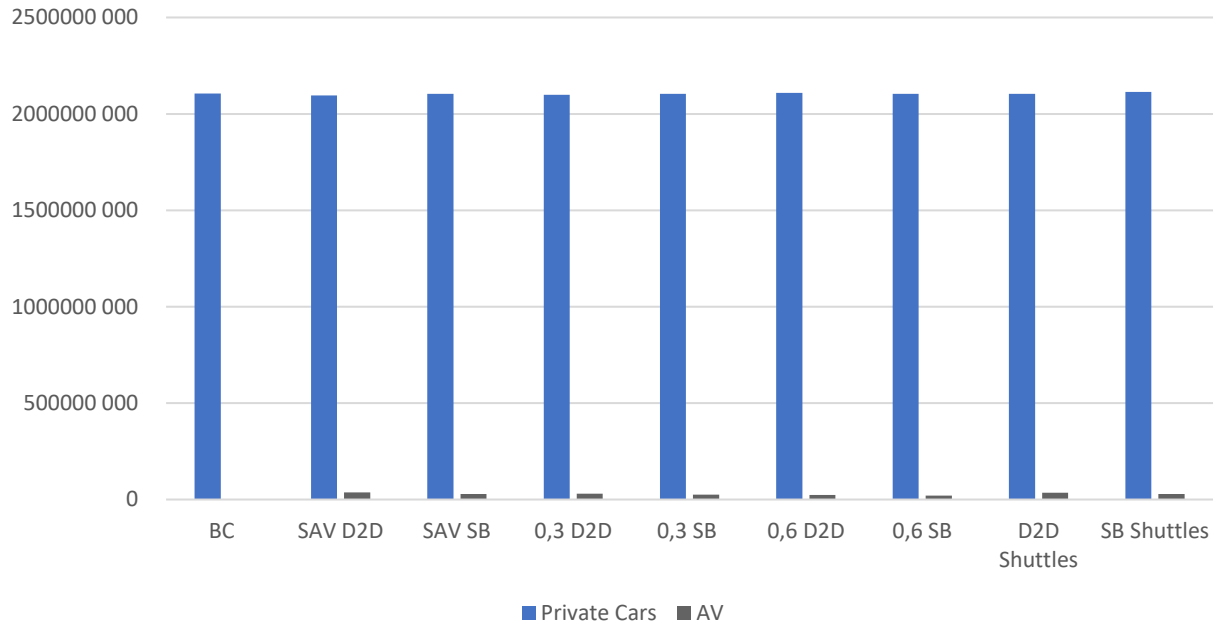

Figure 56. Vehicle Kilometer Traveled
Source: prepared by the author.

b) DRT Focus

AVs performances are sensitive to the routing proposed, the fare level and also the capacity of the vehicles. The comparison of D2D and SB routing

shows that 1) D2D is more attractive than SB (Figure 57) partly due to a better level of service (Figure 59), however at higher AV fees scenario (AV2 to AV5), the average total travel time is equal between D2D and SB, but the access/egress team is higher for the SB routing, giving a slight advantage to the D2D in term of utility 2) D2D is more resource consuming (Figure 60) due to a more important demand.

The D2D consistently presents lower average vehicle occupancy rate (AVO) than the SB service which can be caused by the routing which generates higher detours than SB, thereby pushing away agents from AV ridesharing, this results is consistent with (Carreyre et al. 2023). Despite an higher rate of empty VKT that in the Berlin case study Figure 58, the feeder system where vehicles wait for people to PT station helps to increase the AVO for both SB and D2D. The effect for D2D is straightforward as it corresponds to operate as a semi-SB routing, which increases the AVO. For the SB system, it may help the dispatching algorithm to absorb the demand forcing the vehicles towards station with high level of demand. The empty-VKT are significantly higher (26% to 42%) than for the Berlin case study (8-12%), 7% to 25% for (Haonan, Kockelman, and Gurumurthy 2020), 3% to 13% for (Winter et al. 2018), ~5% for (Ben-Dor, Ben-Elia, and Benenson 2019) and 4% for (Gurumurthy, Kockelman, and Simoni 2019). It might be due to the repositioning of vehicles.

The SB routings, which showed consistent higher AVO by two percentage points in the Berlin case study, presents in the CPS case study a lower AVO, except for the scenarios where shuttle were replacing AVs cars in which the trend changes. The AVO seems to be highly dependent on the fare level and vehicle capacity. It shows that shared on-demand vehicles might benefit from economies of scale (Winter et al. 2018), as the lowest is the fare the highest is the demand (Figure 57) and AVO. The vehicle capacity impact is a novelty in the literature as (Berrada 2019; Vosooghi 2019; Carreyre et al. 2023) shown that bigger than 4-seaters vehicles were struggling to use additional seats. Here, we found that the replacement of cars (4-seaters) by shuttles (8-seaters) help to reduce empty-VKT, increase AVO (Figure 58), and to absorb additional demand (Figure 57), even reducing total travel time in some cases (AV1 versus AV9 in Figure 59). The AVO from all scenario (comprised between 1,21 and 2,26) is significantly higher than most of the literature. (Truong et al. 2017) found from ~1,15 to 1,2, (Haonan, Kockelman, and Gurumurthy 2020) from 1,03 to 1,84, except for (Winter et al. 2018) which found an AVO of 4 people per vehicle with an fixed attributed demand (a mode choice was not used). Further research would be needed to confirm

this finding but the use of on-demand mobility services as a feeder service can help to use on-demand services at their max potential.

Overall, our results suggest that feeder performance is sensitive to routing, fare level, and vehicle capacity, and that D2D and SB services have different strengths and weaknesses that should be carefully considered when designing AV systems. Except for the contribution on the combination of feeder service and vehicle size, all our results are consistent with the existing literature comparing D2D and SB services.

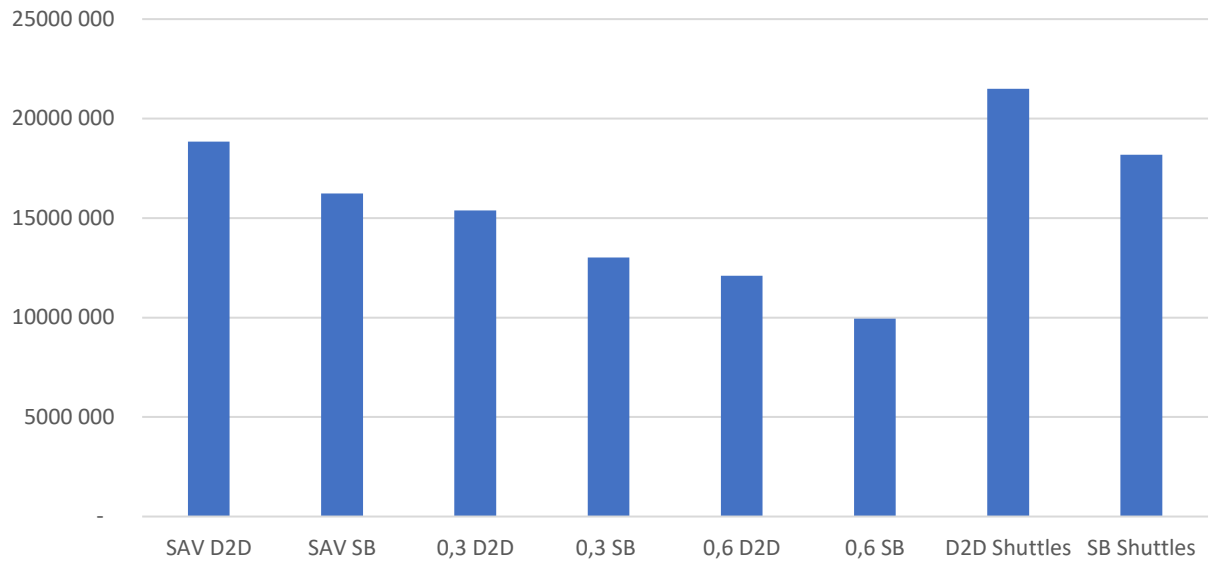

Figure 57. AV Trips per day
Source: prepared by the author.

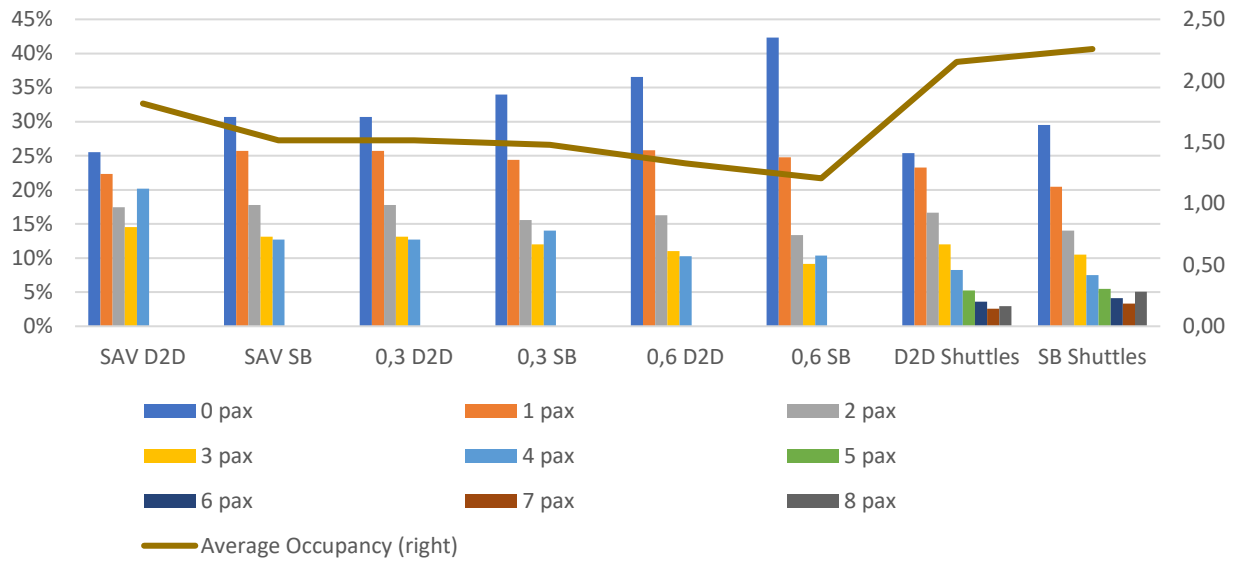

Figure 58. Average vehicle occupancy
Source: prepared by the author.

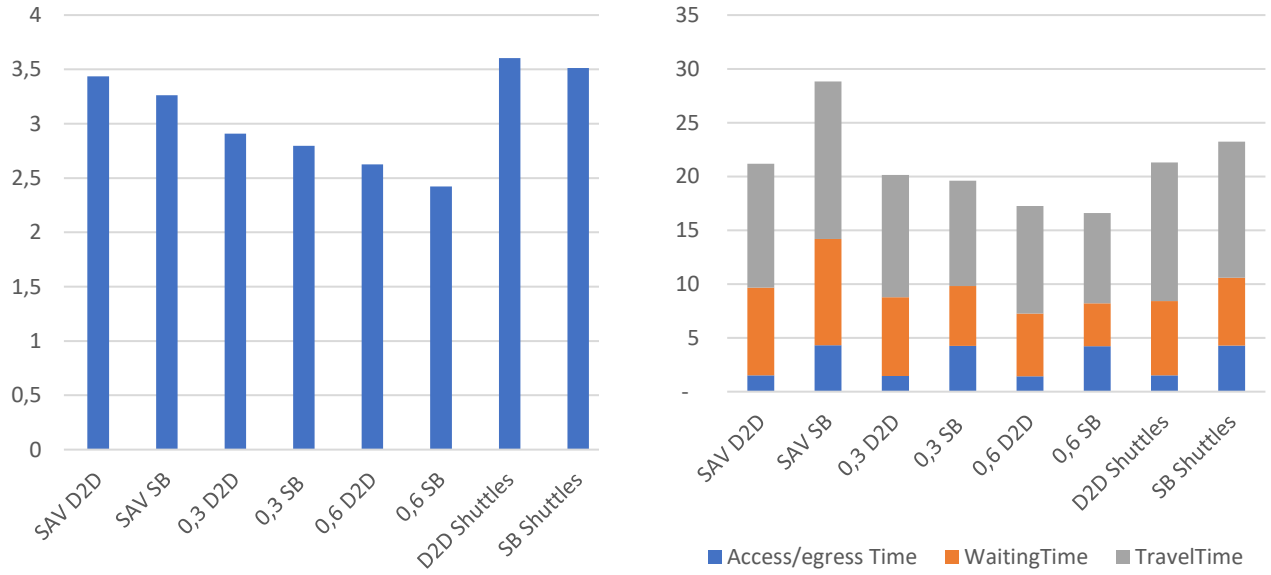

Figure 59. Average Distance Traveled per trip (km, left) and Average Total Traveled Time
Source: prepared by the author.

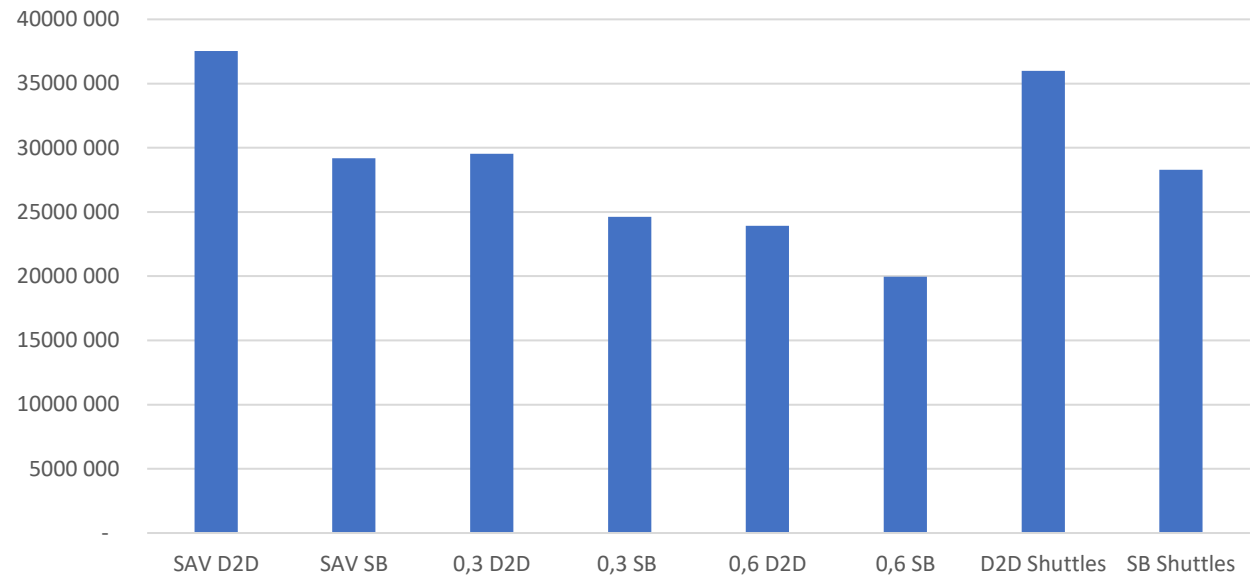

Figure 60. AV Vehicle Kilometers Traveled
Source: prepared by the author.

2) Cost Benefit Analysis Results and Discussion

a) Consumer Surplus (CS)

Before to go start on the Consumer surplus, here is the impact of the introduction of equity VTTS on the utility compared to the behavioral VTTS. The behavioral utilities increase with the number of modal alternatives, the routing and fares. For the modal alternative, scenario V0 presents the lower utility and it is the only scenario without AVs. For the routing, as seen previously, the SB routing consistently causes longer travel times, lowering agents utilities. The AV fares have an impact on AVs attractiveness (Figure 54) and also on agents utilities. For the utilities based on equity VTTS, the highest difference is that the reference scenario presents the highest utilities, by contrast with the behavioral VTTS utilities. It is mainly due to the increase of value of time during time (see Appendix Figure 71) and increase of the aggregated travel times (all modes) between the basecase scenario VO and the scenario in which AVs were introduced.

As mentioned previously in the simulation results section, it is unusual to observe an utility decrease when a new mode is introduced. The behavioral VTTS utilities respect this condition, despite an overall increase of travel time. The pattern leading the utility is relatively straightforward. In the other hand, the equity VTTS utility presents some points of interest. The D2D routing seems to provide higher consumer surplus results than SB routing, except for the shuttle scenarios. For D2D scenarios, AV2 and AV4

counter-intuitively presents higher utilities than AV0 despite the fact that the service is more expensive.

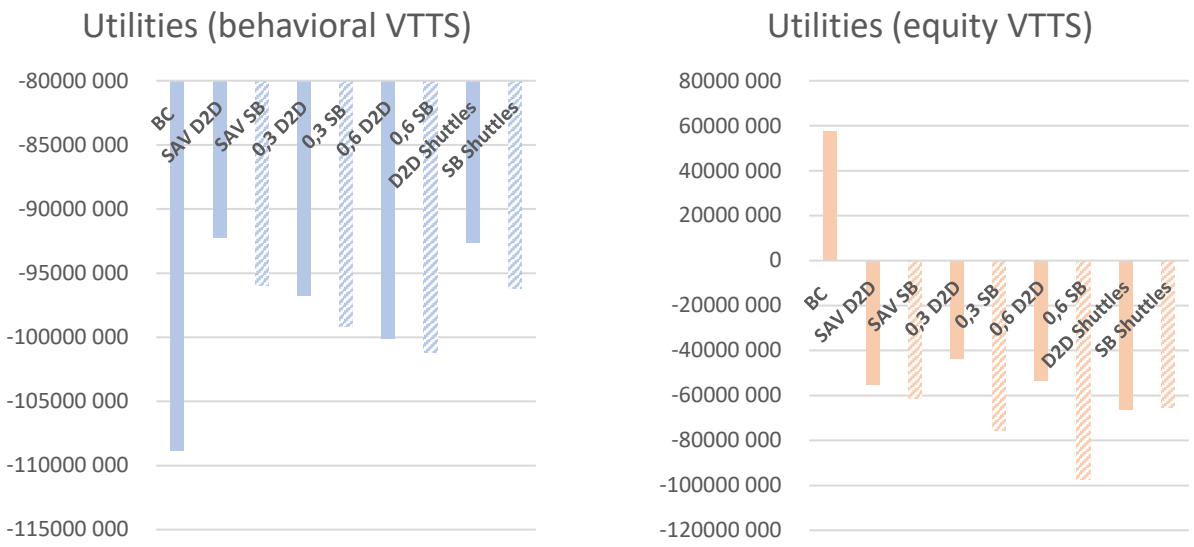

Figure 61. Utilities from behavioral VTTS (left) and Utilities from equity VTTS (right)

Source: prepared by the author.

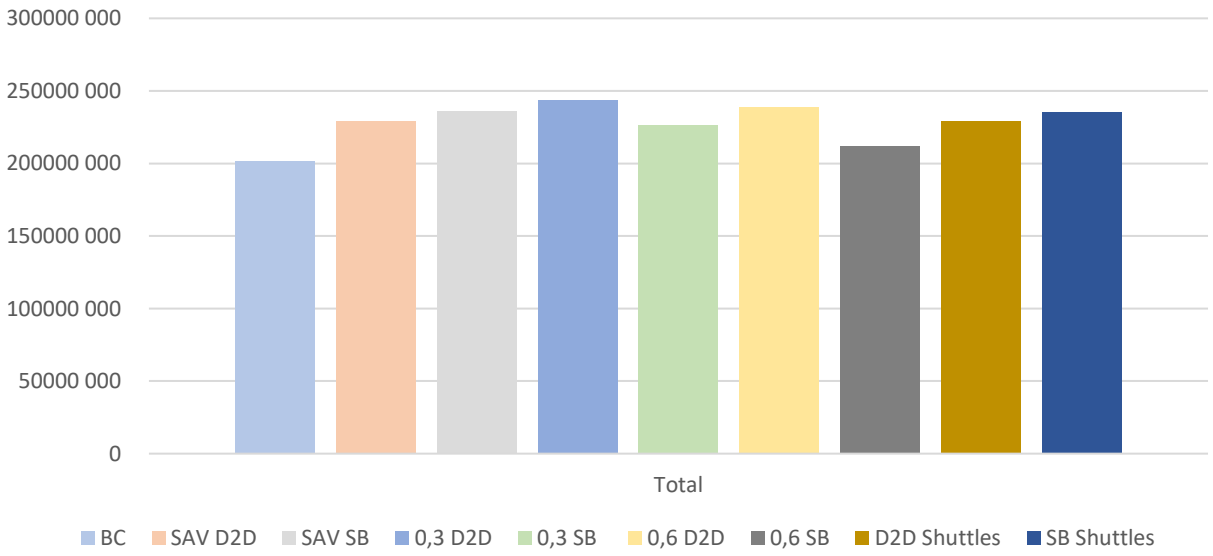

Figure 62. Aggregated total travel times

NB: hours, all modes

Source: prepared by the author.

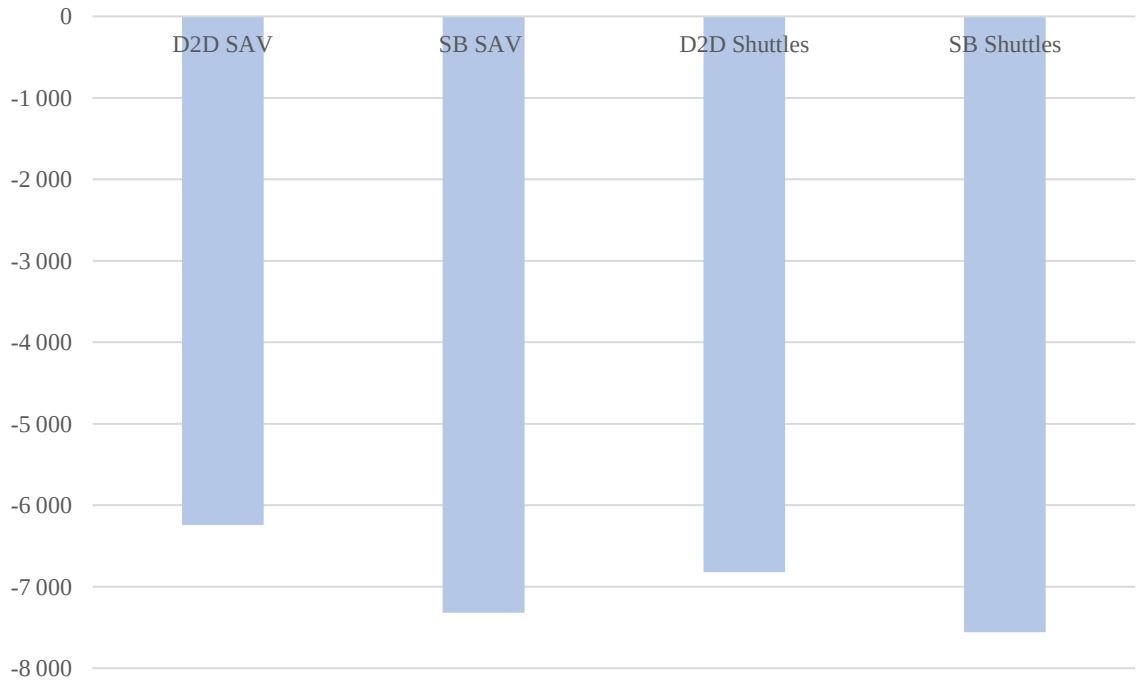

Figure 63. Consumer surplus from equity VTTS
NB: 10 years term, millions € differences with basecase.

Source: prepared by the author.

The CS for all four CBA scenarios presents a negative value. The D2D routing appears to lessen the loss compared to SB routing, thanks to faster travel time (see Figure 59). The overall loss of consumer surplus and its trend might be explained by the overall increase in travel time (13%, 17%, 13% and +16%). The results shows that this decrease is partly due to the increase of travel time for car users (from +7% to 29%), which is mitigated by the decrease of time value for car users. The increase of travel time of travelers using PT and AVS is more important, due to the lever effect of the use of the equity VTTS which doubles the value of travel time from the behavioral VTTS. However, the Consumer surplus based on the behavioral VTTS showed an increase in Consumer Surplus, despite the previously mentioned increase in total travel time. This situation illustrates an anomaly pointed out by (Börjesson and Eliasson 2019) where the introduction of an equity VTTS would lead to such paradoxes. As such, we are presenting both consumer surplus estimation methodologies.

As shown here, the use of equity VTTS for evaluation purposes when behavioral value of time are differentiated by modal alternative in the simulation (as it is in Eqasim) might led to a decrease in importance of the car travel time and an increase of the importance of travel time in the

evaluation. This has a negative impact when evaluating scenarios looking to generate modal shift from car to public transit. The lower behavioral value of time from PT may attract travelers previously using cars, despite a longer travel time. In the evaluation, this increase of travel time might represents a loss of consumer surplus.

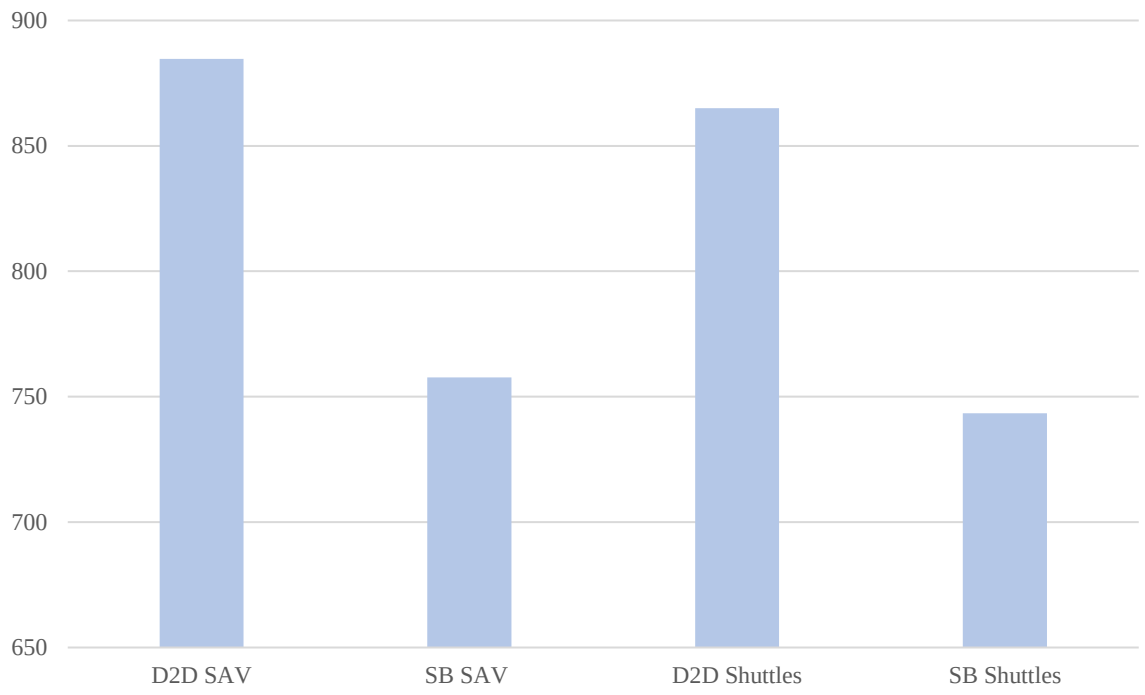

Figure 64. Consumer surplus from behavioral VTTS
NB: 10 years term, millions € differences with basecase. The VoT adjustments based on the GDP/capita rate have not been made. It should decrease the gain of Consumer Surplus.

Source: prepared by the author.

These uncertain results goes against the literature which consider that AVs introduction would lead to an increase in Consumer Surplus (Carreyre et al. 2023). The loss of consumer surplus in (Carreyre et al. 2023) was not due to the use of equity VTTS for the evaluation as the value of time used during the simulation did not differentiate between mode or trip purpose. The modal choice was made based on different modal alternative constants, number of transfers, length trip or financial expenses and not different value of time. The use of equity value of time during the evaluation marginally altered the consumer surplus value but did not change the trend.

The equity KPIs showed that the introduction of AVs has a limited effect on most of the population. The repartition of winners/losers is almost even (19%/18% for AV0 and 18%/19% for AV1, AV8 and AV9) with a stable share of more than 60% of the population which remains indifferent to the new situation. The scope of the feeder service, which aims to complete an already existing offer, does not concern the entire CPS population. As such, more than 99% of the gains are concentrated between the 10% gaining the most. With such a concentration of gain, the analysis has been made for the 5% share and 1% share of people gaining the most for the D2D SAV scenario (the four scenarios have a very similar distribution of gain and losses). The results show that the service introduction really benefit to a minority with a respective 96% and 48% share of the gains. The very low GINI index might surprise with such an important concentration of gains but the gains slop (Appendix Figure 73) and the share of indifferent agents show that the gains (which are often null) are evenly distributed.

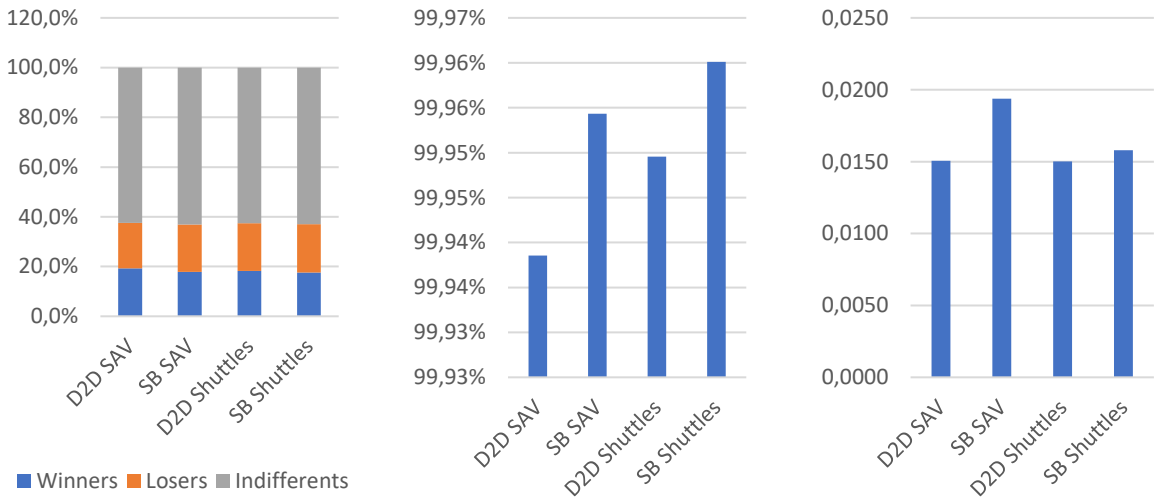

Figure 65. Equity KPIs Winners versus Losers (left), the 10% measure (middle) and Gini index (right)

Source: prepared by the author.

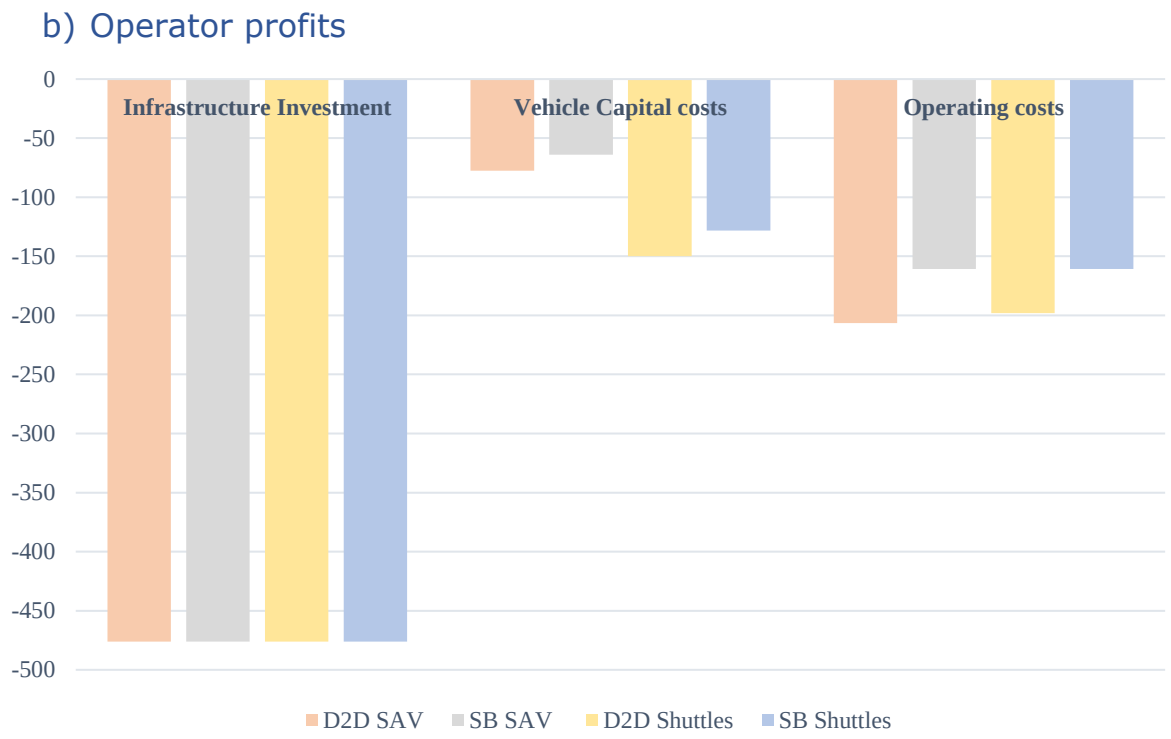

Figure 66. Financial surplus

NB: 10 years term, millions € differences with basecase

Source: prepared by the author.

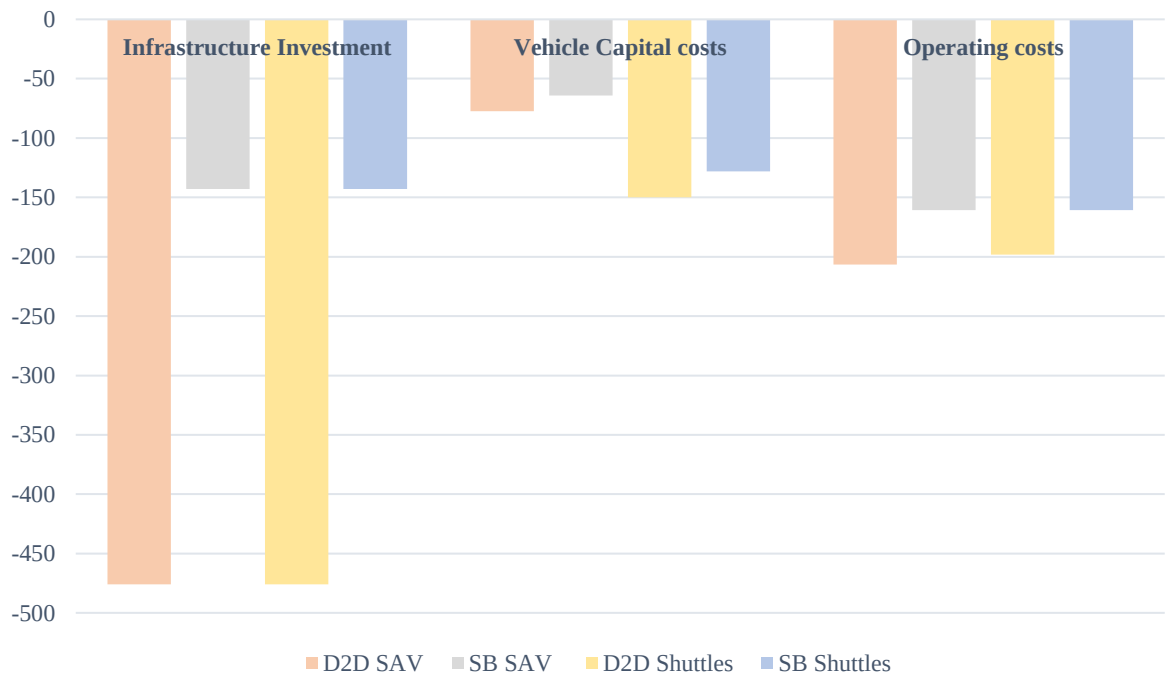

Figure 67. Financial surplus, AV network based on the bus network
NB: 10 years term, millions € differences with basecase

Source: prepared by the author.

The repartition of the costs for the operator(s) are homogenous amongst the four scenarios. The operator(s) costs are composed by more than half of infrastructure investments, by a quarter of operational costs represents than a quarter of these costs and the rolling stock investments represents less than a quarter of the remaining costs. The main difference is the operation of shuttles rather than cars, for which the rolling stock costs doubles when buying shuttles instead of cars, which can be explained by an acquisition price much higher for shuttle despite the fact that they required to be replaced less due to their lower VKT. Meanwhile the operational costs increase by less than 30% for the shuttle scenarios due to an higher operational cost per kilometer traveled and despite a lower overall VKT.

The implementation of a Stop-Based routing using the public transit station system allows to pursue studies in which the AVs system would only operates on the bus network. The bus network in the CPS is composed of 286 kilometers instead of the 952 kilometers road network. As the costs of infrastructure is strictly proportional to its size both for the investments and the maintenance, such a diminution of the network size allows to divide the investment and maintenance costs of the infrastructure by more than three.

In this situation, if the implementation of the service requires to equip the infrastructure, a stop-based routing seems to be a pragmatic solution.

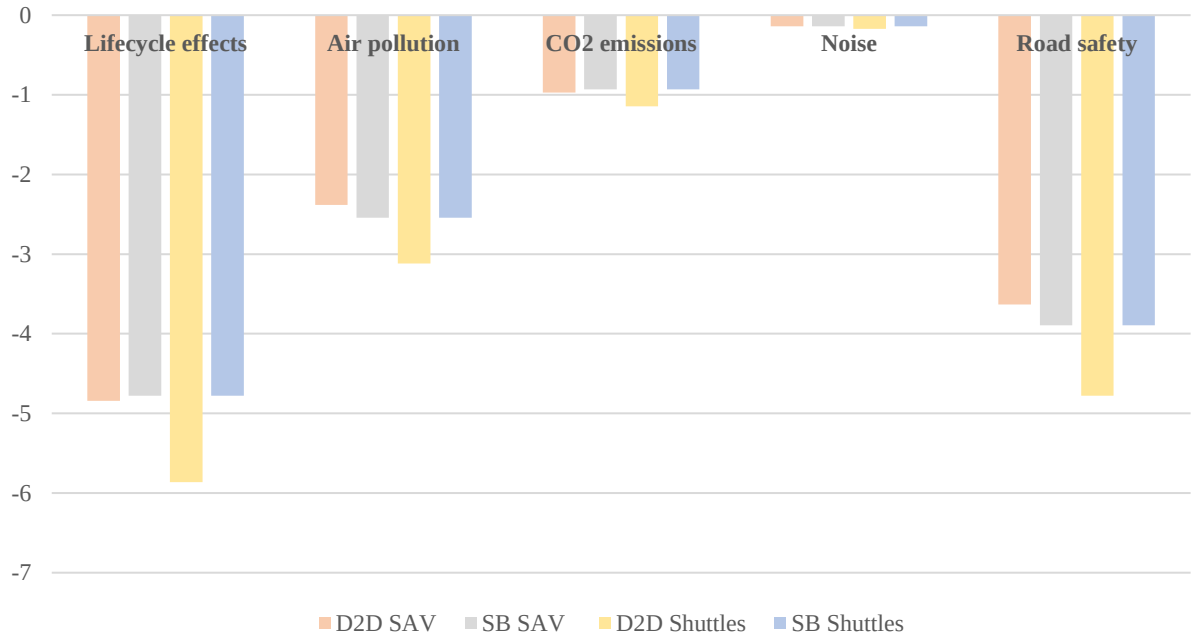

Figure 68. Externalities impact
NB: 10 years term, millions € differences with basecase

Source: prepared by the author.

The externalities impact is negative for all sub-item. Despite a modal shift from private cars, the AVs introduction induce additional VKT. The expected improved driving performances of the AVs are not sufficient to offset the additional traffic. It also seems that the use of Shuttle in D2D has a strong impact on all items of the externalities. The highest rate of emissions and accidents of a heavier vehicle plus the difference of VKT (+25% difference between the SB shuttle and the D2D shuttle scenario) explains such a gap.

The lifecycle impact is the more important, although only the vehicle impact has been taken into account. The infrastructure lifecycle and the supervision impacts should add more weight to the sub-item. The negative road safety impact can be surprising as AVs are considered as betters drivers than humans. (an assumption that we kept), but the VKT increase offset this effect. In this mixed traffic, a 20% decrease of accident per kilometer traveled for AVs has been retained. More optimistic assumption could be made but in different scenarios such as the full replacement of private vehicles fleet. The CO_2 emissions are the least impacting item. The

French energetic mix with a low carbon intensity decrease variation magnitudes.

Despite the implementation of a feeder service, which aimed to reinforce the public transit attractivity by lowering the cost to access train station, all the externalities studied in this work increased.

c) Net Present Value

The Net present value for the four scenarios presents a negative results for all economic agents and the greater loss is amongst the travelers (Figure 69**).** The Consumer surplus is severely impacted by the increase of travel time, and if not positive, it should have decreased less.

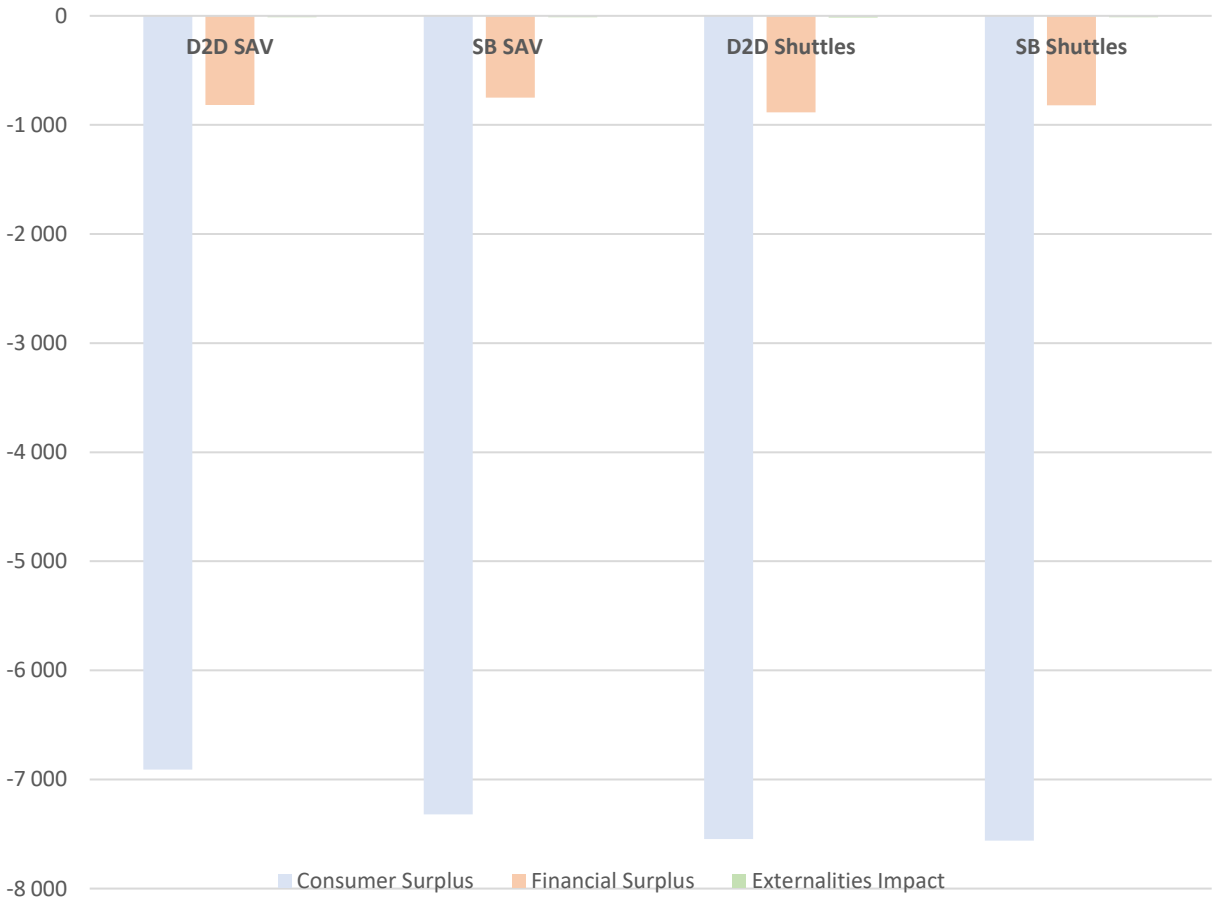

Figure 69. Net Present Value from Equity Value of Time
NB: 10 years term, compared to basecase, millions €

Source: prepared by the author.

However, as seen previously, the Consumer Surplus estimation method had an important impact on the results. As such, the Figure 70 shows the impact of AVs introduction but with the use of behavioral Value of Time (VoT) in the Consumer Surplus estimation. With this consumer surplus estimation method, the D2D scenarios presents a Consumer Surplus which offset the loss in financial costs and the impact of additional CO_2 , local pollution, accidents and noise. The NPV/I for SAV, SB SAV, D2D Shuttle, SB Shuttle is respectively 0,27; -0,01; 0,09 and -0,15.

The reduction of network length to equip for the Stop Based scenario has an important impact on the NPV and also on the NPV/I Figure 70. The four NPV/I are respectively 0,27; 1,67; 0,09; 0,97. The use of a constricted network for a Stop Based service show promising results and should be encouraged.

Figure 70. Net Present Value from Behavioral Value of Time

NB: Net Present Value from Behavioral Value of Time (left), and Net Present Value from Behavioral Value of Time and reduced network for Stop-Based Services (right)

NB2: 10 years term, compared to basecase, millions €. The VoT adjustments based on the GDP/capita rate have not been made. It should decrease the gain of Consumer Surplus.

Source: prepared by the author.

E. Conclusions

In conclusion, this scientific article presents a methodological contribution on the discussion of consumer surplus estimation method, along with three empirical contributions: the implementation of a feeder service, the economic evaluation of AVs in a periurban area, and the consideration of a dedicated Stop-Based infrastructure. The results show that the consumer surplus estimation method plays a crucial role in the outcome the economic appraisal. Despite the implementation of the feeder system to reinforce public transport attractivity, all scenarios present an overall decrease in public transit use (a slight increase in train use but a more important decrease for the buses) as the on-demand service enters in competition with the existing bus lines. The modal shift from buses to this new mode of transportation generates an increase externalities while scenarios where the bus lines would have been deleted may present decrease of externalities. The scenario design bears a limitation in the consideration of this increase of externalities. However, the conscription of the service to feeder operations limited the number of agents which might benefit from the service but it has shown several advantages such an average vehicle occupancy higher than the literature. The SB scenario based on the bus network presents promising results for future development, most notably in case of important infrastructure costs. Overall, these findings contribute to the ongoing discourse on sustainable transport solutions and highlight the need for further research in this field. For the simulation limits, no induced demand (trips which would not have been made if the alternative did not exist) have been generated despite the fact that the integration of an attractive new service is often followed by new trips. The congestion effect measured in this work is higher than might be expected. Electric vehicles were considered in the evaluation whereas no charging behavior has been incorporated into the simulation. The next chapter will introduce AV based services in rural areas, exploring how less densely inhabited area may be impacted.

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G. Appendix

Appendix 1. Utility functions and utility parameters

$$U_{car}(x) = \alpha_{car} + \beta_{travel\,time_{car}} . x_{travel\,time_{car}} + \beta_{travel\,time_{car}} . \theta_{parkingSeachPenalty} + \beta_{travel\,time_{walk}} . \theta_{accessEgressWalkTime} + \beta_{cost} . \left(\frac{x_{crowfly}}{\theta_{averageDistance}}\right)^{\lambda} . x_{cost_{car}}$$

$$U_{pt}(x) = \alpha_{pt} + \beta_{numberOfTransfers} . x_{numberOfTransfers} + \beta_{InVehicleTime} . \beta_{InVehicleTime} + \beta_{TransferTime} . x_{TransferTime} + \beta_{accessEgressTime} . x_{accessEgressTime} + \beta_{cost} . \left(\frac{x_{crowfly}}{\theta_{averageDistance}}\right)^{\lambda} . x_{cost_{pt}}$$

$$U_{bike}(x) = \alpha_{bike} + \beta_{travel\ time_{bike}} . x_{travel\ time_{bike}} + \beta_{age_{bike}} . Max(0, \alpha_{age} - 18)$$

$$U_{walk}(x) = \alpha_{walk} + \beta_{travel\ time_{walk}} . x_{travel\ time_{walk}}$$

$$U_{aMoD}(x) = \alpha_{pt} + \beta_{travel\ time_{pt}} . x_{travel\ time_{av}} + \beta_{transfer\ time_{pt}} . x_{waiting\ time_{av}} + \beta_{cost} . p_{av} . x_{networkDistance_{av}}$$

Car	α_{car}	1.35	
	$\beta_{\text{travelTime,car}}$	-0.0667	$[\text{min}^{-1}]$
Public Transport	α_{pt}	0.0	
	$\beta_{\text{numberOfTransfers}}$	-0.17	
	$\beta_{\text{inVehicleTime}}$	-0.017	$[\text{min}^{-1}]$
	$\beta_{\text{transferTime}}$	-0.0484	$[\text{min}^{-1}]$
	$\beta_{\text{accessEgressTime}}$	-0.0804	$[\text{min}^{-1}]$
Bike	α_{bike}	0.1	
	$\beta_{\text{travelTime,bike}}$	-0.15	$[\text{min}^{-1}]$
	$\beta_{\text{age,bike}}$	-0.0496	$[\text{a}^{-1}]$
Walk	α_{walk}	1.43	
	$\beta_{\text{travelTime,walk}}$	-0.09	$[\text{min}^{-1}]$
Others	β_{cost}	-0.206	$[\text{EUR}^{-1}]$
	λ	-0.4	
	$\theta_{\text{averageCrowflyDistance}}$	40	[km]
Calibration	$\theta_{\text{parkingSearchPenalty}}$	4	[min]
	$\theta_{\text{accessEgressWalkTime}}$	4	[min]

Table 39. Parameters of the discrete mode choice model

Source: Hörl, S., Balać, M., Axhausen, K.W., 2019. Dynamic demand estimation for an AMoD system in Paris. https://doi.org/10.1109/IVS.2019.8814051.

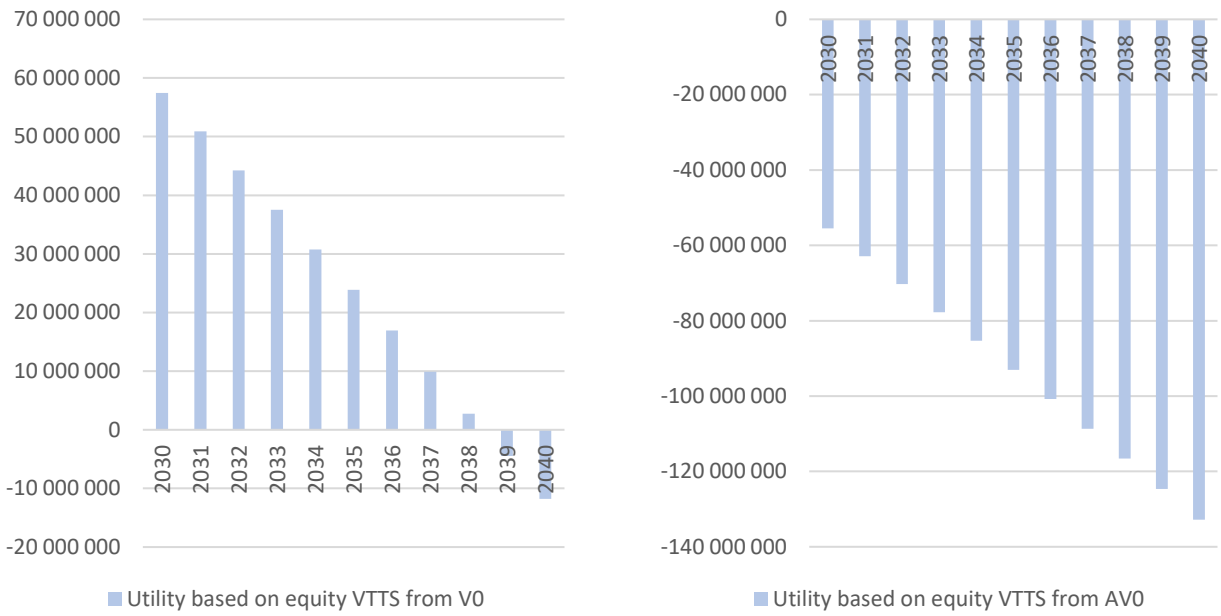

Figure 71. Sub-items utility evolution during time from the basecase scenario V0 (unit in millions)
Source: prepared by the author

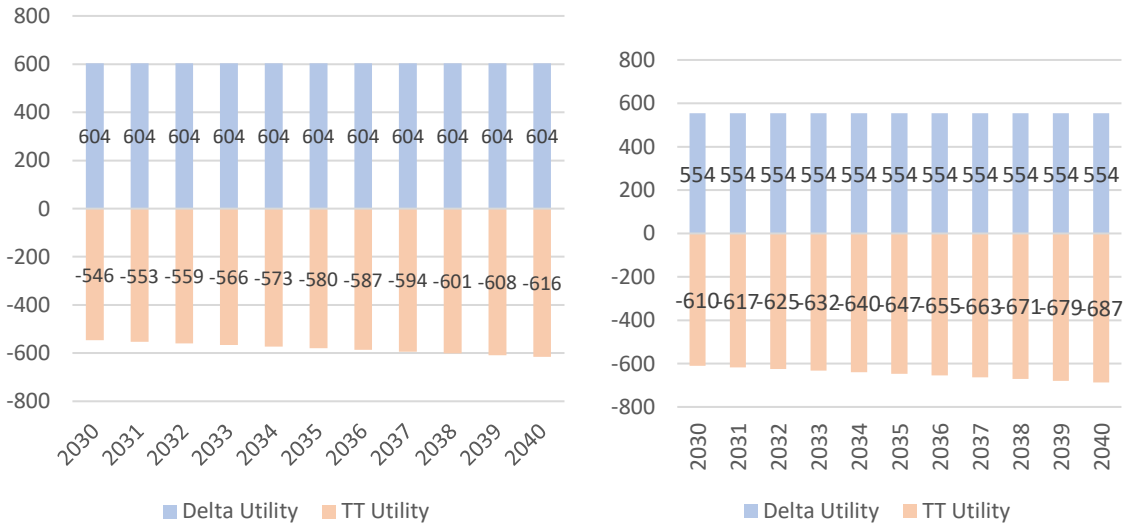

Figure 72. Sub-items utility evolution during time from the basecase scenario V0 (left) and the scenario AV0 (right, unit in

millions)bug

Source: prepared by the author

Figure 73. Gains (or losses) repartition amongst agents for the D2D SAV scenario.

Source: prepared by the author

IV. On-demand Autonomous Vehicles in rural territory: a Cost Benefit Analysis

Abstract

Rural areas, characterized by sparse population and employment density, primarily rely on conventional cars for mobility needs. This study introduces on-demand autonomous vehicle (AV) services to evaluate their economic viability in low-density regions. The research integrates mobility simulations with Cost-Benefit Analysis to comprehensively assess the potential of AVs. Results indicate that AVs find difficulties to compete with conventional cars, which offer no waiting time or shared rides. The economies of scale do not favor AVs in low-density areas as much as in denser counterparts. Simulations reveal a decrease in average vehicle occupancy, making it economically challenging to support dedicated infrastructure. While AVs could benefit specific demographics like people with reduced mobility, non-car owners, or those without a driver's license, it might shrink the overall customer base. Successful AV integration in these areas hinges on managing infrastructure costs, potentially necessitating subsidies to retrofit existing conventional road infrastructure for AV compatibility.

Keywords: Autonomous vehicles, mobility simulation, economic evaluation, transport, cost benefit analysis

A. Introduction

The development of AVs has led to scenarios in which AVs services could be deployed in rural area, where car alternative remain scarce. Many challenges await AVs in these areas. In France, rural areas are known to host a more important share of elderlies, which may encounter difficulties to adopt high-tech new mode of transportation. From an economical perspective, the demand density may limit the ridesharing ability of these service for both consumer (longer detours and waiting time) and operator (lower profitability due to diseconomies of scale). The aim of this chapter is to understand if AV services may find a place in the mobility landscape of rural areas through simulations and an economic appraisal. As seen in (Carreyre et al. 2022), the simulation literature has shown less interest for the these territories, out of the 84 retained works on the topic of AVs simulations, only two were addressing the topic of rural areas (Viergutz and Schmidt 2019; Sieber et al. 2020) and far less economic studies have been performed. However, the introduction of such services could allow to benefit a larger population than the car users such as the previously mentioned elderlies or the youngers, which are dependent on public transit, bike and walk until they become of age to drive themselves. However, introduction of such services also need to be financially assessed and submitted to environmental appraisal. To overcome the limitations of AVs experimentations which focus on technical development, mobility simulations are used to forecast travel behavior, modal shift and trips characteristics when on-demand AVs service are deployed in a rural area. AVs service will be deployed in both share and solo ride routing form. An economic analysis, based on the French economic Cost Benefit framework is pursued to assess consumer surplus, operators profits and externalities impact. This chapter contributes to the simulation literature on introduction of AVs in rural areas. It also helps to define a hierarchy between AV services from an economic perspective. This service brings attention to the magnitude of infrastructure costs in low density areas.

B. Method

The methodology relies on a two-step simulation-to-evaluation pipeline. Simulation is carried out using the MATSim agent-based mobility model, which allows to derive traffic and operational forecasts for the introduction of AV services. These forecasts are then used to carry out the economic evaluation based on the Cost Benefit Analysis (CBA) methodology, which we adapt to the case of AV services.

1) Model

a) MATSIM

MATSim is an agent-based mobility simulation framework (Horni et al. 2016). The use of an agent-based model allows to have a good representation of on-demand services (Carreyre et al. 2022). It allows to simulate various mobility systems in large geographical areas. MATSim is activity-based, it relies on a fine-grained description of a population of agents that comprises a set of activities with location and time attributes that the agents need to perform. They consequently perform trips between the different activities on the relevant times. The road network as well as the mobility systems being capacitated, congestion effects are reproduced and a competition for resources takes place.

b) Equasim

Eqasim is a discrete mode-choice extension of MATSim which introduces a discrete mode choice model instead of the MATSim co-evolutionary algorithm. Based on utility functions and previous iterations travel outputs (travel time, waiting time…), agents may change modes until an equilibrium is found. Compared to MATSim, this mode choice system has the benefit to be based on multinomial logit model, which has been developed in 1974 (McFadden 1974). The academic community has worked on the topic ever since (Ben-Akiva et al. 1985; Train 2002; "Discrete Choice Models" n.d.). (Hörl, Balac, and Axhausen 2018; Hörl 2021) have conceived bridges between the discrete choice models and modal choice model and implemented them in MATSim, an agent-based model. This discrete mode choice also allows to run simulations faster (Hörl, Balac, and Axhausen 2019).

The mode choice is based on utility functions and constraints. If the tour (i.e. the sum of daily trips) respects the constraints, the probability to use the modal alternative i for each trips is based on the following formula:

$$P(i) = \frac{\exp(\hat{u}_i)}{\sum_{i\prime} \exp(\hat{u}_{i\prime})} \quad (1)$$

$P(i)$: probability to chose to alternative i

$\hat{u}_i$: estimated utility of alternative i

$\sum_{i\prime} (\hat{u}_{i\prime})$: estimated utilities of all i alternatives

The tour must respect the following constraints:

- Vehicle continuity: vehicles are located and must be used at their final known location
- Person-based attributes: car ownership or driving license

The utility functions used originate from (Hörl, Balac, and Axhausen 2019) and can be found in appendix Table 39.

c) DRT

MATSim allows to simulate and study Mobility-on-Demand systems through the DRT Module (Maciejewski and Nagel 2013). The latter provides the implementation of an on-demand fleet from which users can request trips in an online manner. A vehicle assignment strategy is then used to select a vehicle to perform the submitted request. The strategy implemented by default tries to find the best way to insert he request in a vehicle's plan. The insertions are evaluated given the expected arrival time for the passenger and constrained by the vehicles' capacities as well as service level requirements: maximum waiting and travel time as well as a detour factor in case of a shared trip (difference between unshared and shared distances) which allows to consider the cost of ridesharing. The DRT module also defines a pricing scheme for the service. This scheme can be parametrized to consider a cost per kilometer, per time, and a minimum fare per trip. Note that the cost per kilometer is applied to the estimated unshared distance and the cost per time to the estimated unshared travel time, which means that the price doesn't increase if the trip is shared in comparison to the trip being unshared. However it also means that the price of a shared trip is not less than an unshared trip. All the parameters used in the following will follow the default parameters (for fare, speed, vehicle size or dispatching strategies) from the DRT module, available in open-source.

During first simulations, the DRT attributions to agents requests were handled by the selectiveInsertionSearch method (similarly with the methodology used in Saclay). It incurred very high rejection rate (up to 90%), even with an available number of vehicles higher than the number of requests. It has been resolved using the ExtensiveInsertionSearch method.

2) Cost Benefit Analysis

The Cost Benefit Analysis (CBA) is a systematic and quantitative method to evaluate transport projects. It attempts to quantify "*the change in the well-being of the individuals living in the society, and this involves calculating, in monetary terms, the magnitude of the potential […] gains compared with the opportunity costs of the resources.".* The theorical background is well covered (de Rus et al. 2020; Boadway 1974; Boardman et al. 2017; OECD 2018). Several criticism and works had risen the last several decades (Asplund and Eliasson 2016; Börjesson and Eliasson 2019; Beria, Maltese, and Mariotti 2012) which led to incorporate topics such as equity in the process. The replicability of the method and its capability to understand the impact of public funds attribution convinced governments to seize this appraisal tool since its introduction in the USA (Flood Control Act, 1936) (Congress 2018). Governments have since published methodological guides (E. Quinet 2013; "Document: Cost Benefit Analysis Guidelines" n.d.; "Cost Benefit Analysis Guidance" 2014) and provided reference values which are regularly updated.

In this paper, we use the French CBA guidelines (E. Quinet 2013), which we adapt by providing a new way to compute the consumer surplus and by providing new reference values for AVs. The structure is divided into three categories (Consumer Surplus, Operator profits and Externalities Impacts), each based on an economic agent and their sub-components (Figure 74Figure 48).

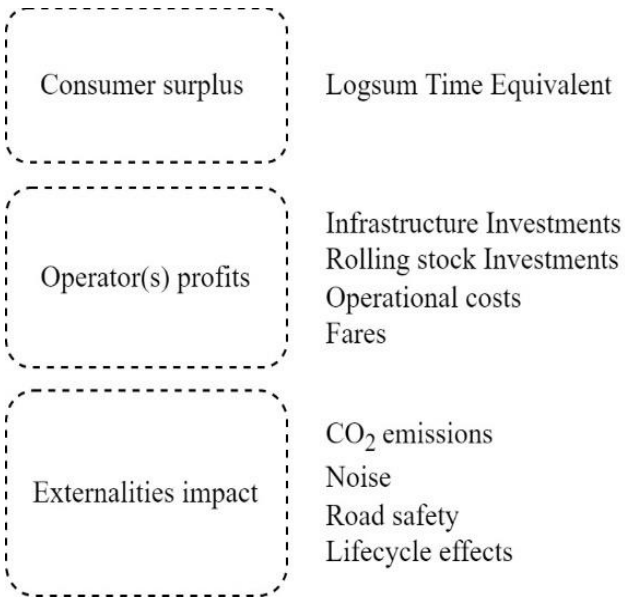

Figure 74. Cost Benefit Analysis sub-components
Source: prepared by the author.

a) Consumer surplus

The Consumer surplus is defined as the monetized value of the utility gains or losses of the mobility consumers. It is based on the logsum methodology, a welfare measure defined as "*the log of the denominator of a logit choice probability, divided by the marginal utility of income, plus arbitrary constants.*" (de Jong et al. 2007). The utility is based on the MATSim plans score according to the methodology developed by (Kickhöfer, Nagel, and Nagel 2016; Kickhöfer 2014). For each agent, the best score is selected and converted into an equivalent monetary term using the marginal utility of income. As all agents do not necessarily have the same value of time and marginal utility of income, a time equivalent approach is used. Based on (Kickhöfer 2014, 54, 55) the overall Consumer Surplus change, with individuals j = 1..J, is:

$$\Delta CS = \sum_{j=1}^{J} \Delta m_j \quad (2)$$

ΔCS is the overall Consumer Surplus change

Δm_j is the monetary compensation required to balance the policy implementation, i.e. the expression of the difference in consumer welfare between both states.

The Logsum expression in Time Equivalent (LTE) can be expressed as follows:

$$\Delta m_j = \Delta t_j \times VTTS_j \quad (3)$$

Δt_j is the number of hours required to counterbalance the policy implementation in agents utility

$VTTS_j$ is the Value of Travel Time Savings (EURO/h)

$$\Delta t_j = \left(\frac{\Delta V_j}{\Delta t}\right)^{-1} \Delta V_j \quad (4)$$

$\left(\frac{\Delta V_j}{\Delta t}\right)^{-1}$ is the inverse marginal utility of time

ΔV_j is the variation of utility between two states, i.e., before and after a policy implementation.

Eqasim has a specific marginal utility of travel time per mode, as such Δt_j is not obtainable. To implement an equity VTTS, the utility from the total travel times (U_{TT}), access/egress/transfer and waiting time included, is obtained from the travel times. It is similar with the 2.15 equation from (Kickhöfer 2014, 55), except that Kickhöfer compensated the difference of consumer surplus between two scenarios with an amount of hours based on the marginal utility of time to reintroduce an equity value of travel time savings. In this work, the equity VTTS is introduced before to compare the utility based on the total travel time, following the same philosophy that *"one could argue that one hour of life time of any individual is equally important for society, and, thus, use some average VTTS for monetization"* (Kickhöfer 2014, 55).

$$U_{B_{TT}} = \sum_{j=1}^{J} \beta_{travel\ time_{mode\ i}} . x_{travel\ time_{mode\ i}} + \beta_{waiting\ time_{mode\ i}} . x_{waiting\ time_{mode\ i}} + \beta_{AET\ time_{mode\ i}} . x_{AET\ time_{mode\ i}} \quad (5)$$

$U_{B_{TT}}$ Total travel time utility based on behavioral VTTS

$\beta_{travel\ time_{mode\ i}}$ marginal utility of travel time for the mode i

$\beta_{waiting\ time_{mode\ i}}$ marginal utility of waiting time for the mode i

$\beta_{AET\ time_{mode\ i}}$ marginal utility of access, egress and transfer time for the mode i

$$U_{B_{TT}} = U_B - U_\Delta \quad (6)$$

U_B: Utility based on behavioral VTTS

U_Δ: difference between the Utility and Utility from total travel time

$$U_{VTTS_{TT}} = \sum_{i=1}^{J} VTTS . x_{travel\ time_{mode\ i}} + VTTS . x_{waiting\ time_{mode\ i}} . WT\ factor + VTTS . x_{AET\ time_{mode\ i}} . WT\ factor \quad (7)$$

$U_{VTTS_{TT}}$: Total travel time corrected Utility based on equity VTTS

$WT\ factor$: correction of the VTTS value to integrate the waiting discomfort

$AET\ factor$: correction of the VTTS value to integrate the access/egress and transfer discomfort

$$U_{VTTS} = U_{VTTS_{TT}} + U_{\Delta} \quad (8)$$

U_{VTTS}= Utility based on equity VTTS

This operation allows to not only integrate an equity value for the valuation of time but also to bear this translation only on the travel time and not on the utility difference between scenarios as it is defined in (Kickhöfer 2014). This utility difference between scenario integrates items such as the number of transfers or financial costs (U_{Δ}) which have no justification to be included in the process of introducing equity VTTS. The VTTS parameter is based on the 11,74 euros (2030 euros) (E. Quinet 2013), adjusted each year by a 0.7 elasticity with the GDP per capita rate. Compared to the behavioral value of time for all mode, this equity value decreases the value of time of the private cars (19,43 euros/h), the walk (26,21 euros/h) and the bicycle (43,69 euros/h) and increases the one from public transit (4,95 euros/h).

b) Operator profits

The operator(s) profit (π) is the difference between costs, including infrastructure investment and maintenance, rolling stock investment and operating costs, and revenues generated by usage fees, sponsoring, advertising and subsidizing.

There is not yet a consensus regarding the investment and maintenance costs of AV infrastructure. The cost to upgrade the infrastructure to accommodate AVs varies from 3 000 dollars (Saeed 2019) per year and per kilometer to more than two millions dollars (Xue 2022, 10). Similarly, maintenance and replacement costs should be based on feedbacks of previous deployments and are thus only roughly estimated as for now. Consequently, these costs will be analyzed in this paper through a sensitivity analysis assuming that the investment cost (I_{infra}) varies from 50,000 to 250,000 EUR/km and that maintenance and replacement costs (M_{Infra}) are based on a yearly replacement rate of 10 to 50% of the

investment cost to 50% (i.e., 50% means that the infrastructure will be fully replaced every two years). The infrastructure length is noted as Km_{Infra}.

The general consensus on the price tag of automated vehicles is that their price is marked up compared to conventional vehicles (Andersson and Ivehammar 2019; Bauer, Greenblatt, and Gerke 2018; Becker et al. 2020; Ongel et al. 2019; Quarles and Kockelman 2018; Tirachini and Antoniou 2020; Wadud 2017; Wadud and Mattioli 2021). The most extensive study on light vehicles such as cars or shuttles can be found in (Becker et al. 2020). Automation is supposed to add 5,000 US dollars to the vehicle price. A similar assumption can be found in (Wadud 2017), who report that automation would cost 5,000 dollars or 3,000 dollars in the second-hand market. A more recent study that builds on previous advances on the subject (Wadud and Mattioli 2021) indicated that automation would cost between 9,400 £ and 15,000 £ more per car. (Tirachini and Antoniou 2020) assumptions on automation costs are more pessimistic, as they proposed that automation would cost between 36% and 86% more, depending on the vehicle. The +36% to +86% markup estimates are consistent with the variation in absolute value found in (Becker et al. 2020; Wadud and Mattioli 2021) based on the 26,000 euro average selling price of a new car in France (Leroy 2021). The total markup estimated for AVs is 7,500 euros per vehicle.

For EVs, (Bösch et al. 2018), on which the study by (Becker et al. 2020) is based, do not consider any markup compared to thermal vehicles. Similar to (Wadud and Mattioli 2021), the electric impact can be found in the operational, maintenance and insurance costs, but no purchase price variation seems to be applied. (Ongel et al. 2019) forecasted the purchase price of Internal Combustion Engine Vehicles (ICEVs), EVs and AVs for the year 2030 close to the shuttle format. They found that an ICEV should cost between 105,000 and 110,000 (2017 constant) dollars, the electric equivalent should be 20% more expensive and the automated and electric counterparts would be 28% more expensive. The estimated price for the AE shuttle is 128,000 euros with a 100,000 euro ICEV equivalent. For cars, (Mitropoulos, Prevedouros, and Kopelias 2017) found a 16% retail price difference between ICEVs (27,130 in 2015$) and EVs (31,590 in 2015$). This value is consistent with the +20% reported by (Ongel et al. 2019). All the aforementioned parameters value can be found in Table 40.

Automation impact vehicle price	Values	Automation impact factor
ICEV car	26,000 €	100%
Electrical car	31,200 €	100%
Automated ICEV Car	33,500 €	+ 29%
Automated Electrical car	38,700 €	+24%
ICEV Shuttle	100,000 €	100%
Automated electric Shuttle	128,000 €	+28%

Table 40. Automation impact factors based on the automation level and vehicle size.

Source: prepared by the author.

The initial rolling stock investment is based on the number of vehicles required (NB_{Veh}) to serve the demand, and the replacement investment on a 300,000 km distance-lifetime of vehicle. The price of an AV is noted as P_{veh}.

(Becker et al. 2020) have produced the most in-depth work on AV operating cost. Considering multiple cities around the world, they provided simulation-backed results for several business models and a large amount of data on cost analysis for private cars, automated taxis and buses. A shuttle cost structure can be found in (Bösch et al. 2018), a paper that also provides more insights into the influence of territory type on costs. (Abe 2019) produces a good overview of the influence of driver costs on the overall costs. The automation savings in operational costs are quite important, as drivers represent an important part of those costs. A total of 29% to 77% of the operational costs can be saved depending on the ratio of supervisors/vehicles required to monitor a taxi fleet (Abe 2019). However, (Becker et al. 2020) hold highly optimistic assumptions on the ability of AVs to drive themselves without supervisors. It seems reasonable that a supervision centre may be needed to regain control of autonomous vehicles that find themselves in situations where human intervention is needed. The supervisor topic has remained underexplored in the literature on AV cost analysis (Scoliege 2021). In the AV financial analysis field, (Nunes and Hernandez 2020) estimated that a supervisor should handle 50 vehicles at once to benefit from the economy of scale. This assumption may need additional discussion as it is not based on studies but rather one projection. As the acquisition costs of AVs are already considered in the investment section for AVs and Automated Shuttles in (Bösch et al. 2018,

fig. Table 2), the depreciation costs (0,054 CHF/km and 0,14 CHF/km) are deducted from the initial 0,48CHF/km and 0,98CHF/km (Bösch et al. 2018, 89). These operational costs are converted to euros and discounted. No supervision cost is considered, which is corrected by adding a +0,05 EUR per Vehicle Kilometer Traveled (VKT). The revenues for the operator will be the results of the fare revenues (F) of the operations. All the aforementioned parameters value can be found in Table 41.

Mode	Invest Infra (per km)	Maintenance Infra Yearly Invest % cost	Vehicle Price	Operating costs (per km)
Private EV	-	-	-	Integrated in CS
Ride	-	-	-	Integrated in CS
SAV (car)	50k-250k €	10%-50%	38 700 €	0,45 €
AV Shuttle	50k-250k €	10%-50%	128 000 €	0,80 €

Table 41. Operator(s) profits parameters

Source: prepared by the author.

NB: The Public Transit are not considered here as their level of service remains equivalent between scenarios. In this case, no differences could be found, whatever the financial parameters values.

Finally, the profit could be expressed as:

$$\pi = F - \begin{pmatrix} \left(I_{infra} * Km_{Infra}\right) * \left(1 + M_{Infra}\right) + NB_{Veh} * P_{veh} \\ + \frac{VKT}{300000} * P_{veh} + VKT * OC \end{pmatrix} \quad (9)$$

c) Externalities impacts

Externalities of AV (Ext) are divided into four sub-components, based on the segmentation by (E. Quinet 2013). Air pollution is not included as all AV vehicles are assumed to be electric.

The political trend restricting thermal vehicle use in European cities (see the low emission zones in Italy, the UK or Paris) makes the development of AVs under thermal propulsion unlikely. Electric and hydrogen vehicles are good candidates, but the development of hydrogen

vehicles does not benefit from the same support as that of EVs. AVs will then be considered electric. For CO^2 emissions, (E. Quinet 2013) provides a monetary value for every ton of CO^2 emitted for every year. This value has been reviewed in (A. Quinet 2019) and fixed at 250 euros. For electric vehicles (EVs), general data need to be interpreted with caution. Electricity consumption is not a direct source of GHGs, but its production is often carbon-based. The mix of energy sources is heavily dependent on geographical political choices. Emissions for EVs or hybrid vehicles will need to be adapted for every use case with similar data to those in (E. Quinet 2013), (Buehler 2014), (Jochem, Babrowski, and Fichtner 2015), or (Jöhrens et al. 2020). The automation impact remains uncertain, as (Liu et al. 2019) point out. In the best-case scenario, a 13.28% reduction could be applied to the fuel consumption of EVs, in contrast with the worst-case scenario, which could increase the fuel consumption by 11.63%. However, Liu estimated that ten percentage points could be saved from the worst-case scenario by limiting speed limits alone. The difference between an automated car and a shuttle vehicle may have an impact on electricity consumption. (Jöhrens et al. 2020, 58) detailed electricity consumption levels based on vehicle size. Automated cars with four to five seats are assigned to the "Small Cars" category, with a consumption of 19.7 kWh/100 km, and automated shuttles are assigned to the "Large Cars" category with a 23,6 kWh/100 km consumption. A ratio of 1.19 based on the relative overconsumption of the shuttle is applied. A 5% fuel consumption is estimated for AVs compared to their strict equivalents, conventionally driven-EVs. The CO_2 emissions include the valuation of all CO_2-equivalent emissions from the use phase of the vehicle lifecycle (Em_{veh}). Private cars emissions are based on German emission for 2030 (Jochem, Babrowski, and Fichtner 2015).

The Lifecycle effects include the valuation of all CO_2-equivalent emissions made during the manufacturing and end-of-life phases, as the use phase is already covered.

In (Kemp et al. 2020), the materials and manufacturing (MM) phase represents 27% and the End-of-Life (EOL) phase represents 1% of the 42 ton of a the lifecycle emissions of an EV. The Use phase, counting for 72% is not accounted for in the lifecycle item as this work has already considered these emissions, the emissions due to the use part of the vehicle life will be subtracted from the lifecycle analysis. The automation sub-system is considered to add 1055 CO_2eq kg. Previously mentioned studies did not include AV shuttles in their scope. (Held and Schücking 2017) introduced the topic. As such, a value of 20,000 kg was estimated for a shuttle ("BEV

(minivan) RheinMobil, elec.-mix" (Figure 3), minus the "charging electricity" item, which is similar to the "Use phase" from (Kemp et al. 2020)). The same automation burden of 1055kg is added to the Shuttle system. All vehicle lifetime is estimated to be 300 000 kilometers, an assumption close to the 200 000 miles in (Kemp et al. 2020). The value of the CO_2eq ton is fixed at 250 euros, accordingly to the Quinet report for 2030. The retained values (V_{LCE}) (0,95 euros for EVs, 0,97 for AVS and 1,75 euros for autonomous shuttles) are close to the 0,9 euros value fixed by (E. Quinet 2013) for a private car. One could have expected a higher value as EV are known to have an heavier environmental impact during the MM phase.

The noise externality is taken into account as the inconvenience that the road traffic might cause (E. Quinet 2013). (Taszka and Domergue 2017) found a -50% effect of the noise externalities due to electrification. Automation was not considered as a lever to reduce noise impact (N_{Impact}) based on (Patella, Aletta, and Mannini 2019) recommendations. Lastly, road safety is considered as AV are also expected to decrease accidents rates. (Papadoulis, Quddus, and Imprialou 2019) found that under a 100% market share of AV on motorways, conflicts can be reduced from 82% to 92%. Less optimistic, Kitajima et al. (2019) used an agent-based model to estimate human-based errors leading to crashes. They found an 18% reduction in collisions, but they warned of the need to consider their results with caution. Mahdinia et al. (2020) also found that automation would lead to a reduction in both driving volatility and time-to-collision, which would significantly affect accidents. (Tafidis et al. 2021) have performed the latest literature review on the topic to date. The fact that their review includes only 24 papers is due to the novelty of the topic. No overall consensus can be found, but most of the papers highlight an improvement in road safety thanks to automation. These results are based on assumptions and may need to be evaluated as soon as field data become available. A conservative approach was adopted, assuming a reduction of 20% of all crashes/VKT. The value of a statistical life is set at 3 million $€_{2010}$ according to Quinet (2013). The type of territories and vehicles will be taken into account, as they have important roles. The rate of accidents/traffic should be available for each case; otherwise, the 2019 rate in France will be used as a reference (ONISR 2019, 18), with 5 deaths per billion vehicle kilometers travelled. All the aforementioned parameters value can be found in Table 42.

Externalities per 100km	Carbon cost	Air pollution	Vehicle Lifecycle	Noise impact	Road Safety
Private EV	1,45 €	0,78 €	0,95 €	0,0005 €	0,0134 €
SAV	1,38 €	0,63 €	0,97 €	0,0005 €	0,0107 €
Difference compared to EV	*-5%*	*-19%*	*+2,1%*	-	*-20%*
Aut. Shuttle	1,64 €	0,99 €	1,75 €	0,0005 €	0,0107 €
Difference compared to EV	*+13,05%*	*+27%*	*+84,2%*	*0%*	*-20%*

Table 42. Externalities impact parameters

Source: prepared by the author.

Consequently, the externalities could be calculated using:

$$Ext = Em_{veh} * VKT * P_{CO_2} + V_{LCE} * VKT + N_{Impact} * VKT + V_{SL} * AR_D * VKT \quad (10)$$

d) Indicators for scenarios comparison

The comparison of scenarios is performed on three different levels: the macroeconomic level, the economic agents' level and the consumer level (Figure 75).

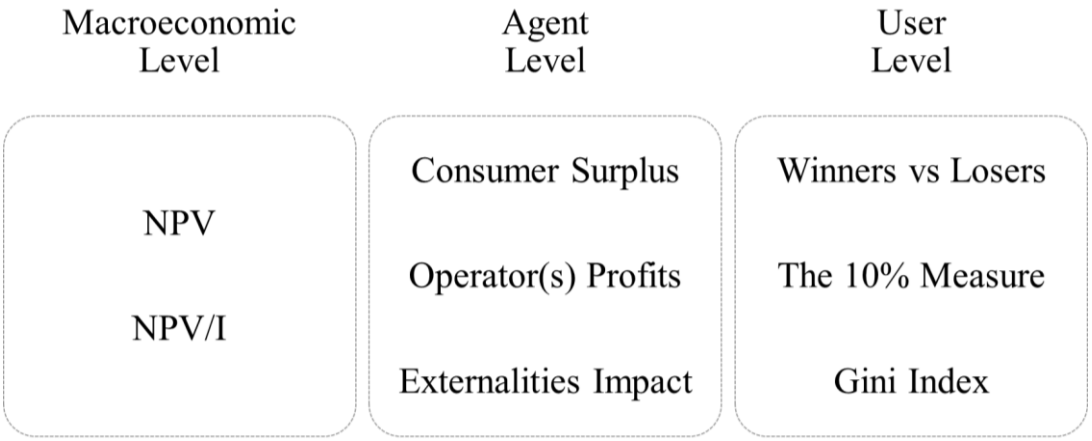

Figure 75. Scenario comparison methodology

Source: prepared by the author.

Comparison at the macroeconomic level is made using the social Net Present Value, "equal to the sum of the change in social surplus or the sum

of changes in willingness to pay and changes in resources" ((de Rus et al. 2020, 28)). All cost and benefits considered in the NPV are not financial costs but also consumer surplus and externalities gain or loss.

$$NPV_s = \sum_{t=0}^{T} \delta^t (B_t - C_t) \quad (11)$$

NPV_s: social Net Present Value

δ^t: Nominal discount rate of period t

B_t: Aggregated Benefits from period t

C_t: Aggregated Costs from period t

Based on (de Rus et al. 2020), the inflation rate (φ) is applied at the same level as the discount rate, introducing the real discount rate instead (r_R) of the nominal discount rate (δ^t):

$$r_R = \frac{r_N - \varphi}{(1+\varphi)} \quad (12)$$

An 1% inflation rate value based on the last decade of inflation rate in Europe has been retained. The Ukrainian war have increased to inflation rates to a higher level, but a more conservative and event-free approach is considered here. (E. Quinet 2013) suggests using a 2.5% annual discount rate, which is close to the 3% recommended by the European Commission for most European countries (de Rus et al. 2020, 33). This value may be considered low compared to the amount that may be attributed elsewhere (up to 15 or 18%), but (Mouter 2018) reviewed the discount practices in the Netherlands, United Kingdom, Norway, Sweden and Denmark, where discount rates were distributed between 1% and 4.5%. The discount rate is fixed at the European Commission level of 3%. Further research could explore the difference in price evolution between autonomous vehicles and autonomous vehicle infrastructure, as well as the overall level of prices. (E. Quinet 2013, 173) recommends to adjust the price of statistical life with the GDP per capita evolution which should evolve at a 1.2% rate ("Cadrage Du Scénario de Référence" 2019). It also recommends to adjust the LCA values by the GDP/capita evolution rate but as these values retained in (E. Quinet

2013) are a composition of externalities in CO_2 with global impact and local pollutant but the LCA in this work is based on CO_2eq emissions, we will make our LCA values evolves with the CO_2 values.

The evolution of CO_2 price is defined in (A. Quinet 2019, 124) at 250euros/t in 2030 and 500euros/t in 2040 giving an average annual growth rate (AGR) of +7.18%. The CO_2 emissions/km for EV by ("Cadrage Du Scénario de Référence" 2019) is defined as 68kwh/100km in 2030 and 126 kwh/100km in 2050 giving an AGR of -1.43%. All the aforementioned parameters value can be found in Table 43.

	Discount rate	Inflation	GDP/capita	CO_2 emissions/km	CO_2 value
AGR	+3%	+1%	+1,20%	-1,43%	+7,18%
Impacts	NPV	NPV	Air pollution	CO2 emissions	CO2 emissions
			Road safety		LCA

Table 43. Contextual parameters

Source: prepared by the author.

The second base of comparison is the NPV/Investment which evaluates the social profitability of the investment.

At the agent level, the comparison is performed through the Agents Surpluses, which indicate the transactions between all agents in terms of gains and losses due to the service production

$$aS = \sum_{t=0}^{T} \delta^t (aB_t - aC_t) \quad (13)$$

aS: Agent Surplus

aB_t: Agent level aggregated benefits from period t

aC_t: Agent level aggregated costs from period t

Finally, "Consumers" is the most heterogenous category of our selection of economic agents. The agent-based model MATSim provides an

analysis based on the agents score. Three main indicators are used to give indications on the surplus allocation of each agent.

- Winners versus losers: Repartition of agents with a better situation (winners), a worst situation (losers) or the exact same situation (indifferent) than in the baseline scenario, expressed as a percentage of the agents' population.

- The 10% measure: estimates how much of the consumer surplus due to the project implementation is being captured by the 10% of the agents winning the most, expressed as a percentage of the aggregated positive consumer surplus.

- A Gini Index based on the distribution of gain or loss for each agent.

C. Case study

The choice of the Dourdan region is justified by 1. its availability as the Eqasim model is available in open access which offers the ability to replicate the research and its typology as a rural area (see later).

Aside from the Île-de-France region, from which the model originates, in 2023, no simulation of the specific territory of Dourdan may be found. The French SAM project ("Projet SAM - Sécurité et Acceptabilité de la Mobilité autonome" n.d.) should work on this territory as well.

For the integration of the service, a 20 minutes car accessibility zone from Dourdan has been selected (which will be later call "Dourdan 20' " or "D20' "), with only Ile-de-France communities. The zoning have been made with the interactive mapping tool from "l'Observatoire des territoires" (in English "the territorial observatory") based on INSEE data. As it appears in the Figure 76, a more important zone would have positioned to case study in a more periurban territory.

1) Territory

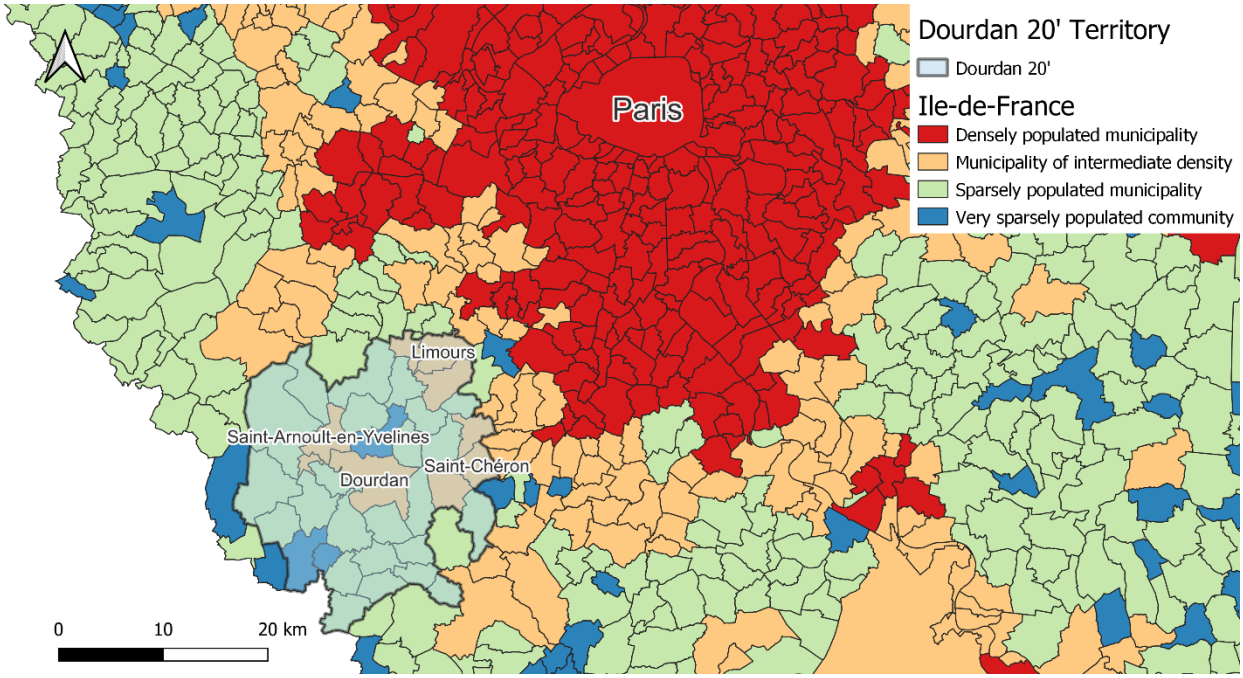

Figure 76. Dourdan 20' position in Île-de-France
Source: INSEE, prepared by the author.

The case study is located 50 kilometers south from Paris. Centered around the Dourdan city which regroups a fifth of the 63 000 people living in the territory for a third of the 15 000 jobs, its creates an imbalance between the Dourdan center which is urban and its areas where the habitation and jobs density is lower. The French national institute of statistics (INSEE) definition of rural integrates all cities belonging to the sparsely populated and very sparsely populated categories ("Une Nouvelle Définition Du Rural Pour Mieux Rendre Compte Des Réalités Des Territoires et de Leurs Transformations – La France et Ses Territoires | Insee" n.d.).The territory is structured with the Dourdan at the center of the zone, surrounded by rural territories (see Figure 76).

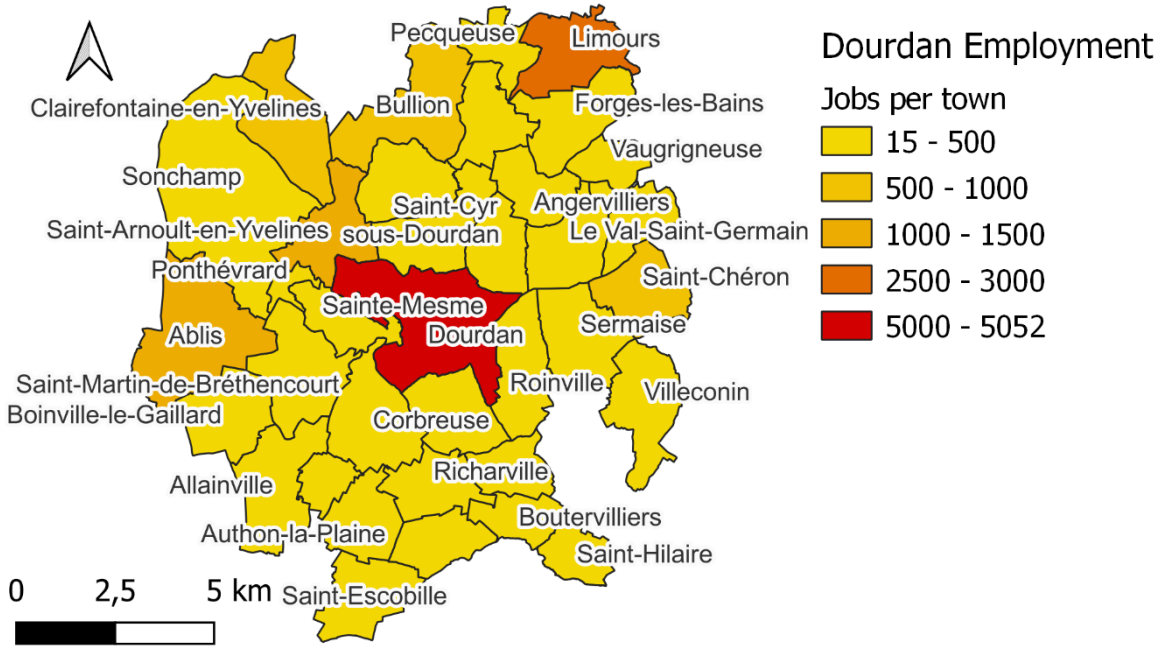

Figure 77. Dourdan 20' employment
Source: INSEE, prepared by the author.

Jobs density are structured around three main points (Dourdan, Saint Cheron and Limours, see Figure 77). RER C, one the major train line in Île-de-France, links Dourdan to Saint-Chéron and further to the Parisian downtown. The A10 is known to a heavy traffic highway due to a junction with the A11 and Saint-Arnoult-en-Yvelines the second most important highway toll station in Europe with its 38 gates (https://www.facebook.com/actu.fr 2022). The presence of the A10 highway may imply that many commuters will either be arriving, leaving or passing through the D20' zone (Figure 78).

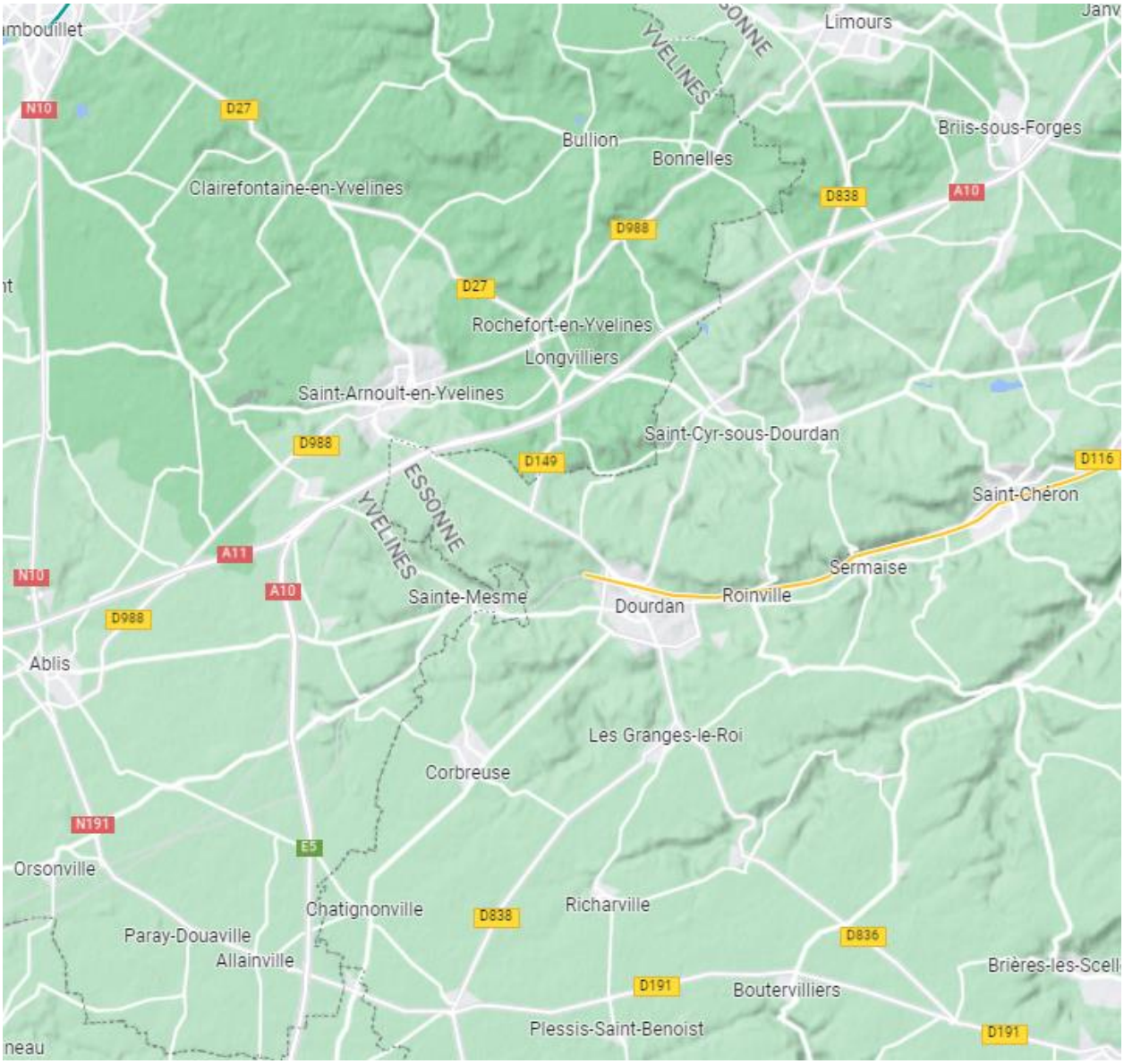

Figure 78. RER C and road infrastructure of the Dourdan 20′ zone
Source: Google maps
Caption: RER C in yellow

2) Île-de-France Eqasim

(Hörl, Balac, and Axhausen 2019) developed a model specific for the Île-de-France territory based public data. The pipeline to constitute such model is described in detail in (Hörl and Balac 2021). A 20% synthetic population has been used to speed the computational times. The process for this rural case study was to cut a 20′ minutes car accessibility around the Dourdan city and introduces an on-demand autonomous vehicles service. At first a 25′ car accessibility zone has been cut and a 20′ AVs

introduction zone was retained to keep liberty to later test other scenarios (with an higher service coverage for example) and to maintain the same scenario evaluation scale. However, simulations were subject to edge effect where people from the 25' zone were coming by walk to get access to AVs in the 20' service zone.

3) Scenarios

The territorial definition of rural territory by the INSEE (French National Institute) is based on the population density which implies a low-density demand. Public transit usually relies on economies of scale which appears when it is possible to massify flows. Rural territories are well known to be heavily reliant on cars (Camarero and Oliva 2019) which are convenient for providing a flexible and point-to-point mobility solution. As such, the scenarios in this case study focus on door-to-door (D2D) services. The capacity to massify flows is also a challenge in rural areas. Half of the AV integration scenario will be done under a private drive operational scheme in order to compare the level of service between a private ride ("AV" scenarios) and a shared ride ("SAV" scenarios) schemes in a rural area.

In this thesis, the experimentation of Stop-Based (SB) routing is present in the other case studies but they are not experimented in this case study. The SB routing is an "*on-demand Stop-Based system is a hybrid between conventional public transit and on-demand door-to-door services. Boarding/alighting is only permitted at stations. Again, the vehicle can be either shared or used privately"* (Carreyre et al. 2022). The implementation of AV introduction aims to substitute car trips which requires a strong level of attractivity. As shown (Carreyre et al. 2022; 2023), the SB routing has been identified as less attractive than the Door-to-Door routing and therefore will not be experimented.

The 300 vehicles fleet size (at 20% scale) is based on the first fleet size to reach a sub-five percent rejection rate for AV request with 100 vehicles steps. The parameters used for these simulations were the default ones. The ride must be done in a D2D scheme, with a 10 minutes waiting time constraint, a fare of 0,3 euros per kilometers traveled and ridesharing enabled. This method allows to remain around the 5% rejection rate threshold for the following simulations when the DRT service attractivity were to be altered.

The scenario set (see Table 44) is composed as follows:

1. Basecase: Reference scenario, based on (Chouaki, Hörl, and Puchinger 2023) paper.
2. AV: A free D2D private ride AV service,
3. SAV: A free shared D2D AV service
4. 0,3 AV: A 0,3euro/km private ride D2D AV service
5. 0,3 SAV: A 0,3euro/km D2D shared AV service

Scenario	Name	Description	Ride-sharing	Routing	Capacity	Fare (€/km)	Fleet size
V0		Basecase scenario	N/A	N/A	N/A	N/A	N/A
AV0	AV	AV	No	D2D	1	0	300
AV1	SAV	Shared AV	Yes	D2D	4	0	300
AV2	0,3 AV	Solo AV	No	D2D	1	0,3	300
AV3	0,3 SAV	SAV	Yes	D2D	4	0,3	300

Table 44. Simulations and evaluation sets

Source: prepared by the author.

D. Results

1) Simulations Results and Discussion

a) General Results

The most surprising result is the fact that the introduction of a new mode which shares similar attributes with the private cars, the most impacted modal alternative is the walk (see Figure 79). Despite cars being the most popular mode of transportation, (which represents ~55% of the modal share), the walk mode (21% modal shares) loses three times more trips to AVs (between 3 and 5% modal share depending on the AV attractivity of the scenario) than cars. The modal shift can be explained by reduced time travel, from which walk travelers had a lot to gain from (see Figure 79). The travelers which choose to switch modes were the ones doing the longer trips, with the introduction of AVs the average distance walked per trip decreased from 1,3km to ~1,15km. This pool of walk travelers in a rural areas might come from the most densely inhabited parts of the case study, from which most of the AV trips originate and terminate (see Figure 80). All modes considered, the overall total travel time (TTT = waiting

time+access/egress time+in-vehicle time) decreases between -3,1% and -5%, despite an increase of 6,3% to 8,8% for the car travelers. The better AVs quality of service allowed to reduce the traveled time of those who had changed from slow modes of transportation (i.e. walk, bike and public transit) to AVs but increased the total VKT (car+AVs, see Figure 81). This VKT increase can be explained be two factors, first the modal shift from the aforementioned modes but also the 9% to 17% empty kilometers traveled by the on-demand service (see the later Figure 85). This increase of VKT might be the explanation of increase of travel time for the car users. As seen previously, AVs trips are largely localized in the most urbanized areas of the territory, which are also origin and destination of car users and the most likely to suffer from congestion. The congestion conjunctures are also backed by (Kaddoura, Bischoff, and Nagel 2020) which found that congestion increased by the city center. All the aforementioned effects intensity increase with AV attractivity, i.e. when the AVs are free compared to when travelers needs to pay 0,3 euros/km traveled. In conclusion, the simulation results indicate that on-demand AVs present a viable option for travelers of all modes in rural areas. However, it is anticipated that the deployment of AVs would primarily benefit those individuals who previously relied on active transportation modes such as walking, cycling, or public transit in highly populated regions. Conversely, users of private vehicles would experience a significant increase in their travel time despite a reduction in the distance traveled, potentially attributable to the additional VKT generated by AVs in the more densely populated areas. This potential increase in congestion has been mentioned in empirical studies, governmental reports or literature studies (DGITM. Direction générale des infrastructures 2018; Madelenat and Grisoni 2021; Zhao and Kockelman 2018; Bahamonde-Birke et al. 2018; Gurumurthy, Kockelman, and Simoni 2019; Simoni et al. 2019; Javanshour, Dia, and Duncan 2019).

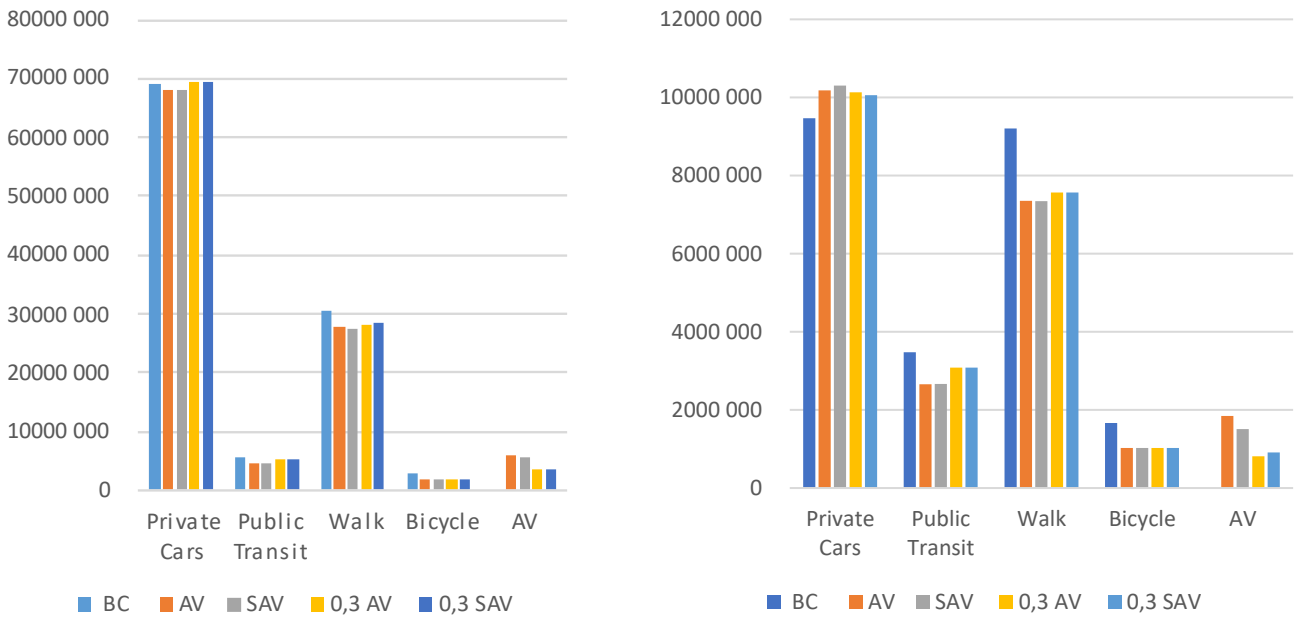

Figure 79. Trips per day (left) and Travel Time (right)
Source: prepared by the author.

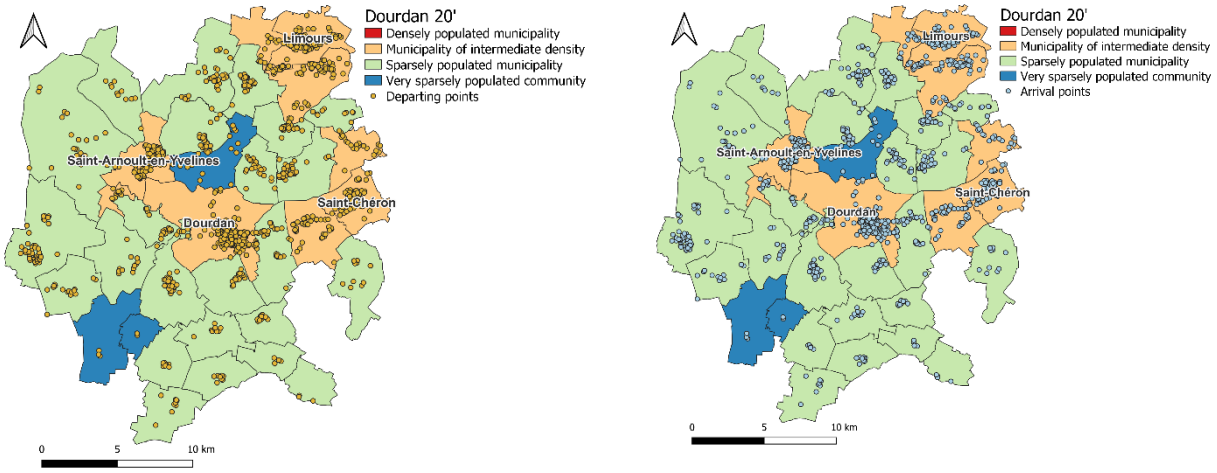

Figure 80. DRT trip departures (left) and arrival points (right) from AV1 scenario.
Source: prepared by the author.

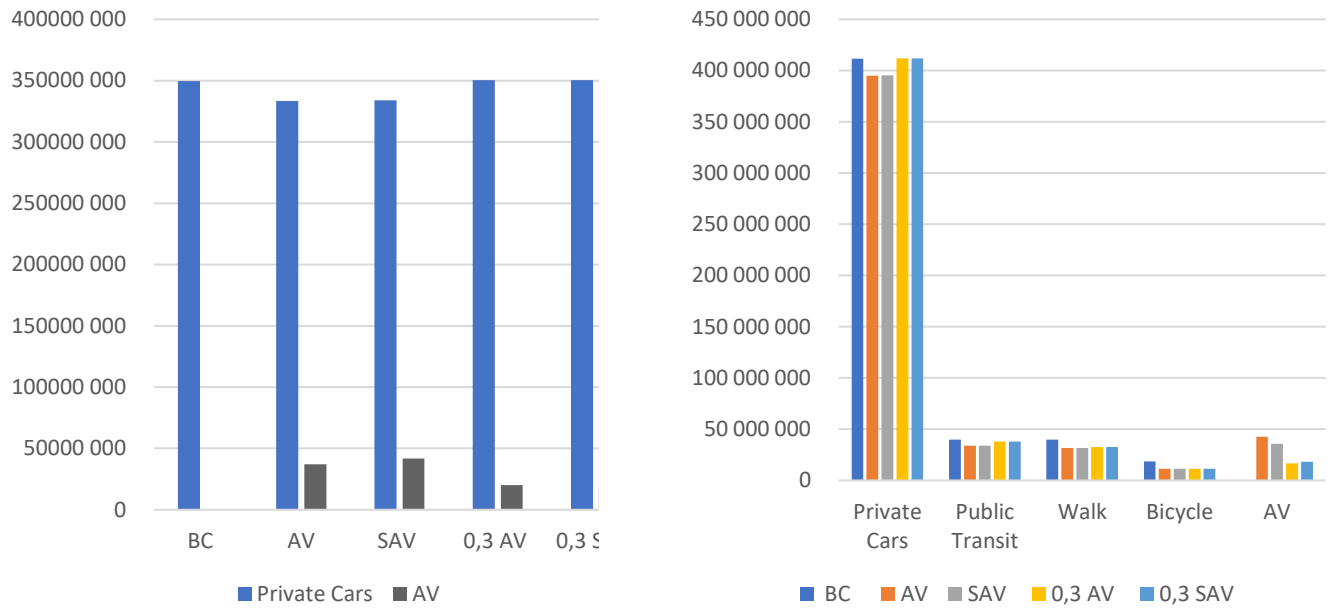

Figure 81. Vehicle Kilometer Traveled (left), Distance Traveled (in pass.km, right)
Source: prepared by the author.

b) DRT Focus

The most important results is the efficiency of SAVs compared to AVs. SAV are more attractive (Figure 82), allow to serve more demand (see Figure 82) with less vehicles (see Figure 84) and less VKT (see Figure 84). The basis of this efficiency comes from their ability to serve multiple demands at once, even if the service struggles to serve more than two rides at the same time (Figure 85). For the SAV scenario, the average vehicle occupation (AVO) of 1,15 is 33% higher than the AV scenario of 0,86 person per vehicle (Figure 85). The 0,3 SAV scenario loses more AVO (down to 1,04) than the 0,3 scenario (0,83), which exhibit the ability of shared on-demand services to benefit economy of scale when the demand increases. As mentioned previously, SAV struggles to serve multiple demands at once, only 3% and 2% (respectively SAV and 0,3 SAV scenarios) of the kilometers traveled are achieved with more than 2 passengers. These results are consistent with the literature which found that the on-demand AVs AVO remained at a relatively low level. Moreover, literature (Soteropoulos, Berger, and Ciari 2019) found that in low-density areas, the share of empty-kilometers travelled was higher than for urban area. The expected ability of on-demand AVs to diminish congestion had two levers. The first lever is the ability to share vehicles sequentially, i.e. to serve more rides distributed

throughout time (i.e. increase the number of trips that a vehicle would do on a determined period of time) than unshared conventional cars. The second lever is the ability to share vehicles simultaneously, i.e. to serve multiple rides at once (massify flows) assuming that detours would represent less traffic than additional rides. In this work, the second lever is considerably weaker (maximum value reach being 1,15 average person per vehicle) than the first lever for which AVs can serve between 7 to 12 rides per day. These results concords with literature findings (Leich and Bischoff 2018; Berrada 2019; Zachariah et al. 2014; Gurumurthy, Kockelman, and Simoni 2019; Farhan and Chen 2018; Vosooghi 2019) indicating that vehicles were rarely filled by more than two persons.

The attractiveness of SAV compared to AV (Figure 82) remains difficult to understand when considering the lower level of service that they provide. The Access/Egress times are similar. This time is attributed to agents in the simulation when they meet AVs on their link, despite the door-to-door feature of the service. The Waiting Times are also similar but with a slight disadvantage for SAV. The IVTT is more important for SAV service than AV service due to longer trips in lengths (Figure 82) and time (Figure 83). These increments can be attributed to the additional detours made to accommodate the pick-up and drop-off of other passengers in the SAV service.

All our results are consistent with the existing literature comparing D2D and SB services (Heilig et al. 2017; Marczuk et al. 2015; Javanshour, Dia, and Duncan 2019; Gurumurthy and Kockelman 2022).

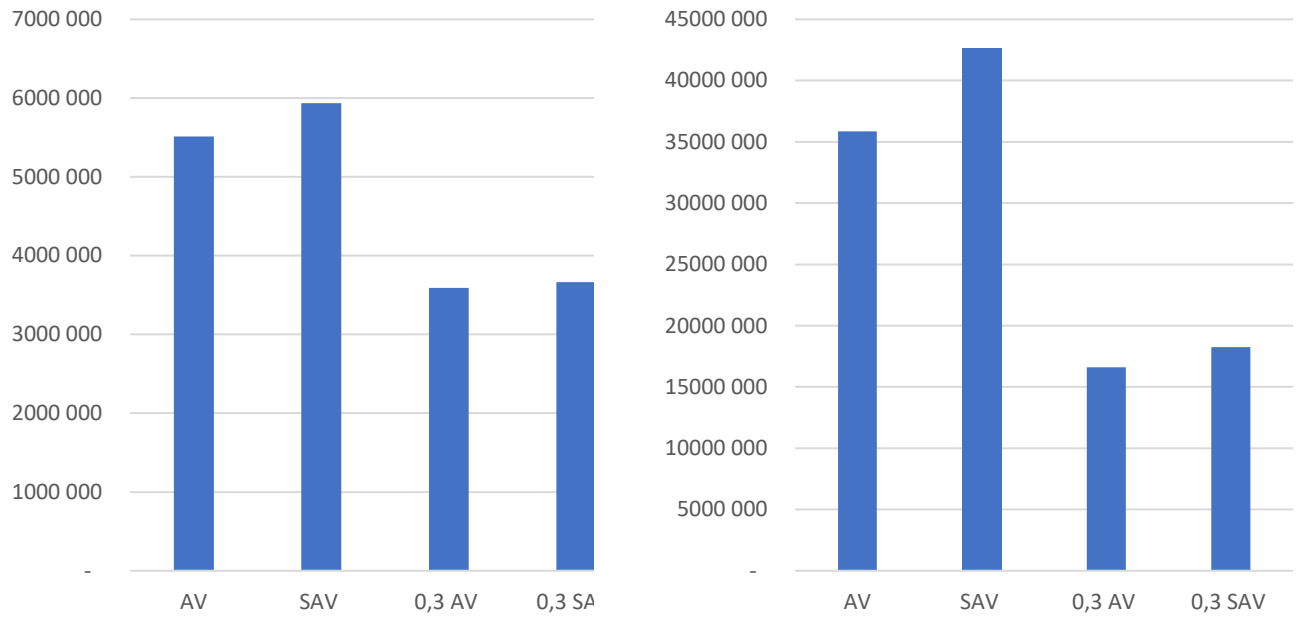

Figure 82. AV Trips per day (left) and Distance Travelled (pass.km)
Source: prepared by the author.

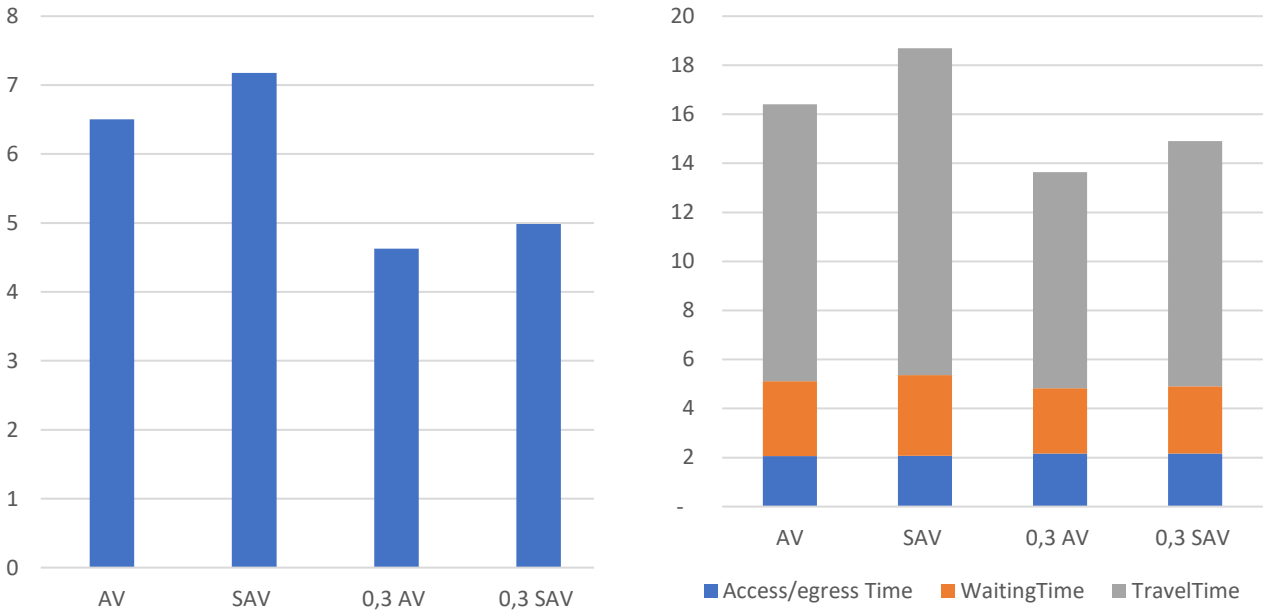

Figure 83. Average Distance Traveled (km, left) and Average Total Traveled Time (in min, right)
Source: prepared by the author.

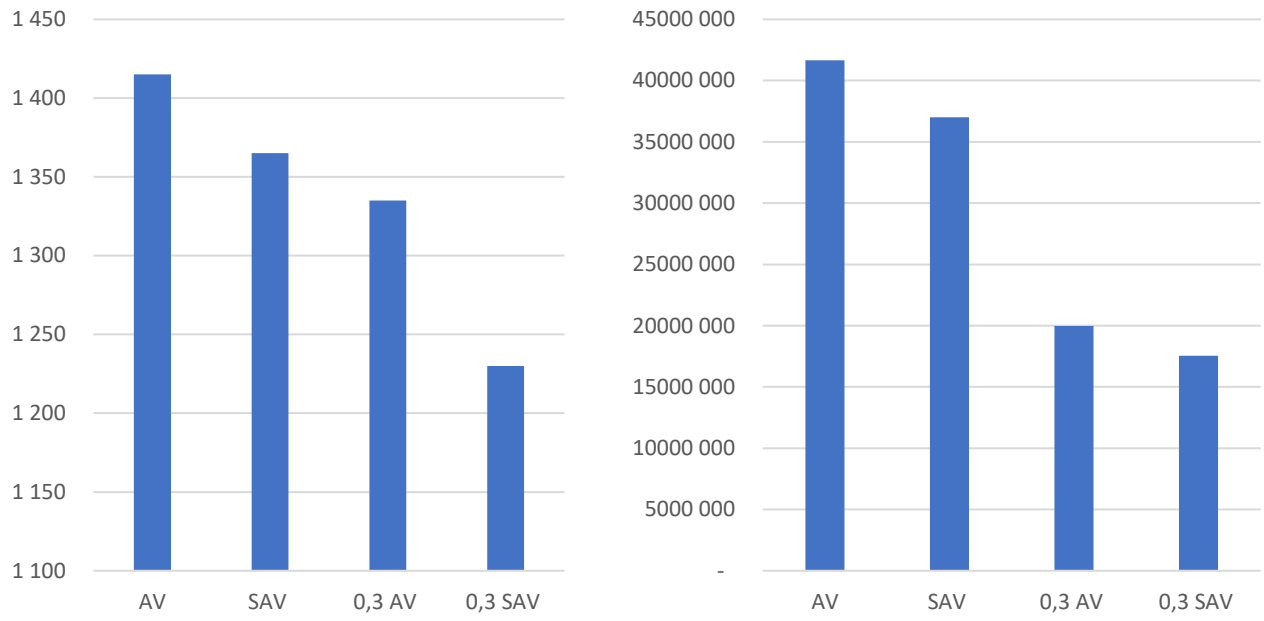

Figure 84. AV Fleet Size (left) and AV Vehicle Kilometers Traveled
Source: prepared by the author.

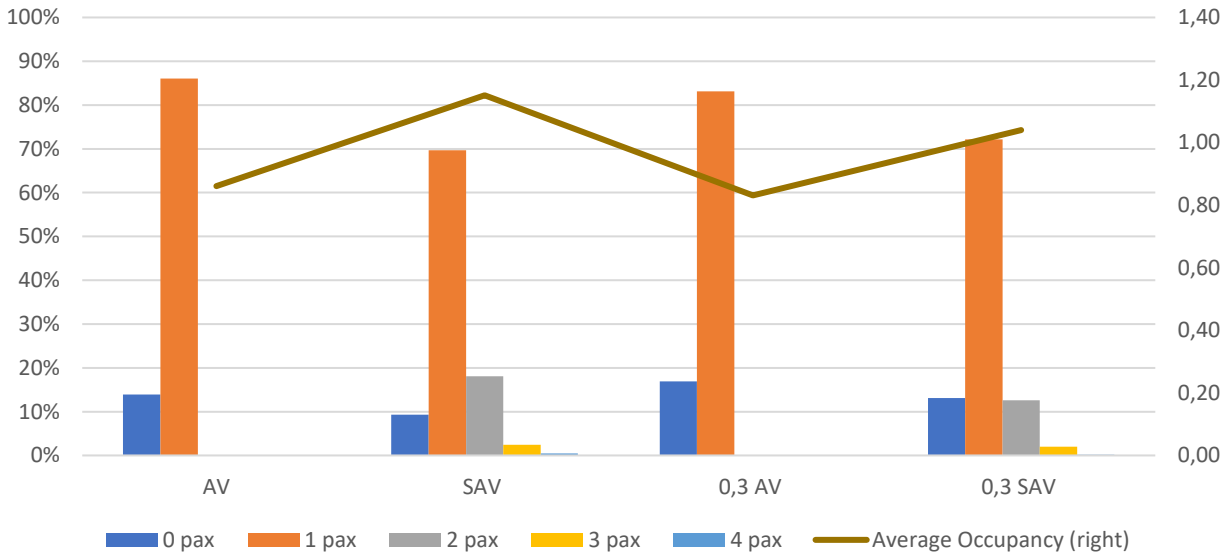

Figure 85. Vehicle occupancy profile (left) and average vehicle occupancy (right)
Source: prepared by the author.

2) Cost Benefit Analysis Results and Discussion

a) Consumer Surplus (CS)

The Consumer Surpluses evaluation presents counter-intuitive results. As agents utilities were increasing with the introduction of AVs, the use of equity VTTS in the CS calculation shifted the trend. Moreover, the introduction of Equity VTTS also disrupted the trend between AVs scenarios. When evaluated through the prism of Equity VTTS, shared rides (SAV and 0,3 SAV) scenarios presents a worse CS loss than scenarios in which AVs offer private rides (AV and 0,3 AV) while when these scenarios are evaluated through the prism of Behavioral VTTS, the shared rides scenarios presents more interesting solutions for the consumer (Figure 86). The Equity VTTS evaluation will be shown in this work, but the analysis if the Consumer Surplus will be based on the Behavioral VTTS. The Equity VTTS evaluation presents the paradoxical results of having a negative Consumer Surplus when the price of AVs increases and the overall total travel time decrease the most (-3,1%; -4%; -5%; -4,9% for AV, SAV, 0,3 AV and 0,3 SAV respectively). The difference between the free AV and SAV scenarios and the 0,3€/km AV and SAV scenarios can be explained by the structure of the modal shift from walk and bike which have an higher beta travel time than autonomous vehicles services in the eqasim utility function. As for the equity VTTS consumer surplus evaluation, the difference between the two pairs of scenarios can be explained by the tariffication, lowering the accessibility gained by the introduction of the service.

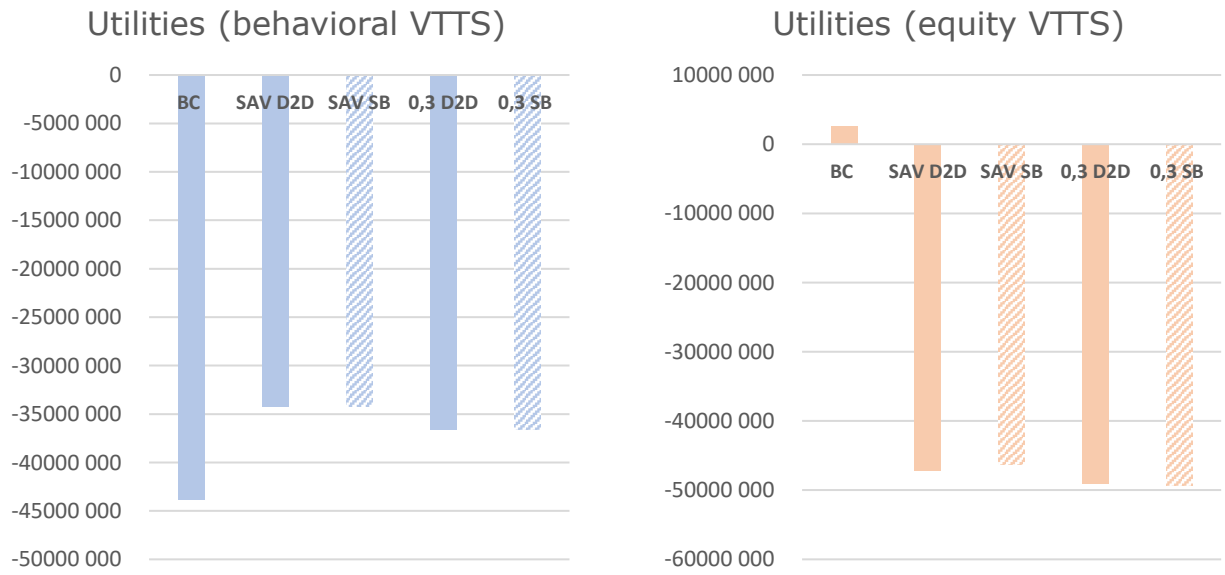

Figure 86. Utilities from behavioral VTTS (left) and Utilities from equity VTTS (right)

Source: prepared by the author.

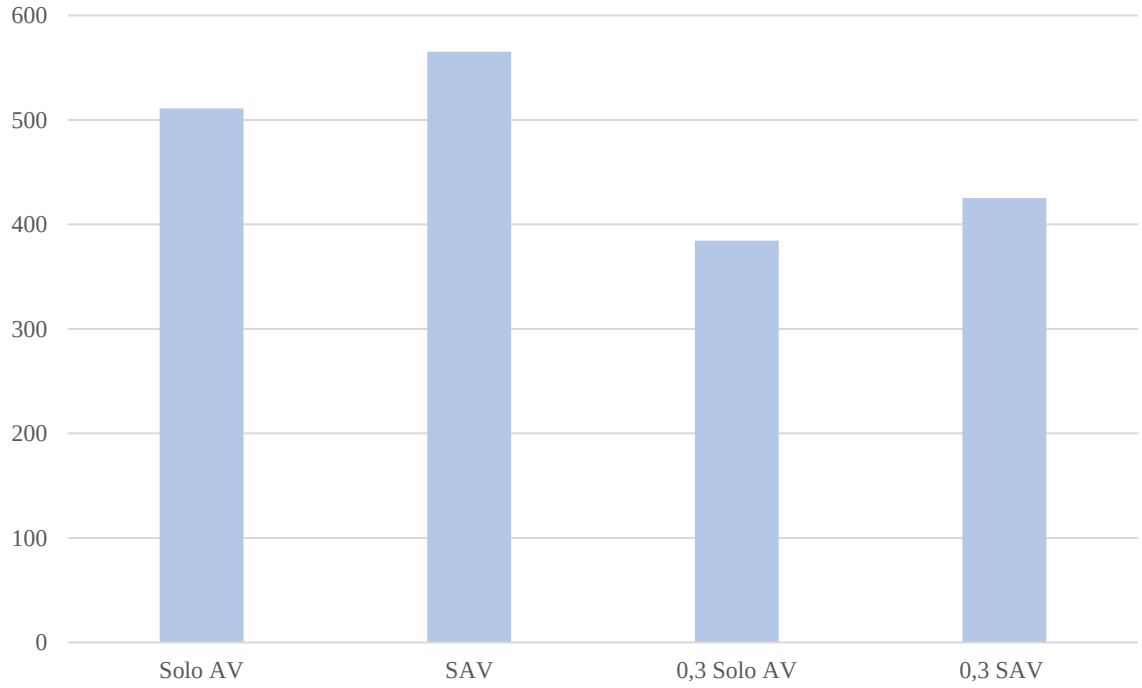

Figure 87. Consumer surplus from behavioral VTTS
Source: prepared by the author.

NB: The VoT adjustments based on the GDP/capita rate have not been made. It should decrease the gain of Consumer Surplus.

The introduction of on-demand automated vehicles service has improved the consumer surplus in all scenarios but with disparities amongst scenarios. This increase in CS is based on a combination of two mechanisms. First the overall decrease of total travel time (between -3,9% and -5% compared to the basecase for the four scenarios) has a direct effect on the CS. Second, the modal shift from walk, car and bicycle which have an more important valuation of travel time, respectively 26,21; 19,43 and 43,69 euros per hour (translated from the beta travel time from Eqasim utility function with the marginal utility of time) than the 4,95 euros per hour for the on-demand service. The increase of travel time of car travelers due to congestion does not offset the previously mentioned gains. As expected, the price of the service lowers the increase in CS. SAV service presents an higher performance than AV service despite longer travel time in vehicles. It is due to the attractivity of the service which is more popular (Figure 82) and benefits more from the difference in value of time between modes. The aggregated total travel time decreases more with SAVs than AVs when the service is free but this difference tighten when the service

transitions to a paid model. The difference in consumer surplus also tightens with the introduction of fees (54 million for the two free scenarios and 41 million for the two 0,3 euros/km scenarios).

The equity KPIs (Figure 88) all indicates an important concentration of gain amongst a minority of agents. Two thirds of the agents are indifferent to the introduction of the on-demand service which is not unexpected in an area where the private car is often the best alternative with no waiting time. Despite the overall gain in consumer surplus, the share of losers is more important than the share of winners for all scenarios. It may be seen in the repartition gain curve (Appendix Figure 94) that the individual gains per winners seems to be more important than the individual loss per loser. The concentrations of gains indicators shows that for the four scenarios, between 99,975% and 99,997% of all positive gains are concentrated amongst the 10% of the agents winning the most. The difference in concentration of gains appears at the 5% level of the population winning the most, as in the two first scenarios (AV and SAV) they gain 97% of the positive gains while in the two paying scenarios (0,3 AV and 0,3 SAV) the 5% of the population benefits from 99,931% and 99,924% of the total gains. The gap widens when comparing the 1% concentration measure where in the two first scenarios the 1% of the population gaining the most gains ten percentage points (54%) less than the two paying scenarios (64%). This important concentration of gains compared to the other case studies is confirmed by a GINI index relatively high comprised between 0,41 and 0,48. The detailed data of the equity KPIs are joined in Table 46.

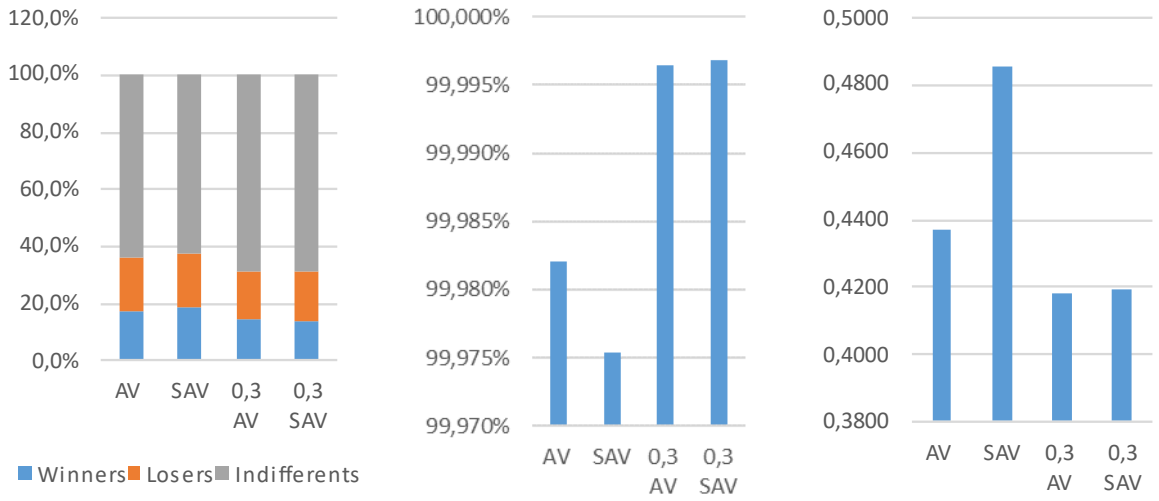

Figure 88. Equity KPIs Winners versus Losers (left), the 10% measure (middle) and Gini index (right)

Source: prepared by the author.

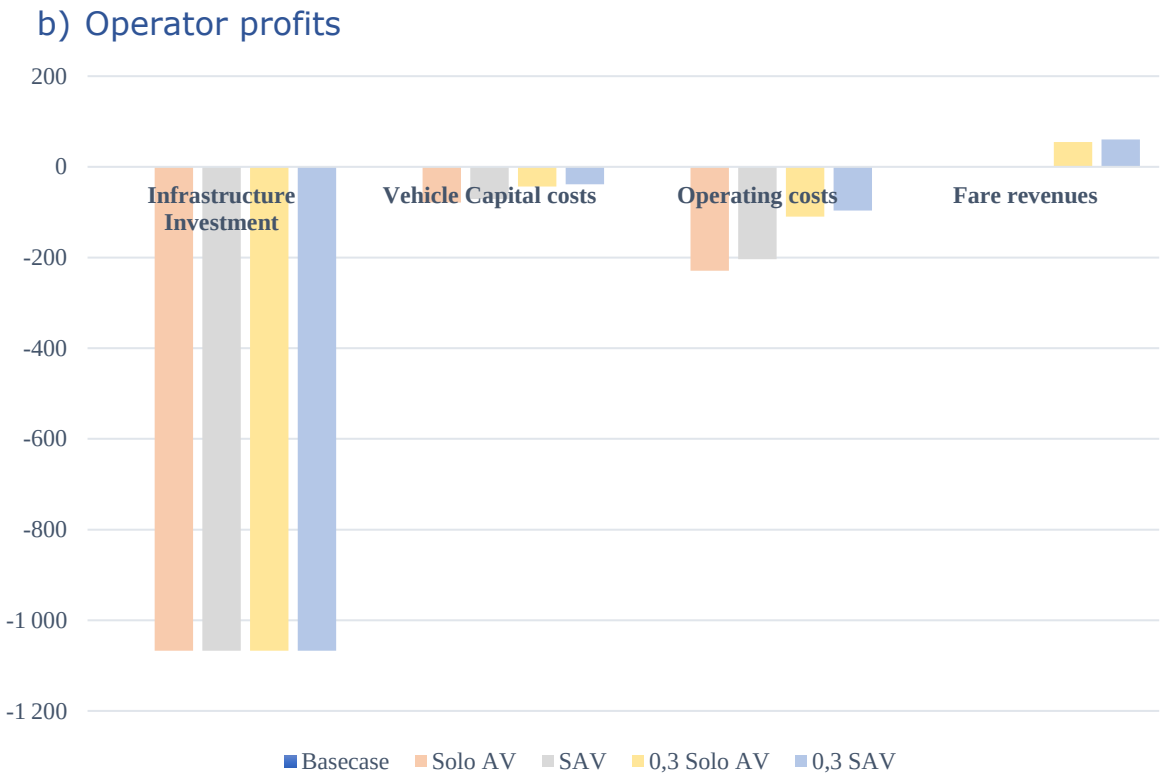

Figure 89. Financial surplus (10 years term, millions € differences with basecase)
Source: prepared by the author.

In the profits category, the infrastructure costs represent most of the costs in all four scenarios (Figure 89). By example, in the 0,3 SAV scenario, they represent up to 88% of the costs. These results are highly dependent on the hypothesis made. A sensitivity analysis discussing both the cost of equipment and maintenance required is available in appendix (Appendix Table 47). Similarly with the CPS use, another evaluation scenario is proposed here with the alternative of a "No equipment network" (Figure 90), assuming that autonomous cars would be able to drive on the road without additional costs for the network (such as maintenance costs for road marks or connected traffic light).

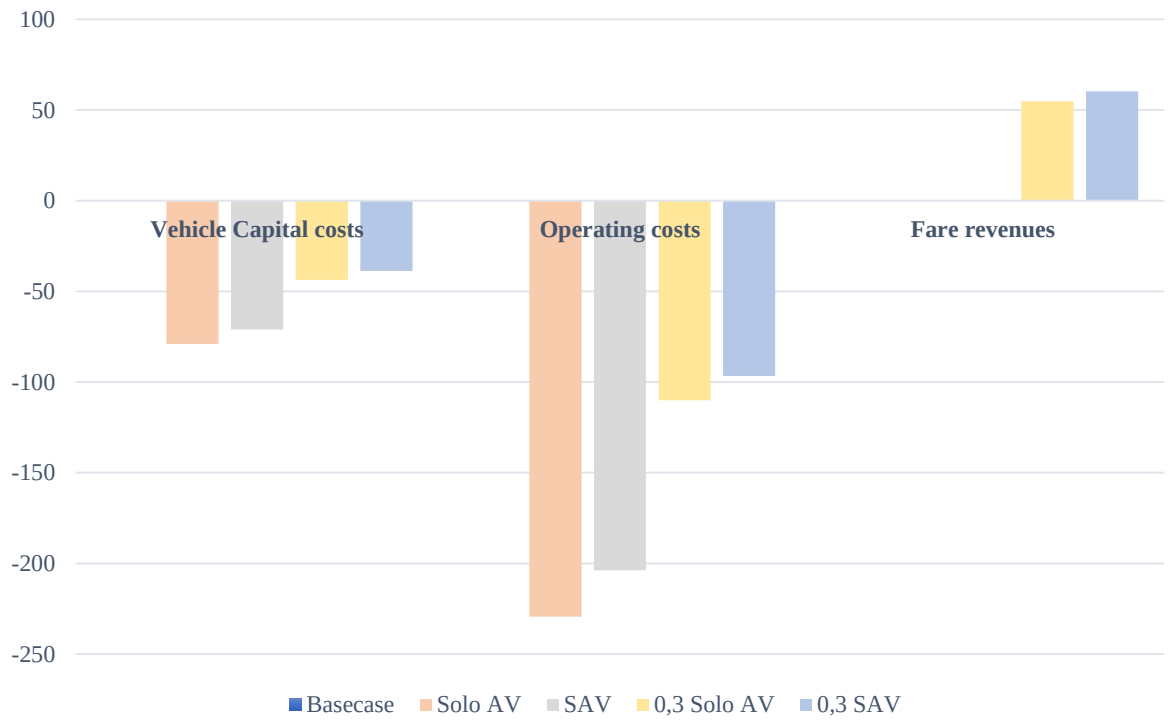

Figure 90. Financial surplus without the infrastructure costs (10 years term, millions € differences with basecase)
Source: prepared by the author.

In this configuration, the costs are driven by two main factors, the number of vehicles required to operate the service and the distance driven by the aforementioned vehicles. The ridesharing scenarios allow to reduce the need of both of these factors for a more attractive service.

The fares gathered cover up for more than the vehicle investments or for more than half of the operational costs. More important fares would cause a reduction of the service attractivity and thus a reduction of the vehicles required and the operational costs. (Hörl, Balac, and Axhausen 2019) define an optimal fleet size (regarding the demand) and use the cost model used as input in this CBA framework (Bösch et al. 2018) for a Parisian case study. His results present a fare-covering costs of 0,27 euros per kilometer traveled. If the literature forecasts the autonomous fares around the 0,3euros/km, on-demand mobility services may increase their prices a little bit further to cover up for structure costs and margins which goes in the direction of ("The Price Isn't Right: Autonomous Vehicles, Public Health, and Social Justice" n.d.) which found a range of costs of 0,85 and 3,18 euros per km (1,5$ to 6$ per mile), including profits in USA where price levels are higher than in France ("Taux de conversion - Parités de pouvoir

d'achat (PPA) - OCDE Data" n.d.). For reference, the maximum price for Parisian taxis has been fixed at 1,16 euros per kilometers (*Arrêté Du 29 Mars 2022 Portant Revalorisation Infra-Annuelle Des Tarifs Des Courses de Taxi En 2022* n.d.) in 2022, almost four times the amount chosen in this scenarios.

c) Externalities

Similarly to the Berlin and Saclay case studies, the introduction of AVs lead to an increase in overall VKT and vehicles used. This increase in resources consumed lead to an overall increase of the externalities impact. The AV efficiency (less emissions and less accident per kilometers) do not compensate.

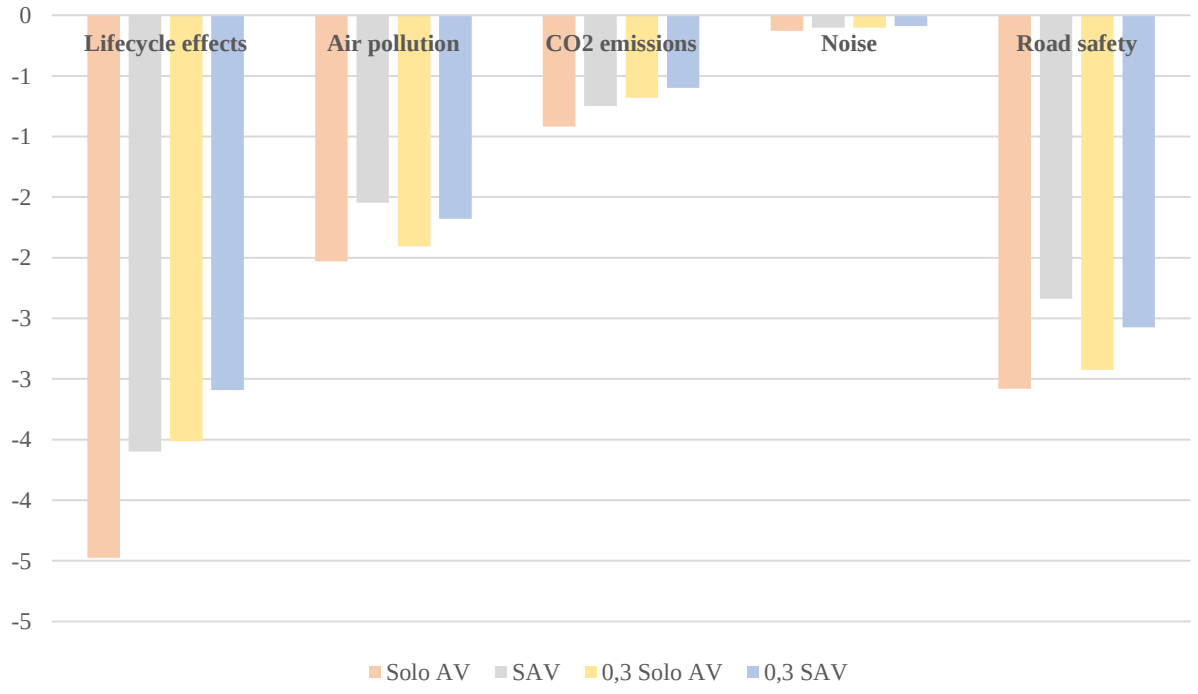

Figure 91. Externalities impact (10 years term, millions € differences with basecase)
Source: prepared by the author.

The negative externalities impact was to be expected when considering the overall increase in kilometer traveled. The structure of these impacts is slightly different than the profits. For air pollution and road safety, the routing has more impacts than the service price (Figure 91). The other items follow the trend based on vehicles required and VKT.

These results are consistent with the other case studies of this thesis. If a share of this increase of externalities could be attributed to the scenario

design (adding a new mobility alternative often increase mobility consumption). The structure of the modal shift indicates that the domination of the conventional cars in rural areas does not seem to be threatened by AVs.

d) Net Present Value

The introduction of SAVs in the Dourdan rural area presents a negative Net Present Value for all scenario (see Figure 92). The gain of Consumer Surplus is partly carried out by previous walk or bike agents, reducing their travel time but adding more people on the roads. These additional VKT increased the externalities despite AVs, the empty kilometer traveled and the modal shift do not balance the shared rides and better driving abilities. The fares introduction has an important impact on consumer surplus and financial balance but relatively low on the externalities impact due to the vehicles required to operate the service which acts as an externality fixed cost. The externality impact do not contribute much to the NPV equilibrium. The scenario design comparing electric vehicles to autonomous electric vehicles with the French energetic mix does not give to carbon emissions the same weight that they usually have in the balance. The financial burden associated with AVs consists primarily of infrastructure costs, accounting for over 80% of the total. The NPV/I are respectively -0,8; -0,77; -0,79 and -0,78 but negative NPV/I can express a distorted view of the social interest of the investment.

If the infrastructure costs were to be fixed at zero (i.e. the AV would be autonomous from the infrastructure), the NPV could be positive. The NPV/I become 2,71; 3,57; 7,03 and 8,62. The magnitude (and the uncertainties) of infrastructure costs plays an important role in the NPV results. With the similar assumptions of maintenance costs (10% of the initial cost per year), the NPV would have started to be positive at the infrastructure investment cost of respectively 47 000; 56 000; 68 000, and 74 000 euros per kilometers.

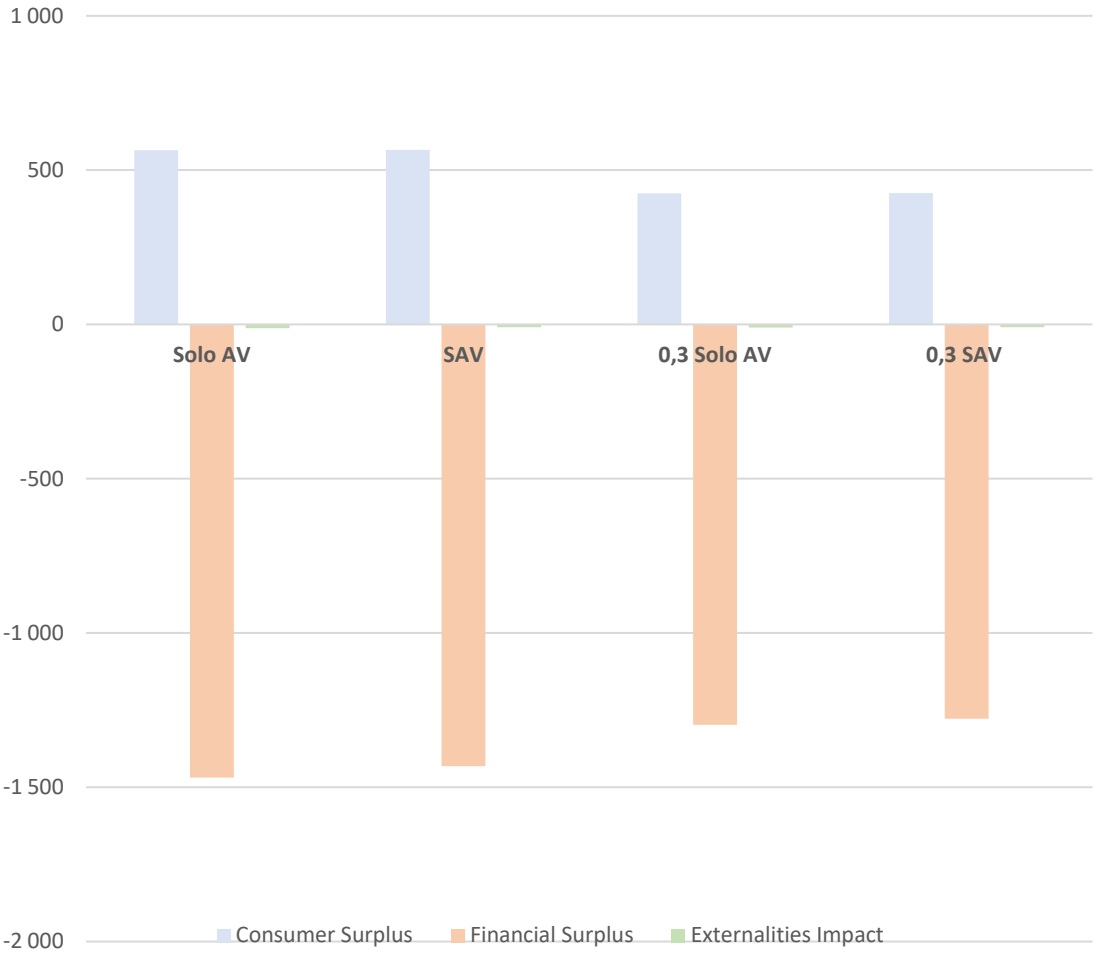

Figure 92. Net Present Value (10 years term, compared to basecase, millions €)

Source: prepared by the author.

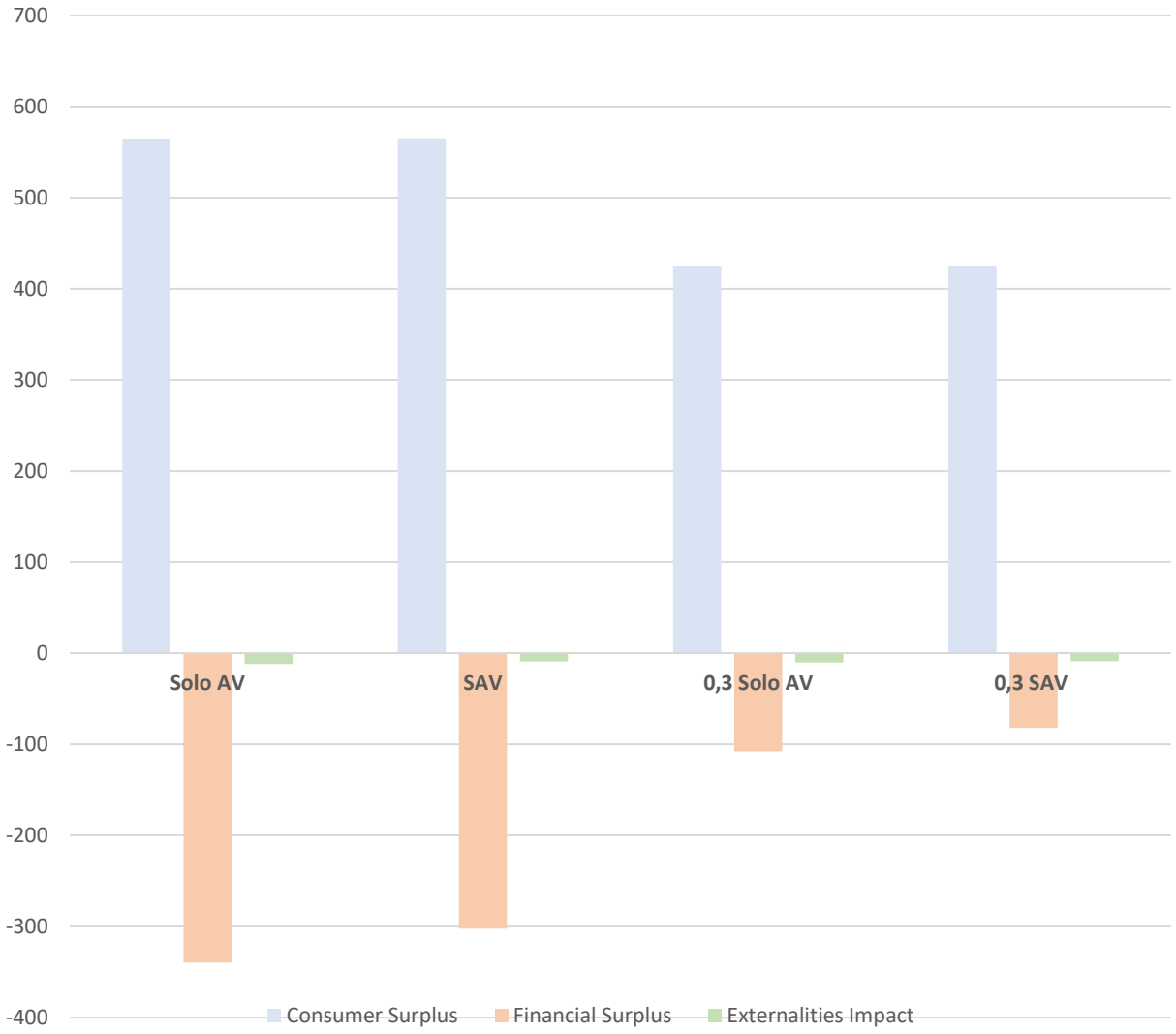

Figure 93. Net Present Value, without network costs (10 years term, compared to basecase, millions €)
Source: prepared by the author.

E. Conclusion

The aim of this chapter was to offer insights of on-demand AV-based services in a rural territory. To do so, mobility simulations have been used to have a better understanding of variation in the mobility paradigm and ultimately an economic appraisal has been performed. The introduction of AVs under an on-demand service form in the rural territory of Dourdan led to an overall gain for the consumer, a gain which is concentrated amongst a minority of agents. The profits are highly dependent of the infrastructure costs, which represents an important fixed cost for the service. The externalities impact is negative due to additional traffic on the road. The

main results of this case study is the importance of infrastructure costs in a rural area which does not benefit from economies of scale. This chapter contributes to the existing literature by its focus on a rural territory, which is one of the dead angle of the academic community working on AV-based mobility services. It brings better understanding of the operational capabilities of the aforementioned services where the demand is lower than for urban center. It become increasingly difficult to mutualize trips when the demand diminish. As for the economic evaluation, it shows that AVs will need to offer high level of service (i.e. low waiting time) and attractive prices to compete with conventional cars. Regarding the limitation, the simulation part did not include a charging behavior for electric vehicles despite considering all cars electric in the evaluation. For the economic evaluation part, the infrastructure costs level remains the most uncertain item in the evaluation and should be treated with cautious. This chapter marks the end of the case studies. After introducing AVs in three different types of territories, the next step will be to summarize the results and provide recommendation based on the results of the case studies.

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G. Appendix

Appendix 1. Utility functions and utility parameters

$$U_{car}(x) = \alpha_{car} + \beta_{travel\,time_{car}} . x_{travel\,time_{car}} + \beta_{travel\,time_{car}} . \theta_{parkingSeachPenalty} + \beta_{travel\,time_{walk}} . \theta_{accessEgressWalkTime} + \beta_{cost} . \left(\frac{x_{crowfly}}{\theta_{averageDistance}}\right)^{\lambda} . x_{cost_{car}}$$

$$U_{pt}(x) = \alpha_{pt} + \beta_{numberOfTransfers} . x_{numberOfTransfers} + \beta_{InVehicleTime} . \beta_{InVehicleTime} + \beta_{TransferTime} . x_{TransferTime} + \beta_{accessEgressTime} . x_{accessEgressTime} + \beta_{cost} . \left(\frac{x_{crowfly}}{\theta_{averageDistance}}\right)^{\lambda} . x_{cost_{pt}}$$

$$U_{bike}(x) = \alpha_{bike} + \beta_{travel\,time_{bike}} . x_{travel\,time_{bike}} + \beta_{age_{bike}} . Max(0, \alpha_{age} - 18)$$

$$U_{walk}(x) = \alpha_{walk} + \beta_{travel\,time_{walk}} . x_{travel\,time_{walk}}$$

$$U_{aMoD}(x) = \alpha_{pt} + \beta_{travel\,time_{pt}} . x_{travel\,time_{av}} + \beta_{transfer\,time_{pt}} . x_{waiting\,time_{av}} + \beta_{cost} . p_{av} . x_{networkDistance_{av}}$$

Car	α_{car}	1.35	
	$\beta_{travelTime,car}$	-0.0667	$[min^{-1}]$
Public Transport	α_{pt}	0.0	
	$\beta_{numberOfTransfers}$	-0.17	
	$\beta_{inVehicleTime}$	-0.017	$[min^{-1}]$
	$\beta_{transferTime}$	-0.0484	$[min^{-1}]$
	$\beta_{accessEgressTime}$	-0.0804	$[min^{-1}]$
Bike	α_{bike}	0.1	
	$\beta_{travelTime,bike}$	-0.15	$[min^{-1}]$
	$\beta_{age,bike}$	-0.0496	$[a^{-1}]$
Walk	α_{walk}	1.43	
	$\beta_{travelTime,walk}$	-0.09	$[min^{-1}]$
Others	β_{cost}	-0.206	$[EUR^{-1}]$
	λ	-0.4	
	$\theta_{averageCrowflyDistance}$	40	[km]
Calibration	$\theta_{parkingSearchPenalty}$	4	[min]
	$\theta_{accessEgressWalkTime}$	4	[min]

Table 45. Parameters of the discrete mode choice model

Source: Hörl, S., Balać, M., Axhausen, K.W., 2019. Dynamic demand estimation for an AMoD system in Paris. https://doi.org/10.1109/IVS.2019.8814051.

Figure 94. Repartition of utility gains amongst agents, from losers to winners

Source: prepared by the author.

NB: for illustration reasons, the upward scale has been limited to 15 but 75 agents have a more important gain that 15 utility points. The agent with the most important gain wins 54 points.

	AV	SAV	0,3 AV	0,3 SAV
Winners	17,2%	18,5%	14,3%	14,0%
Losers	19,2%	18,7%	16,7%	17,2%
Indifferents	64%	63%	69%	69%

	AV	SAV	0,3 AV	0,3 SAV
The 10% Measure	99,98%	99,975%	99,996%	99,997%
The 5% Measure	97,65%	97,617%	99,931%	99,924%
The 1% Measure	54,84%	54,816%	64,201%	64,181%

	AV	SAV	0,3 AV	0,3 SAV
Gini	0,4372	0,4857	0,4183	0,4196

Table 46. Equity KPIs

Source: prepared by the author.

As a reminder the:

- Winners versus losers: Repartition of agents with a better situation (winners), a worst situation (losers) or the exact same situation (indifferent) than in the baseline scenario, expressed as a percentage of the agents' population.

- The 10% measure: estimates how much of the consumer surplus due to the project implementation is being captured by the 10% of the agents winning the most, expressed as a percentage of the aggregated positive consumer surplus.

- A Gini Index based on the distribution of gain or loss for each agent.

Total 10 years cost		Maintenance and replacement cost per year				
		10%	20%	30%	40%	50%
Infrastructure Equipment cost	50 000	100 000 €	150 000 €	200 000 €	250 000 €	300 000 €
	100 000	200 000 €	300 000 €	400 000 €	500 000 €	600 000 €
	150 000	300 000 €	450 000 €	600 000 €	750 000 €	900 000 €
	200 000	400 000 €	600 000 €	800 000 €	1 000 000 €	1 200 000 €
	250 000	500 000 €	750 000 €	1 000 000 €	1 250 000 €	1 500 000 €

Table 47. Infrastructure Cost Sensibility Analysis

Source: prepared by the author.

V. Cross-comparison of case studies and recommendations

A. Introduction

A key goal of this thesis is to assess the performance of AV services by considering the perspective of the main stakeholders (i.e., users, operators and externalities impact), and how it varies depending on territories. To do so, three case studies were selected, with on-demand AV services designed specifically for each case study. The AV service scenarios have been evaluated using Cost Benefit Analysis (CBA), completed with additional KPIs. The aim of this chapter is to summarize the main results and provide recommendations for the implementation of AV services in accordance with the territory characteristics.

Several types of on-demand AV services were investigated in three categories of territories: urban, periurban and rural. The comparison of these scenarios requires to understand that these results are more than just the application of methodologies for both simulations and evaluations, but also the conjunction of data collection for the generation of synthetic population and scenario design. The territory classification is a long debate amongst geographers and the classification used in this thesis - based on the Insee classification - may be viewed as strict while transitional environments (Simard 2012) can be identified. As such this chapter also reintroduces nuances in the analysis. By example, despite having most of its surface covered by rural areas, the Dourdan case study is structured around a city of 10,000 inhabitants which polarized flaws. Thus, this thesis aims to offer insights on the relation of specific types of territories and specific type of AV services, under the design and technical constraints. If the results should not be essentialized, neither at the territory level nor the service level, this chapter will provide external validity through territory and service characteristics.

In the second section, the various scenarios and the choice of parameters in each case are recapitulated. The third section then carries out a comparative analysis of the various scenarios based on key performance indicators. The fourth section provides recommendations for the implementation of on-demand AV services, while the fifth section provides some words of conclusion.

B. Scenario parameters

For each scenario, the methodology comprised two steps, first the mobility simulation then the evaluation. During the simulation step, the service design focused on five key characteristics, presented in Table 48. We also recall which mode choice model was used for clarity. During the evaluation step, four main parameters were considered. The following subsections go more thoroughly into the different parameter values.

	Parameters	**Berlin**	**Saclay**	**Dourdan**
Simulation	Mode choice	MATSim	Eqasim	Eqasim
	Ridesharing	Yes	Yes	No
	Intermodality	No	Strictly	No
	Routing	D2D/SB	D2D/SB	D2D
	Veh. Capacity	4/8	4/8	4
	Fare (€/km)	0	0	0/0,3
Evaluation	Utility function	MATSim Scoring	Eqasim IDF*	Eqasim IDF*
	VTTS	Equity	Equity/ Behavioral	Equity/ Behavioral
	Network size	Full length	Full length/ Bus network	Full network/ No network*
	Energy mix	German	French	French

Table 48. Scenarios parameters, simulation step (above) and evaluation step (below)

Source: prepared by the author.

**IDF: Ile-de-France, the Paris region*

**No network: i.e. no additional network cost than for conventional cars network*

1) Urban setting: Berlin

The scenarios of the Berlin case study were centered around autonomous vehicles working as an on-demand service offering shared rides either in a door-to-door (D2D) or stop based (SB) scheme routing (Table 49). The two last scenarios feature a car ban scenario which were supposed to increase the potential demand for AVs. As for the fare policy, the price was set to zero to analyze the impact of the service under the most favorable conditions. AVs capacity has been increased to 8 seats (to

a shuttle size) in order to help accommodate this additional demand and assess the ability of on-demand services to massify flows.

Scenario name	N°	Model	Ridesharing	Intermodality	Routing	Vehicle Capacity	Fare
B_D2D SAV	S1	MATSim	Yes	No	D2D	4	No
B_SB SAV	S2	MATSim	Yes	No	SB	4	No
B_D2D SAV/ Car ban	S3	MATSim	Yes	No	D2D	8	No
B_SB SAV/ Car ban	S4	MATSim	Yes	No	SB	8	No

Table 49. Simulation scenarios for the Berlin case study.

Source: prepared by the author.

NB: for details on service features see (Carreyre et al. 2022)

The consumer surplus was estimated using the MATSim scoring function, adapted to consider equity VTTS (based on the French CBA guidelines value). The road network considered for AV operations – which also serves to estimate the AV infrastructure costs - was the full Berlin road network (Table 50).

Scenario name	N°	Utility function	VTTS	Network size	Energy mix
B_D2D SAV	S1	MATSim scoring	Equity	Full length	German
B_SB SAV	S2	MATSim scoring	Equity	Full length	German
B_D2D SAV/Car ban	S3	MATSim scoring	Equity	Full length	German
B_SB SAV/Car ban	S4	MATSim scoring	Equity	Full length	German

Table 50. Evaluation scenarios for the Berlin case study.

Source: prepared by the author.

2) Periurban setting: Communauté d'agglomération Paris Saclay (CPS)

The CPS case study focuses on an intermodal use case in a periurban area. The AV services were designed to work in interaction (Table 51) with heavy public transit (trains, tram and metros). Agents were not allowed to emit request unless they were to also use one of the previously mentioned modes. The AV fare would be integrated in the public transit fare, in the same way as if travelers took a bus to make the first/last mile trip in an intermodal trip. The routing was either D2D or SB, but given the condition to use a public transit mode before/after the AV trip, the D2D case resulted in practice in a semi-SB routing. Two sizes were considered for the autonomous vehicles: car and shuttle.

Scenario name	N°	Model	Ridesharing	Intermodality	Routing	Vehicle Capacity	Fare
D2D SAV	S1	Eqasim	Yes	Strictly*	D2D	4	No
SB SAV	S2	Eqasim	Yes	Strictly*	SB	4	No
D2D Shuttle	S3	Eqasim	Yes	Strictly*	D2D	8	No
SB Shuttle	S4	Eqasim	Yes	Strictly*	SB	8	No

Table 51. Simulation scenarios for the "Communauté d'agglomération de Paris-Saclay" case study.

Source: prepared by the author.

** AV trips were contingent on the agent to use (before or after the AV trip) a train, a tram or a metro.*

For the evaluation step, the consumer surplus was estimated using the Eqasim utility function (Table 52).

The consumer surplus has been estimated through both the equity VTTS and the behavioral VTTS. The use of equity VTTS resulted in paradoxes where the consumer surplus would decrease instead of increasing. As such, this chapter has focused on the use of behavioral VTTS.

For the financial evaluation, scenarios where the SB AVs would only use the bus network were considered. Finally, the French energy mix was used in both the CPS and Dourdan case studies.

Scenario name	N°	Utility function	VTTS	Network size	Energy mix
D2D SAV	S1	Eqasim	Equity/ Behavioral	Full length	French
SB SAV	S2	Eqasim	Equity/ Behavioral	Full length/ Bus Network	French
D2D Shuttle	S3	Eqasim	Equity/ Behavioral	Full length	French
SB Shuttle	S4	Eqasim	Equity/ Behavioral	Full length/ Bus Network	French

Table 52. Evaluation scenarios for the "Communauté d'agglomération de Paris-Saclay" case study.

Source: prepared by the author.

3) Rural setting: Dourdan

The scenario for the Dourdan case study focused on designing an on-demand service which would be adapted to a rural/low density area (Table 53). As the demand density is lower than for the other case studies, detours to pick-up additional passengers are likely to result in significant additional travel times. As a result, it is the only case study where solo riding was considered. It is also the only case study where a non-null fare policy has been experimented. Similarly, only D2D routing was tested to limits access and egress times.

Scenario name	N°	Model	Ridesharing	Intermodality	Routing	Vehicle Capacity	Fare
D2D SAV	S1	Eqasim	Yes	No	D2D	4	No
D2D AV	S2	Eqasim	No	No	D2D	1	No
0,3 SAV	S3	Eqasim	Yes	No	D2D	4	Yes
0,3 AV	S4	Eqasim	No	No	D2D	1	Yes

Table 53. Simulation scenarios for the Dourdan case study.

Source: prepared by the author.

The evaluation step did not consider any financial differences between services providing private rides or shared rides (Table 54). Regarding infrastructure costs, additionally to a sensitivity analysis, two alternatives were considered: either equipping the full network, as in the other case studies (for D2D routing), or no need to equip the network. The infrastructure network cost to balance the NPV has also been provided.

Scenario name	N°	Utility function	VTTS	Network size	Energy mix
D2D SAV	S1	Eqasim	Equity/ Behavioral	Full length/ No network**	French
D2D AV	S2	Eqasim	Equity/ Behavioral	Full length/ No network**	French
0,3 SAV	S3	Eqasim	Equity/ Behavioral	Full length/ No network**	French
0,3 AV	S4	Eqasim	Equity/ Behavioral	Full length/ No network**	French

Table 54. Evaluation scenarios for the Dourdan case study.

Source: prepared by the author.

C. Comparative analysis

The economic appraisal of AVs introduction has shown heterogenous results depending on territories specifications. This section compares each results based on comparative KPIs and highlights territorial differences. This comparative analysis investigates the economic performance of each service, firstly with the help of the Net Present Value/Investment KPI. Secondly, it considers the equity KPIs produced for each case study in order to look into the winners/losers ratio and the repartition of gains and losses.

1) Overall economic performance

Case study	VTTS	Network	**S1**	**S2**	**S3**	**S4**
Berlin	Equity	Full road network	-3,5	-3,4	-15,6	-22,4
	Equity	No network	-4,5	-4,8	-16,5	-24,1
Saclay	Equity	Full road network	-14,0	-14,3	-13,5	-13,9
	Equity	Bus network	-14,0	-37,3	-13,5	-29,6
	Equity	No network	-93,4	-118,3	-53,0	-61,5
Saclay	Behavioral	Full road network	**0,3**	0,0	**0,1**	-0,1
	Behavioral	Bus network	**0,3**	**1,7**	**0,1**	**1,0**
	Behavioral	No network	**8,4**	**7,8**	**3,7**	**3,2**
Dourdan	Equity	Full road network	-3,9	-3,8	-3,9	-3,9
	Equity	No network	-41,7	-45,0	-74,0	-83,0
Dourdan	Behavioral	Full road network	-0,8	-0,8	-0,8	-0,8
	Behavioral	No network	**2,7**	**3,6**	**7,0**	**8,6**

Table 55. NPV/I

Source: prepared by the author.

NB: Please keep in mind negative NPV/Is display counter-intuitive results. By example, a project costing 1 million euros which would generate a minus 2 million euros NPV and a project costing 10 million euros which would generate a minus 20 million euros NPV would both have a -2 NPV/I while the second being more detrimental to a higher cost.

The NPV/I ratio measures the efficiency of the investment. Before to review the results, one should remember the impact of scenario design. As seen in the case studies results, the infrastructure costs have an impact on the NPV inversely proportional to the density of the case study. On the fourteen NPV/I found to be positive (on the forty-eight NPV/I produced during this thesis, see Table 55), twelve have either a smaller network ("bus network" equipping only the bus network) or consider that the infrastructure should not be equipped more than for conventional vehicles (No network). Furthermore, the only two positive NPV/I evaluating the equipment of a full road network were respectively the smallest and third

smallest of the fourteen found. In this section, NPV/I which had not been displayed before in their dedicated case study (such as the Berlin one with no network equipped) have been integrated to assess all scenarios with similar characteristics.

The use of VTTS also had an important impact on the NPV, none of the scenario evaluated with the integration of equity VTTS (as the French governmental guidebook recommends) has shown positive results (at the consumer surplus level but also at the NPV level).

The Berlin case study exhibits the overall negative impact of the introduction of on-demand AVs in an urban and dense environment. When introduced as a new mode of transportation in addition to the existing solutions, AVs services impact negatively the Consumer Surplus and the externality due to additional Vehicle-Kilometer Traveled (VKT) and congestion. The two scenarios where conventional private cars were banned are the only ones of the selection reducing the externalities impact.

The Saclay case study has different results. Firstly, the consumer surplus methodology had a strong impact on the Consumer surplus which appeared to become negative with the use of equity VTTS and positive when evaluated with the use of behavioral VTTS. The infrastructure costs become more important in the financial balance. For the evaluation, a scenario in which AVs were supposed to drive on the bus network allowed to introduce an alternative scenario lightening the infrastructure investments burden. The externalities impact was found to be negative for all scenarios.

The Dourdan case study shown comparable results with the Saclay case study for the consumer surplus results. The use of equity VTTS resulted in a paradoxical negative Consumer Surplus. The use of behavioral VTTS implied an overall gain. The Dourdan case study is the only one where fares has been introduced, which contributed to pull the financial balance towards zero. The externalities impact was found to be negative for all scenarios. Dourdan two big scenarios: the use of fares had a negative impact on consumer surplus but the reduced attractivity of the service decreased the operational costs and the number of vehicles. Moreover, the fares provided a contribution which helped pull the financial balance towards the equilibrium. The introduction of fares had little effect on externalities in absolute terms. The externalities impact variation has almost no part on the variation of the NPV. Despite the compensation principle (de Rus et al. 2020, 5), the environmental impact should not be considered as taken into account within the NPV. The CBA attractivity for decision support holds on the ability to produce a mono criterion comparison between projects with

multiple variables concerned. The NPV/I makes the environmental impacts invisible for simplicity. As the valuation method of externalities (CO_2 for example) reduces the value to a non-decisive amount, the NPV (and NPV/I by extension) only provides a Consumer Surplus versus operators profits trade-off. For any environmental insight of the project, the reader should specifically look into the CBA sub-item.

The comprehensive financial assessment reveals a negative overall financial balance across all scenarios. This outcome aligns with expectations, considering that, in almost all scenarios, no fares were implemented when utilizing AVs to explore their potential at maximum demand levels. The absence of fare implementation underscores a choice to prioritize a thorough examination of AV capabilities and potential without factoring in revenue from fares. Consequently, the negative financial balance is a predictable outcome in this context, highlighting the need for further financial analysis considering fare structures and revenue streams for a more comprehensive evaluation of the economic viability of AV-based services.

For the externalities, except for the two "car ban" scenario (scenarios 3 and 4) in the Berlin case study, the externalities impact is negative for all scenarios. This result is consistent with the literature reviews (Madelenat and Grisoni 2021). (Taiebat et al. 2018) warns that focusing on the environmental benefits of AVs vehicle system should not cover up the costs at the society level. (Lecomte et al., under review) performed a Study-Method-Impact providing data from scientific literature which indicates that, despite a likely increase in distance traveled, the GHG emissions should decrease (NB: they indicated that their processed data on GHG emissions was low and should be consider as uncertain for this point).

The scenario design may introduce an additional charge to the system when adding a new alternative instead of replacing existing solution by a new one. On the limits considering the measure of externality impacts is the ability of the simulation models to induce trips (i.e. additional trips). MATSim is not able to simulate additional demand due to the introduction of a new mode of transportation, only the trip length or travel time could vary. The literature should be aware that an AVs introduction may surely results on negative outcome concerning any environmental item considered.

2) Equity

a) Winners versus losers

The analysis of the winners, losers and neutrals shows that the share of winners is generally inferior but still relatively close to the share of losers for the Saclay and Dourdan case studies (Table 56). For the Berlin scenario, the share of losers is more important, with 31-32% of losers in the regular scenarios as opposed to only 25-27% of winners. This is likely due to the additional congestion caused by the AV service, which would impact more travelers in denser areas. In the car ban scenarios, the share of losers is even greater as a result of the stricter mobility conditions.

Berlin	Free D2D SAV	Free SB SAV	Free D2D SAV / Car ban	Free SB SAV / Car ban
Winners	27%	25%	19%	21%
Losers	32%	31%	53%	36%
Neutrals	42%	45%	29%	43%

Saclay	D2D SAV	SB SAV	D2D Shuttles	SB Shuttles
Winners	19,3%	17,8%	18,3%	17,6%
Losers	18,2%	19,1%	19,2%	19,4%
Indifferents	62%	63%	63%	63%

Dourdan	AV	SAV	0,3 AV	0,3 SAV
Winners	17,2%	18,5%	14,3%	14,0%
Losers	19,2%	18,7%	16,7%	17,2%
Indifferents	64%	63%	69%	69%

Table 56. Winner versus Losers

Source: prepared by the author.

b) The 10% measure

The 10% measure evaluates the share of the benefits that is captured by the 10% of the agents who gain the most from the introduction of the AV service. In all scenarios I find that the benefits are highly concentrated (Figure 95). This is consistent with AV modal shares which have remained below a 5% threshold for all scenarios (except the car ban scenarios) and thus benefits only a relatively small share of the population.

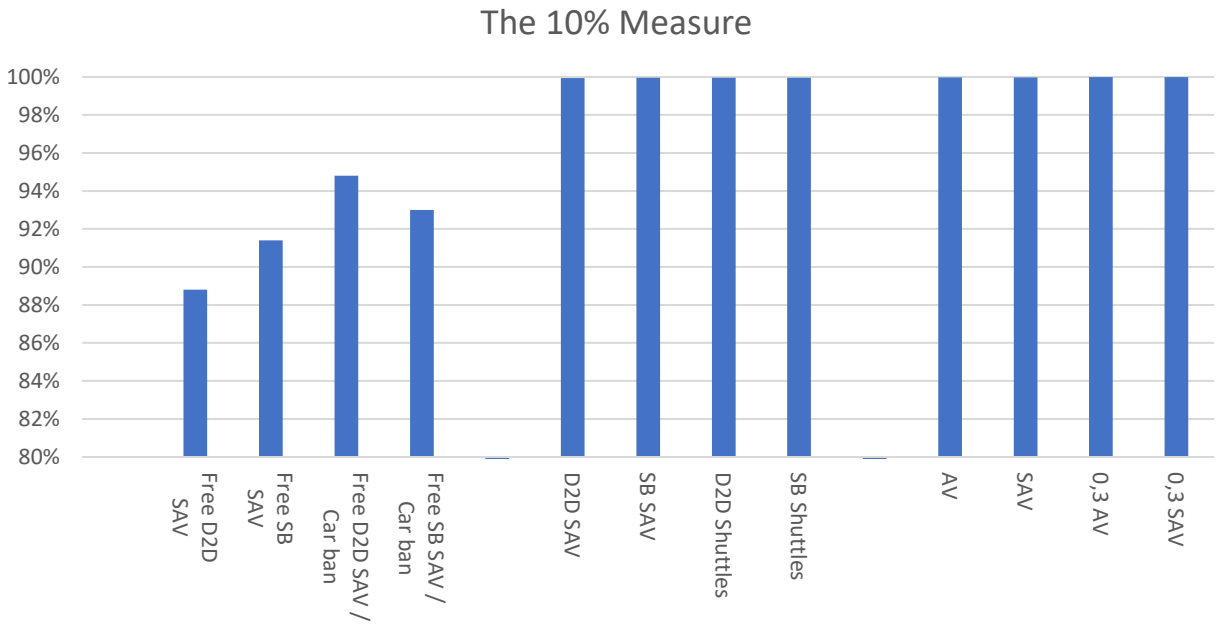

Figure 95. The 10% measure

Source: prepared by the author.

NB: estimates how much of the consumer surplus due to the project implementation is being captured by the 10% of the agents winning the most, expressed as a percentage of the aggregated positive consumer surplus.

c) Gini index

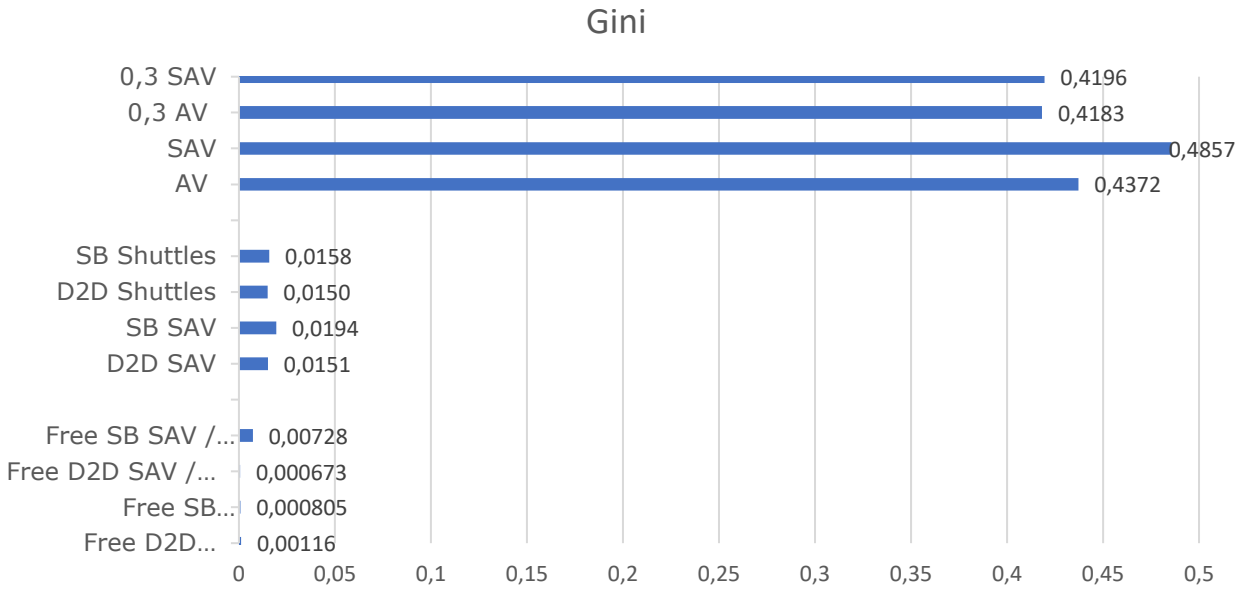

Figure 96. Gini Index of the split of benefits amongst agents
Source: prepared by the author.

The Gini index is here an indicator on the inequality of the split of benefits, not of wealth or earnings inequality. Here the Gini index clearly indicates that the split of benefits is less equitable in the rural case study (Figure 96). The differences between the Berlin scenarios and the Saclay scenarios are tight, but a trend based on the demand density can be identified. The competitiveness of the conventional car in rural territory might decrease the potential AV market share, concentrating the gains amongst fewer agents. Further research will be necessary to confirm or infirm this finding. One should note that the impact of the mode choice model (MATSim for Berlin, Eqasim for Saclay and Dourdan) does not seem to have a strong impact on the repartition of gains.

D. Discussion and recommendations

1) Urban territories

As seen in the Berlin chapter (Carreyre et al. 2023), the addition of on-demand AV services to the current transport supply is not beneficial to any economic agent category in urban settings (see Table 57 and Table 58). The introduction of an additional road transport, which capture a modal share of other non-road transports, has led to an increase in congestion. This result changes when private cars are banned from the city center,

which lows the consumer surplus and increases operating costs, but results in a decrease in the environmental externalities. If the simulations results share similar conclusions with the literature, the evaluation step has shown differences with the literature. By example, both (Kockelman et al. 2017; Andersson and Ivehammar 2019) found positive impacts at the introduction of AVs. These differences may find their origins on scenario design (by example, the differences between the four scenarios presented in this case study illustrate the difference of results) and on value of travel time savings choice.

In the reference scenario, the cumulative modal share of walk, bike and public transit was 56%, which is an important pool of potential customers. The territory showed an important sensibility to road congestion, the consumer loss due to congestion is provoked by a 4% modal share only (mostly originating from bike and PT). The modal shift from public transit and bike can also be found in (Nahmias-Biran et al. 2021). Urban territories with configurations similar to Berlin (important potential modal shift from non-road modes and sensibility to road congestion) should avoid the use of AVs under the tested configurations. The results may increase inversely with the two aforementioned parameters, but the increase in VKT found in this thesis seems to become a general consensus amongst the academic community, (Meyer et al. 2017; Correia and van Arem 2016; Patella et al. 2019; Kloostra and Roorda 2019; Harper Corey D., Hendrickson Chris T., and Samaras Constantine 2018; Zhu et al. 2018; Javanshour, Dia, and Duncan 2019; Childress et al. 2015; Schlüter et al. 2021) also found similar results where the AV introduction would cause an increase of congestion in city centers. This conclusion is shared with (Kockelman et al. 2017) which says that "*for a high-traffic city in the AM peak, these results [*NB: the increased congestion*] are not encouraging for a switch to SAVs*". For example, cities from United-States of America may be less impacted by the externalities due to their more important road infrastructure (two times more road kilometers/inhabitant and two times more parking lots (Joly, Masson, and Petiot 2006)) and already low use of public transit (Joly, Masson, and Petiot 2006).

In the car ban scenarios, the loss of the best modal alternative that the conventional car represents should inverse the trend. The results of an AV introduction may improve as the level of service of existing public transit deceased, raising the interest of an AV service which would not generate congestion. The introduction of AV-based on-demand services should not be introduced in urban areas such as Berlin without concomitant policy (such as a private car ban/restriction). For example, (Poulhès, Berrada, and

Berrada 2022) found a reduction in carbon emissions when introducing electric AVs to replace diesel buses, combined with a 50% modal shift from ICEV private cars trips and active modes trips. Further research on the topic should look into service closer to conventional public transit. Subway automation is known to present high social benefits (Fouillé 2012), so that the road mobility automation may find inspiration in such success. The research focus should shift to heavier modes such as bus lines. The environmental impact should be reduced and the expected operational costs would open an opportunity to arbitrate a tradeoff between consumer surplus (increase the level of service) or operators profits (reduce subsidies and/or increase profits).

Furthermore, the open-environment of the road may include more parameters to handle for in-development AVs than a more controlled area such as a bus line. It may bring benefits to the technical development in addition of those solely based on the infrastructure costs. The 2018-2022 Strategy ((DGITM. Direction générale des infrastructures 2018) NB: this work followed an industrial roadmap which started in 2014) focuses on a car-oriented plan either on highways or periurban and rural areas with a shuttle plan of experimentation for diverse territories. The 2023-2025 Strategy shifted the focus towards more a controlled environment (closed sites, campuses…), stop-based service, line-based service and first-and-last-mile mobility segment. There is no mention of an on-demand door-to-door service on public area anymore. The (Plannig for autonomous vehicles 2023) report found that AVs could be introduced under two service forms, one as an on-demand service and one as a fixed line service. The report warns on the possibility to witness an induced demand with the introduction of AVs. The AVENUE project (now ULTIMA) found comparable results where the replacement of cars by AVs minibuses may reduce externalities, they emphasize the need for urban policies such as "*road pricing or no-car zones*" [12]. Highlights of the urban case study results are summarized in Table 57 and Table 58.

	B_D2D SAV	B_SB SAV
CS	-	-
Profits	-	-
Externalities	-	-
Strength	- Led to a reduction of conventional car trips and conventional car use	- Led to a reduction of conventional car trips and conventional car use
Weakness	- Increases congestion and externalities	- Increases congestion and externalities but less than the D2D alternative
Further research	Optimal congestion pricing and regulation Rebalancing and ridesharing optimization	Optimal congestion pricing and regulation Rebalancing and ridesharing optimization

Table 57. Introduction of on-demand AVs in urban area

Source: prepared by the author.

Recommendations:

In the configuration evaluated in this thesis, on-demand SAV introduction in an urban environment should be avoided, unless furthers research find solutions with the help of optimal pricing or regulation.

Other way of introducing on-demand AVs:

- Heavier modes (bus lines)
- More limited use case (medical, PRM…), intermodality with CPT

	B_D2D SAV/Car ban	B_SB SAV/Car ban
CS	-	-
Profits	-	-
Externalities	+	+
Strength	- The car ban allowed to reduce externalities.	- The car ban allowed to reduce externalities.
Weakness	- Do not succeed to use the increased capacity (8 seats)	- Do not succeed to use the increased capacity (8 seats) - SB less able to compensate the consumer loss due to car ban
Further research	Other concomitant policies should be researched	Other concomitant policies should be researched

Table 58. Introduction of on-demand AVs in urban area in conjunction with a car ban policy

Source: prepared by the author.

Recommendations:

The introduction of shuttles with the car ban has shown more contrasted results. The reduction of externalities gain results more from the car ban than from the introduction of SAVs. As such, SAV introduction may become a part of a comprehensive policy looking to reduce mobility externalities with a compensation for the accessibility loss and financial costs.

Other way of introducing AVs:

- Heavier modes (bus lines)
- More limited use case (medical, PRM), intermodality with CPT

2) Peri-urban territories

For the peri-urban area, the results are more nuanced. The consumer surplus may increase but the financial costs and externalities decrease if the service is added to the existing pool of mobility solutions. The cost to equip the infrastructure and the share of the road network to equip become a more important item to take into consideration when implementing AVs on such a territory. It also has consequences on the type of service which could be implemented. As mentioned previously, the infrastructure costs remain an uncertain item. In case of heavy equipment costs, the AVs service to implement should not be in a door-to-door routing scheme. A Stop-Based routing, with stops fixed at existing public transit stations would allow to equip only the existing public transit itineraries.

As seen in all case studies, shared on-demand AVs benefits from economies of scale when the demand allows it but the intermodality scenario design, where passengers linked one side of their trip to a rail station, shown strong positive results concerning average vehicle occupancy. This intermodality allowed the vehicles to be twice as effective as the rest of the literature may found (see the Saclay Chapter).

For the CPS case study, the simulation results showed that the AVs introduction in intermodality with train station has led to a decrease of the bus lines attendance, which had a similar role with the AVs, i.e. first and last mile segment. Two public modes of transportation in competition may improve the consumer surplus but would surely cost more to operate and would have a negative impact on the environment. (Berrada and Poulhès 2021) found that replacement of CPT by DRT (*NB*: non-autonomous) is not beneficial in a territory comprised in the CPS but outlines the fact that SAV may be more profitable depending on the evolution of CPT and SAV costs. Based on a periurban experiment of SAVs operating in conjunction with a rail station, the same author declared in 2019 that "*The two main B2C forms of mobility services that are expected to emerge are aTaxis and aTransit. The first one is based on mid-sized and/or small vehicles, which ensure a door-to-door on-demand service, probably in a limited operating area, and with the option of ridesharing. The second form of service uses larger vehicles, with fixed route service and loosely scheduled or on-demand service.*" (Berrada 2019, 122).

The periurban area is likely the type of territory where AV on-demand services and conventional public transit services (with fixed routes) may have similar performances. The environmental impact of implementing AVs by replacing existing bus lines or even train lines may be even beneficial if the existing public transit in place had a low average occupancy rate

(Taiebat et al. 2018). The Saclay territory benefits from important rail coverage which explain the potential of the feeder service. The efficiency of the AV feeder service would surely decrease with the decrease of density of the heavy public transit services (rail but also tramway or Bus Rapid Transit). (Sieber et al. 2020) presents comparable recommendations and states that replacement of conventional public transit (i.e. trains) by on-demand services was detrimental when the length of trips and the utilization increased. Similarly with our results, (Poulhès, Berrada, and Berrada 2022) showed that the introduction of AVs in periurban territories rather than in urban territories would have benefits more impactful for the users. As for the operational design of an feeder service, ("Intermodal Autonomous Mobility-on-Demand" n.d.) showed that its implementation could decrease travel times, fleet size and costs. (Song et al. 2021) pointed out that the transit users are a more prone to use an AV service than non-transit users.

Highlights of the periurban case study results are summarized in Table 59 and Table 60.

	D2D SAV	**SB SAV**
CS	+	+
Profits	-	-
Externalities	-	-
Strength	- High Average Vehicle Occupancy	- High Average Vehicle Occupancy - May reduce the network length to equip
Weakness	- Increases congestion and externalities	- Increases congestion and externalities
Further research	Rebalancing and ridesharing optimization	Rebalancing and ridesharing optimization

Table 59. Introduction of on-demand AVs in periurban area under an intermodal system

Source: prepared by the author.

	D2D Shuttle	SB Shuttle
CS	+	+
Profits	-	-
Externalities	-	-
Strength	- High Average Vehicle Occupancy	- High Average Vehicle Occupancy - May reduce the network length to equip
Weakness	- Increases congestion and externalities	- Increases congestion and externalities
Further research	- Other concomitant policies should be researched - Rebalancing and ridesharing optimization	- Other concomitant policies should be researched - Rebalancing and ridesharing optimization

Table 60. Introduction of on-demand AVs in periurban area under an intermodal system

Source: prepared by the author.

Recommendations:

- The intermodality and Stop Based routing combination shows promising results. The combination of both of these features allows to massify flows. The stop network based on existing public transit station reduces the investment required.

Other way of introducing AVs:

- The low occupancy rate bus lines could be replaced by Stop Based Shuttles or Door-to-Door Shuttles.
- The highest congestion which could be attributed to AVs introduction was near the train station. A specific traffic regulation in these areas may mitigate these externalities.

3) Rural territories

The rural case study highlights two significant challenges for the implementation of AVs, the low demand density which does not allow to the

system to benefit from economies of scale, both at the infrastructure level (the rural use is the one for which the fixed costs of infrastructure equipment is the most influential due to lower traffic) and at the vehicle level (i.e. low average vehicle occupancy) and the competition of the existing conventional vehicles with human drivers. To effectively address rural areas, AV manufacturers would need to either deploy AVs with low infrastructure costs or no additional infrastructure requirements, or seek subsidies to offset the financial challenges. The conventional cars represent an important competitor in rural territory. As the fixed price is a sunk cost, the marginal cost to travel with a conventional car will remain lower than the one for an on-demand AV. There is no waiting time, no detour time and space is available both on the road and for parking. These results go against the conclusion of (Childress et al. 2015) which found that the rural inhabitants would likely benefit from accessibility gains, an results which can be explained by their assumption of a reduction of the perception of value of travel time.

The rural case study was the only one where non-rideshared AVs have been experimented. Non-rideshared service shows less interesting results from all economic point of view. However, no comfort penalty has been applied during the simulation for shared rides (except additional detour travel time) which, if some were to be applied, could lead to results more favorable towards non-rideshared service. (Le Gallic and Aguilera 2022) also shown that ridesharing was preferred in denser areas than in rural areas where people would rather chose privately owned vehicles. Research on the willingness to share from econometrics studies show that users show higher estimation value of their travel time when the ride was private (Kolarova 2021, 75), trust issues also arise with ridesharing, especially for women (Bulteau et al. 2023). However (Lavieri and Bhat 2019) show that the additional travel time due to potential delays is "*a greater barrier to shared rides than the actual presence of strangers*".

Despite having most of its area considered as rural, the territory selected for the case study is centered around the Dourdan municipality which is a city with a denser demand than its surroundings. In the other hand, the on-demand service could only serve ride starting and finishing in the area without the ability to operate intermodal trips. This case study outcomes could be generalized in territories organized around a central city which polarizes the flows and with low density of public transit. (Sieber et al. 2020) shows that public transit was advantageous when the distances lengthen and the demand increases. To maintain an acceptable level of service (i.e. a competitive waiting time) in such territories, the operator

would need to increase its fleet size and thus its costs. Highlights of the rural case study results are summarized in Table 61 and Table 62.

	AV	SAV
CS	+	+
Profits	-	-
Externalities	-	-
Strength	- Allows non-car owners to benefit from a similar mode	- Allows non-car owners to benefit from a similar mode
Weakness	- Low Average Vehicle Occupancy - Increases congestion and externalities - Highly dependent on infrastructure costs	- Increases congestion and externalities - Highly dependent on infrastructure costs
Further research	- Rebalancing and ridesharing optimization - Equity analysis based on the social classes	- Rebalancing and ridesharing optimization - Equity analysis based on the social classes

Table 61. Introduction of on-demand AVs in rural area

Source: prepared by the author.

	0,3 AV	0,3 SAV
CS	+	+
Profits	-	-
Externalities	-	-
Strength	- Allows non-car owners to benefit from a similar mode	- Allows non-car owners to benefit from a similar mode
Weakness	- Low Average Vehicle Occupancy - Lower increase in congestion and externalities* - Highly dependent on infrastructure costs	- Lower increase in congestion and externalities* - Highly dependent on infrastructure costs
Further research	- Other concomitant policies should be researched - Rebalancing and ridesharing optimization	- Other concomitant policies should be researched - Rebalancing and ridesharing optimization

Table 62. Introduction of on-demand AVs in rural area

Source: prepared by the author.

**Compared to its free counterpart, the externality impact still increase compared to the basecase*

Recommendations:

- The fares had a positive impact on the CBA results, reducing externalities and financial expenses despite limiting the consumer surplus gains. If many AV users came from walk and bike mode, an additional toll (or any other reglementary tool) on private car use may help to integrate AVs in the mobility landscape with better social results.

Other way of introducing AVs:

- For technical reasons, intermodal scenarios were not simulated despite the presence of major train line stations both at Dourdan and Sermaise. The implementation of on-demand service may allow to

increase the accessibility of train stations. The flexibility and reduced operational costs from AVs may allow to deploy such services.

- The low occupancy rate bus lines could be replaced by Stop Based Shuttles or Door-to-Door Shuttles.

E. Conclusion

As this thesis has shown in the state of the art chapter (Chapter One), AVs services (see Appendix 2) are expected to be deployed under on-demand services (Carreyre et al. 2022) due to the drivers costs savings. This form of service offers a flexible way of transport but may generate externalities when introduced in crowded environments. As seen in (Joly, Masson, and Petiot 2006), the density has a strong relationship with the public transit share, capable of handling massive flows. The yellow part of the Figure 97 should then be avoided in urban environments, but may be of interest in less densely populated areas such as periurban or rural areas. This conclusion confirms the results from (Meyer et al. 2017) which had shown the heterogenous distribution of accessibility gains amongst different types of territories.

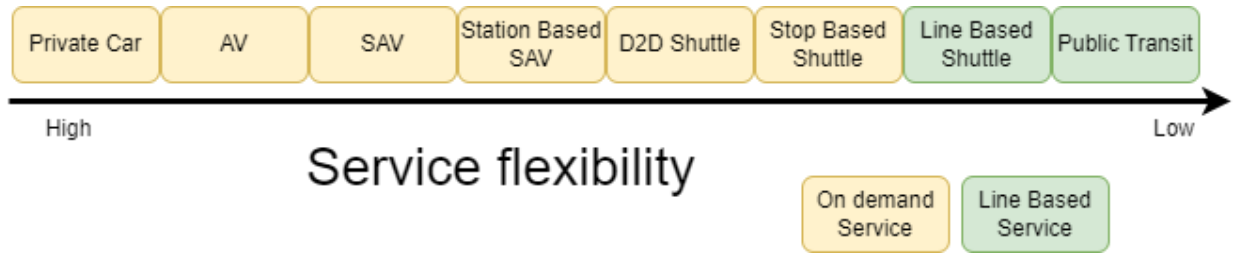

Figure 97. Services flexibility
Source: prepared by the author.

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G. Appendix

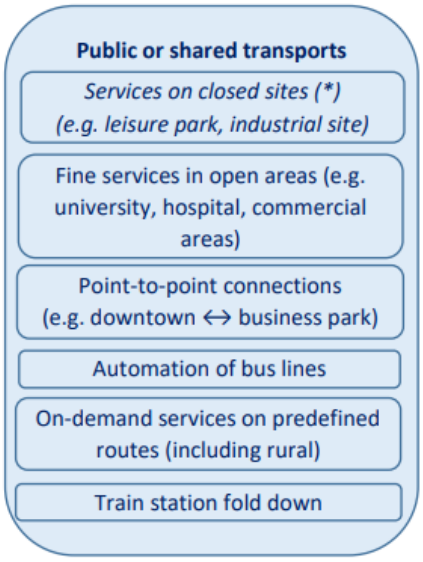

Figure 98. AVs Use case according to French government 2022-2025 Strategy

Source: (DGITM. Direction générale des infrastructures 2023).

Vehicle Type/Capacity	Vehicle Ownership Models	Pooled Option	Temporal Service Attributes	Spatial Service Attributes
Large vehicles (20+ pax)	-B2C model -Hybrid B2C/P2P model	Yes	Fixed-schedule service with potential for some demand-based flexibility	Fixed-route service with potential for some demand-based flexibility
Mid-sized vehicles (7 – 20 pax)	-B2C model -Hybrid B2C/P2P model	Yes	Varies from fixed-schedule service to more flexibly-scheduled service depending on offering	Fixed-route service with slightly more demand-based flexibility than larger vehicles
Small vehicles (3 – 7 pax)	-B2C model -P2P model -Hybrid B2C/P2P model	Yes, depending on the service	Varies from on-demand service to loosely-scheduled service	Varies from point-to-point service to flexible-route and deviating service
Micro vehicles (1 or 2 pax)	-B2C model -P2P model -Hybrid B2C/P2P model	Some cases	Likely on-demand	Likely point-to-point with little or no route deviation

Table 63. Potential SAV Types/Capacities and Service Models

Source: (Stocker and Shaheen 2017)

Conclusion

I. Research questions

The approval in August 2023 of the Californian regulator regarding Waymo operations in San Fransisco - allowing the tech company to operate 24/7 and charge for its service (Choo 2023) after a six hours long debate (Hawkins 2023) - proves the confidence of the regulator in the technical development of autonomous vehicles. As industrials were focusing on the technical development of AVs, academics on assessing their future impacts, the main focus of the research was on operational and commercial AV performance and less and on the type of territories which could benefit form an AV introduction. This thesis endeavors to fill the academic gap through investigating the following research questions with a focus on economic appraisal and territories:

What is the economic performance of AV-based services by considering the perspectives of main stakeholders (i.e., users, operators and public authorities) and how this performance varies with territories? Which configuration/ operating model of AV-based services is more performant to deploy on each type of territory (i.e., urban, peri-urban and rural)?

II. Key findings

In the first chapter, a review of the existing literature on simulation-based assessments of AVs, including both a bibliometric analysis and a meta-analysis have been carried out. Based on the bibliometric analysis, it was found that existing scientific studies focus on operational indicators, and that economic appraisal has seldom if at all been used in previous studies. The meta-analysis provides insights on the relative performance of the main services considered in the literature so far. The main findings are that AV services are expected to result in an increase in mobility at the intensive margin (meaning both in travel time and distance travelled), but with the benefit of a reduction in fleet size. A summary of the main results and limits of this chapter can be found in the dedicated section.

Method	Main results	Limits
Bibliometric analysis	Lack of economic appraisal in the simulation literature Agent-based models are the most used to represent on-demand AV services. Few studies on rural territories	Scope limited to the AV simulation literature
Meta-analysis	On-demand AV services are the most represented in the literature AV services are expected to increase VKT and Travel Time but may reduce the fleet size. Stop-based routing may limit externalities	Heterogeneity in scenario design limiting the pertinence of a meta-analysis Limited statistical occurrences for some comparisons Scope limited to the AV simulation literature

Table 64. Key findings of Chapter 1, and limits

Source: prepared by the author.

The second chapter presents the economic appraisal methodology based on the adaptation of the standard Cost Benefit Analysis (CBA) framework to AV services, which will be applied in the case studies of (Chapter 3. Case Studies).

The third chapter is structured around three case studies, one for an urban territory (Berlin), one for a periurban territory (Saclay or "CPS" for "Communauté d'agglomération de Paris-Saclay") and one for a rural territory (Dourdan, a rural area south of Paris).

The Berlin case study highlights the congestion risk of introducing AVs without regulation. Even if some travelers could benefit from a new alternative, the introduction of a new road transportation service should increase congestion by adding an additional burden on the road network. A summary of the main results and limits of this chapter can be found in Table 65. My findings suggest that transport planners in urban areas should avoid introducing on-demand AVs and favor heavier modes of transportation (train, metro, tramway), or use AVs as a tool in a strategic urban plan (such as a mitigating action to reduce the impact of a conventional car restriction policy).

Method	Main results	Limits
Agent-based simulation	Increased congestion 8 seats are not necessary Door-to-door (D2D) services are more attractive but more resources intensive than Stop-Based (SB) services	No intermodality (except within public transit) No battery charging behavior for EV
Cost-benefit analysis	An overall utility loss for travelers Increase in externalities if the AV service is added to the current mobility mix Decrease in externalities if the AV service is coupled with private car ban.	Environmental impact of AV infrastructure not included Uncertainties regarding the cost parameters

Table 65. Berlin case study, main results and limitations

Source: prepared by the author.

NB: EV stands for "electric vehicles"

The Saclay case study, in a periurban area, provides insights into the integration of on-demand AV services with train services, enhancing intermodal connectivity. This allows for high average occupancy levels for AVs, despite a substantial share of empty kilometers travelled. The AV feeder service competes with bus lines, while increasing the usage of trains. A summary of the main results and limits of this chapter can be found in Table 66. The use of Stop Based routing in coordination with a limited network may motivate to implement AVs in such areas.

Method	Main results	Limits
Agent-based Simulation	Compete with bus lines, feeds train lines High average vehicle occupancy 8 seats are useful Door-to-door (D2D) services are more attractive but more resources intensive than Stop-Based (SB) services	Limited intermodality No battery charging behavior for EV
Cost Benefit Analysis	An overall utility gain for travelers A stop-based routing may reduce AV infrastructure costs An increase in externalities when the service is added.	No environmental impact of the infrastructure Uncertainties concerning financial parameters

Table 66. Paris Saclay (periurban territory) case study, main results and limitations

NB: EV stands for "electric vehicles"

Source: prepared by the author.

Dourdan, the rural case study, presents poor AVs operational performances, compared to the two other case study and the literature. The limited demand in this territory hinders the development of economies of scale, which are necessary for depreciation of potential infrastructure costs. A summary of the main results and limits of this chapter can be found in Table 67. On-demand AVs, which are more in competition with public transit, bike and walk trips than conventional cars, may face challenges to find a place into such territories where conventional cars dominate as the primary mode of transportation.

Method	Main results	Limits
Agent Based Simulation	Compete with bus lines, feeds train lines High average vehicle occupancy 8 seats are useful Door-to-door (D2D) services are more attractive but more resources intensive than Stop-Based (SB)	Limited intermodality No battery charging behavior for EV
Cost Benefit Analysis	A general utility gain for the travelers Infrastructure costs become decisive in the appraisal An increase of externalities when the service is added.	No environmental impact of the infrastructure Uncertainties concerning financial parameters

Table 67. Dourdan (rural territory) case study, main results and limitations

Source: prepared by the author.

NB: EV stands for "electric vehicles"

This thesis has shown that the introduction of on-demand AVs services is a delicate operation. The introduction of AVs should not be pursued solely based on the specific case studies examined in this thesis. Without concomitant policies and well-designed pricing schemes, the introduction of AV is likely to generate undesirable externalities. The most promising use case has been the combination of the feeder service in periurban territory, working in coordination with public transit. This result offers an alternative to the existing business model developed by Waymo which deployed a commercial service of a door-to-door service in urban territory (Choo 2023). As seen in the urban case study, this configuration of robotaxis has shown poor economic perspectives.

III. Main contributions

This thesis contributes to a better understanding of AVs abilities, from an economic perspective, these contributions are both methodological and empirical.

As for the methodological contributions, a Cost Benefit Analysis framework has been developed and a parametric set of reference values

(costs structure, VTTS, environmental impacts, safety) for AVs is proposed. Because AV is a new mode of transportation, the Rule Of The Half is unreliable and an explicit computation of the consumer surplus should be preferred. Here this can be done using the logsum approach in MATSim. This thesis also considers equity considerations by leveraging the disaggregate approach of agent-based models (which allows to study winners and losers) with an easily repeatable framework.

As for the empirical contributions, the economic appraisal framework developed is applied, paired with mobility simulations into three distinct territories. These simulations allowed to forecast mobility behavior and the Cost Benefit Analysis to produce an economic assessment of the forecasted situation. This thesis provides the first systematic and economic comparison of AV introduction in diverse types of territories. The first case study allows to better understand on-demand AVs in an urban environment. The second case study integrates an on-demand AVs service with train lines in a periurban area. Lastly, the third case study implements an on-demand AVs service in a rural area, where solo-ride AVs are assessed. The results of these case studies contribute to a better understanding of the economic performances of on-demand AVs services, considering different routing configurations (door-to-door or stop based) or ridesharing strategies. Finally, during this thesis a tool has been co-developed with CentraleSupelec and SystemX to help gather the most used KPIs in mobility simulation for MATSim users.

IV. Limits

A. Scenarios

For practical matters, a thesis cannot pursue to test all conceivable scenarios. As mentioned in (Lang et al. 2020; Balac et al. 2019; Le Gallic and Aguilera 2022) the scenario design plays an important role in shaping the thesis's results. Here are two scenario design choices which may have influenced the current results. A service implementation can either compete, replace or be integrated with existing mobility solutions. AVs have been implemented in competition, without replacing any existing mobility solutions, the only exceptions to this are the two scenarios involving a ban on conventional cars in Berlin. If there is no attributed externality (such as congestion), this scenario choice should increase the consumer surplus. As for the fare policy, except for the two scenarios for which AVs have a 0.3 euros/km traveled fee, AVs were made free to use. In addition with the competition scheme, this configuration decreases the operators profits

balance. Each result is also limited due to the difficulty to generalize any of the findings when working on social field of experiment.

Secondly, during the simulation step, uncertainties arise at both the vehicle capability level and in traveler behavior. The capacity of vehicle to navigate diverse scenarios, such as separated lanes or mixed traffic, compared to the skills of an average human driver remains an open question. The choice made was to maintain the vehicle's driving ability at the aforementioned average human driver level. On the passenger side, the willingness to use this mode may vary substantially. Further work may be necessary to finetune the utility functions used to define the modal choice and the consumer surplus.

The last uncertainties rely on the financial potential of AVs. The infrastructure needed to facilitate the integration of AVs on conventional roads may constitute an important share of the financial commitment, depending on factors such as the marginal cost of equipping the infrastructure, its length, and its specific characteristics. A decrease in marginal cost of equipping the infrastructure would benefit more to low density areas than high density areas where it is easier to amortize this cost. Similarly, operational costs are forecasted to be at a very low level, estimated at three to four times lower than taxis fares in France (Becker et al. 2020; "Taxis"). A seen in the methodology section, this estimation may represent the optimistic side of the forecast scope. An increase of the operational costs would result in more difficulties to implement them, especially in rural areas where the cost to operate on-demand services is known to be a barrier (White 2016). It would also have an indirect effect on the ability of AVs to capture economies of scale. Higher costs, if reflected in increased prices for customers, would dampen demand and subsequently lower demand density, complicating the aggregation of rides.

B. Mobility simulation

MATSim, the mobility simulation model used for this thesis bears its own limitations. The demand is defined from mobility surveys and the number of trips is attributed to each agent without interaction with the supply side. As such, the level of travel demand (ie. the total number of trips) is fixed: it is not possible to take into account induced demand when creating a positive supply shock, as intended in this thesis. Travel demand works on the topic has highlight that the increase in trips intensity found during this thesis would also be translated into an increase of numbers of trips (Mohammed and Horváth 2023). It may be more important in the rural

areas where people with reduced mobility or non-car owners suffer from a lack of modal alternative and would benefit from the introduction of AVs.

Intermodal trips have not been integrated in the base model, and the development of such features is costly and difficult to implement. Except for the Saclay for which a limited intermodality (as it was an exclusive AV-rail intermodality) was implemented by the IRT SystemX, it was not possible to use such features with the others case studies. It would have positive impact on AV attractivity. The use of on-demand mobility service in intermodality with public transit would increase to pool of potential customers.

Lastly, a limit mentioned at the end of each case study is the AV behavior asymmetry between the simulation and the evaluation step. During the evaluation, all vehicles were considered electric despite the fact that in the simulations, vehicles behavior were calibrated on a ICEV base. No charging behavior has been implemented.

C. Cost Benefit Analysis

1) Valuation of travel, equity and environmental considerations

The Cost Benefit Analysis provides a monocriterion analysis of transport projects. If this criterion has a positive value (i.e. a positive Net Present Value) and that the diverse efficiency ratios (Net Present Value/Investment or Benefit/Cost ratio) are high enough the project should be accepted. This does not exclude the possibility of having agents losing in the operation. The consumer surplus variation is being highly correlated to the speed of the best available mode for each agents, which supposedly allow to gain time. From an historical perspective, the last half century has shown that the speed gain were mostly due to the car market penetration (see Figure 99). The car being the worst regional mode carbon-wise (Bigo 2020, 69 Fig. 32), the increase speed lead to an increase of carbon emissions. With a conventional CBA, the value of travel time savings would have shown preference towards the scenario in which the speed would increase. As the CBA is a decision helper tool to rank project amongst each other based on a monoriterion, the parametrical superiority of the VTTS on the carbon value will predominantly favors scenarios with a negative environmental outcome. Similarly (Bonnafous and Masson 2003) showed that the economic appraisal values projects where more important traffics already exist, leading to the attribution of public fundings (at least the recommendation to fund) in project in already well-equipped areas.

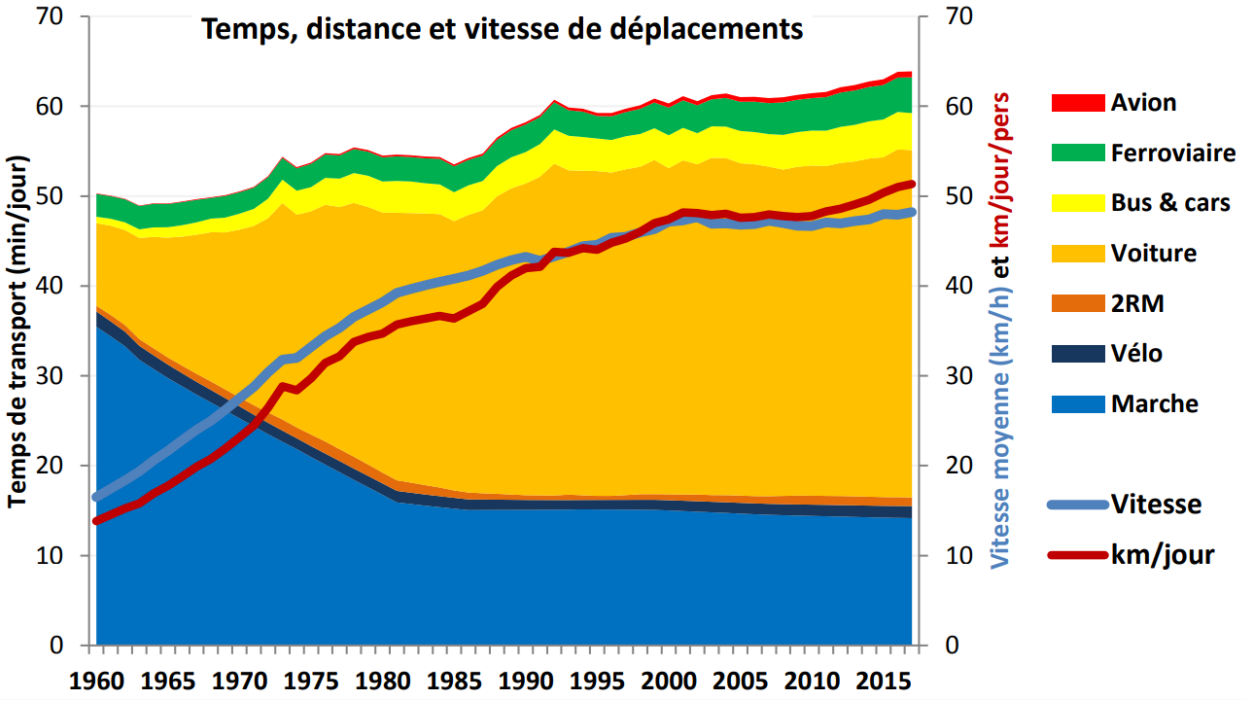

Figure 99. Time, distance and speed of trips
Caption: (left axis: travel time (min/day); right axis: average speed and km/day/people.

Source: Figure 28 from (Bigo 2020)

The Kaldor-Hicks criterion in transport involve that winners should compensate losers. It requires to have a type of compensation that does not have an impact on the marginal cost of use of the solution. "*Farrow (1998) who argues that this compensation – in these sort of cases – should be actual rather than potential."* In OECD, *Cost-Benefit Analysis and the Environment*. CO2 emissions do not comply with the "finite (exhaustible) natural asset" definition (OECD) for which a share of the benefit of exploiting must be save in order to develop a new asset when CBA is dealing with sustainability matter. As seen in this thesis, the AV introduction might generate additional carbon emissions. As such using the CBA as a fundamentally monocriterion analysis may substantially overlap environmental analysis. Increasing the carbon price may be a false good idea, depending on the curb price. If the price increase is progressive, it may cause the counter-intuitive results of increasing carbon emissions known as the Green Paradox firstly introduced by Hans-Werner Sinn in (Sinn 2012). As mentioned in (OECD 2018, chap. 14) : "*The Green Paradox states that certain policies that are aimed at reducing carbon emissions and*

abating climate change, may have the reverse effect of increasing emissions in the near-term, and potentially reducing welfare. The mechanism via which this can happen is that a steeply rising carbon tax, or rapidly falling cost of renewables (the backstop technology), has a similar effect as an expropriation risk: it makes fossil fuels worthless in the future and hence accelerates extraction by fossil fuel companies now (Sinn, 2008; van der Ploeg and Withagen, 2015). (Schneider 2023) recommends to fix an high carbon tax value and to make it rise quickly ("*starting high, rising fast*") but the critical impact of climate deregulation challenges the limited impact of carbon price on CBA. The CBA should then be used as a multicriteria decision tool rather than a monocriterion as is it intended.

V. Recommendations for future research

Future research should focus on deepening the economic appraisal framework developed in this thesis with the regular update of the reference values proposed. Additionally, a complementary approach would be highly beneficial, as seen previously, the Cost Benefit Analysis fails to appreciate the environmental impact. The use of a multicriteria analysis or environmental impact assessment would complement the economic analysis delivered in this thesis. The uncertainty surrounding AV costs will also necessitate frequent updates as the understanding of the technology improves.

As for the simulation steps, the use of a more detailed synthetic population may allow to provide a better understanding of the impacts of AVs on different types of population. The promises of AVs services to provide a mobility service for vulnerable populations such as people with reduced mobility, the elderly or the younglings could be evaluated. The consideration for accessibility would reinforce the induced demand mechanism. Furthermore, following works should focus on developing intermodal feature to evaluate scenarios of AV as an integrated mobility solution.

Future works on AVs service design should focus on diversifying scenarios. Concomitants policies should be implemented in concert with AVs experimentations. The use of free car zone, modifications of traffic network or public transit supply may have important impact on relative AVs attractivity amongst the pool of mobility alternatives. AVs pricing policies or fiscal policies should be experimented to optimize AVs implementation outputs. Finally, other types of AVs services should be tested. The results of the Berlin case study indicate that automated bus lines may have better

economic results than on-demand AVs services in dense areas. Autonomous vehicles services will not solve all mobility challenges, they may even exacerbate a few if not integrated correctly in mobility policies.

VI. References

La mise à jour automatique des citations est désactivée. Pour voir la bibliographie, cliquez sur Actualiser dans l'onglet Zotero.

Abstract

The 2010’ has seen a spectacular interest for autonomous vehicles. This thesis delves into the potential economic impact of this upcoming mode of transportation. Employing mobility simulations and economic assessment tools, the study investigates the effects of on-demand mobility services across urban, peri-urban, and rural landscapes.

The findings shed light on differing impacts. In urban settings, the introduction of autonomous taxis could exacerbate traffic congestion and disrupt the travel experience. However, in peri-urban areas, integrating autonomous vehicles with existing train systems could enhance overall accessibility. Conversely, in rural regions, on-demand vehicle services struggle to rival the prominence of conventional cars.

These insights emphasize the need to regulate the introduction of autonomous vehicles in order to limit the undesirable externalities as well as the financial costs, firstly of infrastructure.

Résumé

Les années 2010 ont été marquées par l'engouement pour les véhicules automatisés. Cette thèse analyse les potentiels impacts économiques des différentes formes de ce nouveau mode de transport. Ce travail utilise des simulations de mobilité et des outils d’évaluation économique pour appréhender les impacts de service de mobilité à la demande sur trois territoires différents (urbain, périurbain et rural).

Les résultats montrent que l’introduction de taxis automatisés en milieu urbain pourraient provoquer des embouteillages et nuire au bien-être des voyageurs. Cependant, en milieu périurbain, une combinaison train - véhicules autonomes pourrait améliorer l'accessibilité. En milieu rural, les services de véhicules peinent à contester la place de la voiture conventionnelle.

Ces travaux contribuent à mettre en lumière la nécessité d’une régulation des VA afin d’éviter des externalités indésirables et des dépenses importantes, notamment celles d’équipement d’infrastructure.