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

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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 online-based options such as automated bus services.

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

INTRODUCTION

Autonomous vehicles (AV) have attracted strong attention from both the industry and academics. AV market size is expected to hit up to 2 trillion dollars by 2040 [1]. 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 [2]–[5].

While simulation models allow forecasting operational trends, they lack a comprehensive scope to include the perspectives of main economic agents. [6] 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. [7] 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 [8]. [9] 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. [10] 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 [1], [11], [12], 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 [5] 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 [13]–[15] which have been adopted in many countries as the reference method to evaluate projects [15, p. 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.

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.

Model

MATSIM

MATSim is an agent-based mobility simulation framework [16]. 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 [5]. 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. 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.

Demand Responsive Transport (DRT)

MATSim allows to simulate and study Mobility-on-Demand systems through the DRT Module [17]. 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 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 [18].

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 [13], [19]–[21]. Several criticism and works had risen the last several decades [22]–[24] 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) [25]. Governments have since published methodological guides [26]–[28] and provided reference values which are regularly updated.

In this paper, we use the French CBA guidelines [26], 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 on three different use cases, 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 use cases 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 [26], [29]) 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 1).

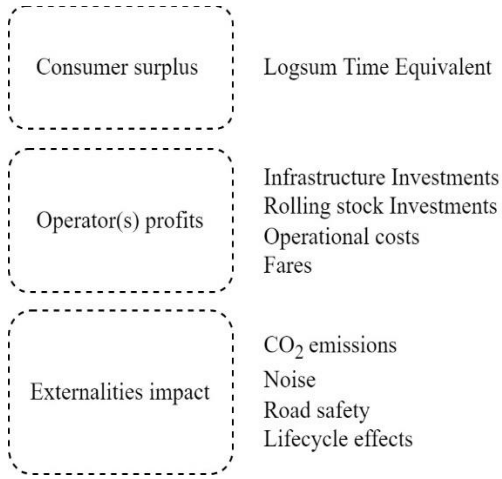


Figure 1 Cost Benefit Analysis sub-components

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.*" [30]. The utility is based on the MATSim plans score according to the methodology developed by [31], [32]. 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 [32, pp. 54, 55] the overall Consumer Surplus change, with individuals j = 1..J, is:

$$\Delta CS = \sum_{j=1}^{J} \Delta m_j \tag{1}$$

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:

$$\Delta m_j = \Delta t_j \times VTTS_j \tag{2}$$

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).

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

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

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 [33] per year and per kilometer to more than two millions dollars [34, p. 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 $\left(M_{Infra}\right)$ 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 [10], [35]–[41]. The most extensive study on light vehicles such as cars or shuttles can be found in [36]. Automation is supposed to add 5,000 US dollars to the vehicle price. A similar assumption can be found in [40], 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 [41] indicated that automation would cost between 9,400 £ and 15,000 £ more per car. [39] 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 [36], [41] based on the 26,000 euro average selling price of a new car in France [42]. The total markup estimated for AVs is 7,500 euros per vehicle.

For EVs, [43], on which the study by [36] is based, do not consider any markup compared to thermal vehicles. Similar to [41], the electric impact can be found in the operational, maintenance and insurance costs, but no purchase price variation seems to be applied. [37] 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, [44] 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 [37]. All the aforementioned parameters value can be found in Table 1.

Table 1. Automation impact factors based on the automation level and vehicle size.

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%

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}.

[36] 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 [43], a paper that also provides more insights into the influence of territory type on costs. [45] 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 [45]. However, [36] 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 [46]. In the AV financial analysis field, [47] 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 [43, 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 [43, p. 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 2.

TABLE 2 Operator(s) profits parameters

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 €

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:

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

Externalities impacts

Externalities of AV (Ext) are divided into four sub-components, based on the segmentation by [26]. 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, [26] provides a monetary value for every ton of CO^2 emitted for every year. This value has been reviewed in [48] 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 (See Appendix 1). Emissions for EVs or hybrid

vehicles will need to be adapted for every use case with similar data to those in [26], [49], [50], or [51]. The automation impact remains uncertain, as [52] 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. [51, p. 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 [50].

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 [53], 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 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. [54] 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 [53]). 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 [53]. 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 [26] 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 [26]. [55] 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 [56] recommendations. Lastly, road safety is considered as AV are also expected to decrease accidents rates. [57] 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. [60] 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 [61, p. 18], with 5 deaths per billion vehicle kilometers travelled. All the aforementioned parameters value can be found in Table 3.

TABLE 3 Externalities impact parameters

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%*

Consequently, the externalities could be calculated using:

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

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 2).

Figure 2 Scenario comparison methodology

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" ([13, p. 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 [13], 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. [26] suggests using a 2.5% annual discount rate, which is close to the 3% recommended by the European Commission for most European countries [13, p. 33]. This value may be considered low compared to the amount that may be attributed elsewhere (up to 15 or 18%), but [62] 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. [26, p. 173] recommends to adjust the price of statistical life with the GDP per capita evolution which should evolve at a 1.2% rate [63]. It also recommends to adjust the LCA values by the GDP/capita evolution rate but as these values retained in [26] 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 [48, p. 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 [63] 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 4.

TABLE 4 Contextual parameters

	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 Road safety	CO2 emissions	CO2 emissions LCA

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.

USE CASE

The appraisal methodology is applied to Berlin, Germany. The choice of Berlin as an urban use case follows two criteria. First, most simulations have taken place in urban environments [5], 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 [64], which allows to easily replicate the tested scenarios.

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.

MATSim Berlin

Ziemke et al. opened access to a new MATSim Berlin model [64] 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 compared 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.

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 [5] 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 [12, p. 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 [65], has launch a robo-taxi service in Phoenix [66]. 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 [5] 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 [67]–[70], 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 [5], 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 [71].

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 5). 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[1]. In a second step, the CBA scenarios set will be composed of four AV scenarios and the basecase (can be found in the Table 1, "CBA scenario" column). AV scenarios can be found in-between "forecasts" and "what-if" scenario" [72]. 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) prompt 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.

TABLE 5 Simulations and evaluation sets

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	*

[1] 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.

RESULTS

Simulations Results and Discussion

General results

The most significant result is that, except for car ban scenarios, AV will attract passengers from all other modes (Figure 3) and contribute to road congestion. Car drivers, even if they travel less distance overall (Figure 4), spend more time travelling due to the increase in congestion (Figure 3). 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 A.1). 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 [5].

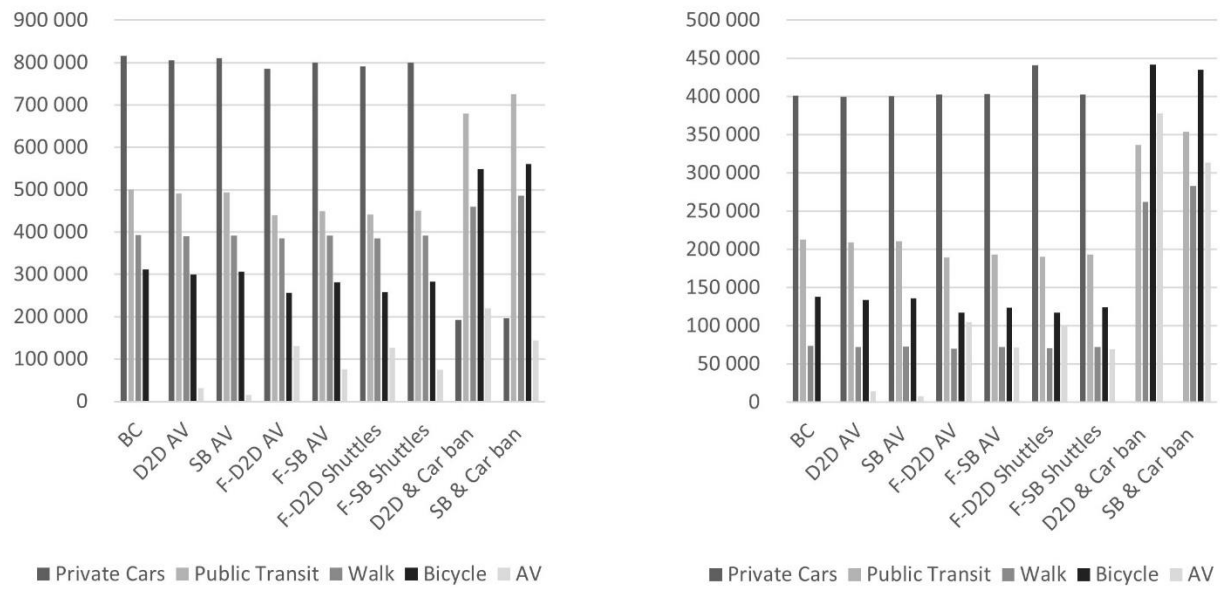
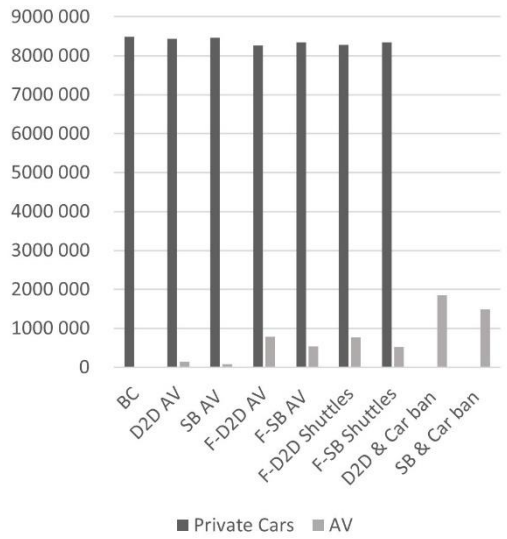


Figure 3 Trips per day (left) and Travel Time (right)



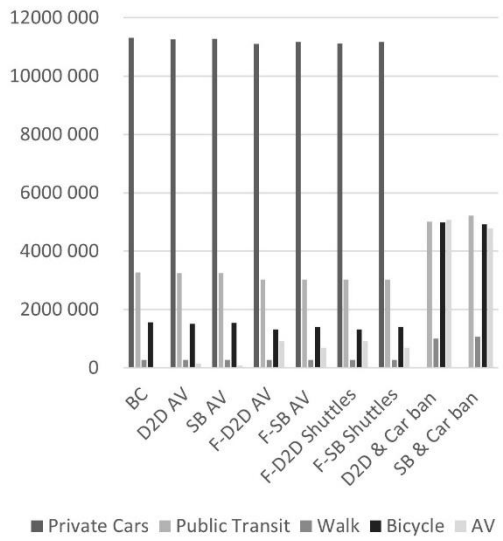


Figure 4 Vehicle Kilometer Traveled (left), Distance Traveled (in pass.km, right)

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 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.

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 5), probably due to a better level of service (Figure 6) 2) D2D is more resource consuming (Figure 7) due to a more important demand. The D2D consistently presents 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 [67]–[70].

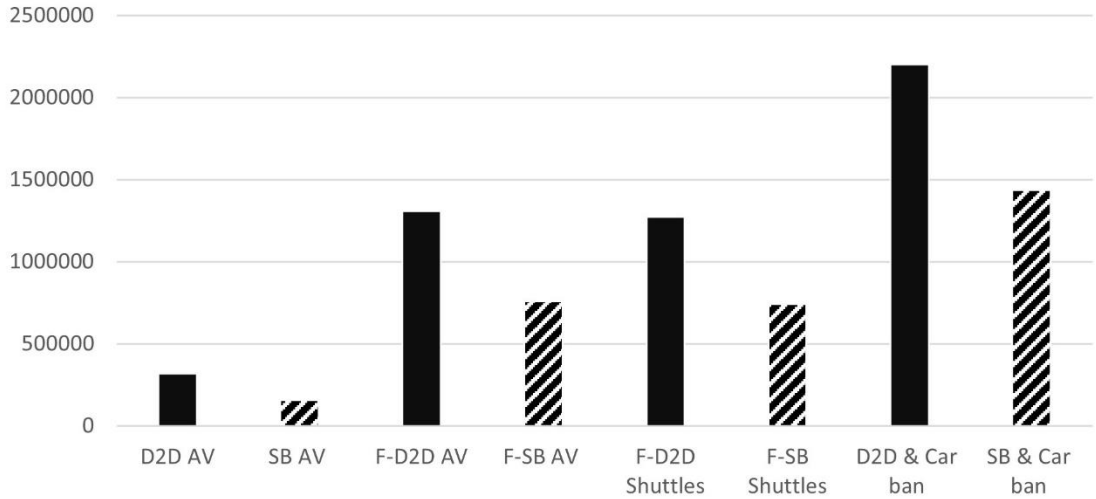


Figure 5 AV Trips per day

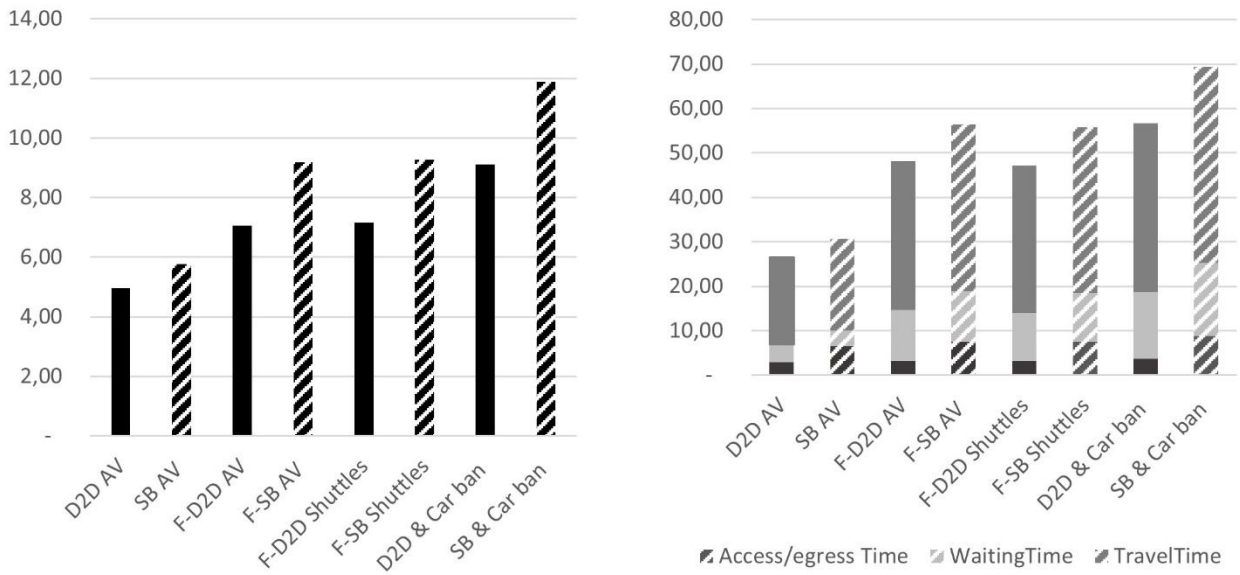


Figure 6 Average Distance Traveled per trip (km, left) and Average Total Traveled Time (min, right)

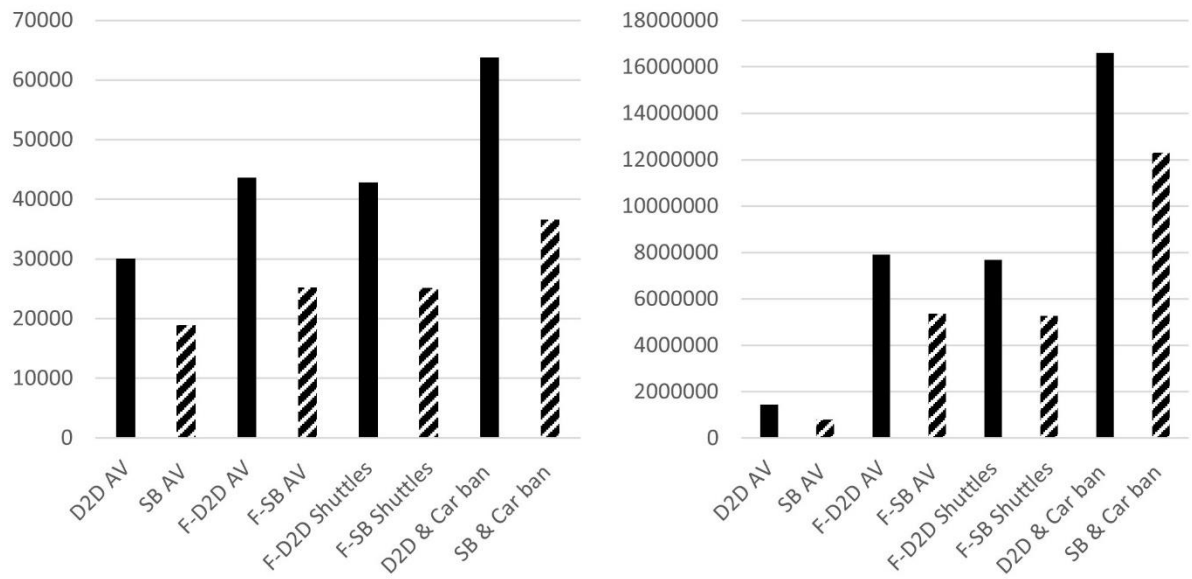


Figure 7 AV Fleet Size (left) and AV Vehicle Kilometers Traveled (right)

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

Cost Benefit Analysis Results and Discussion

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 8). 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.

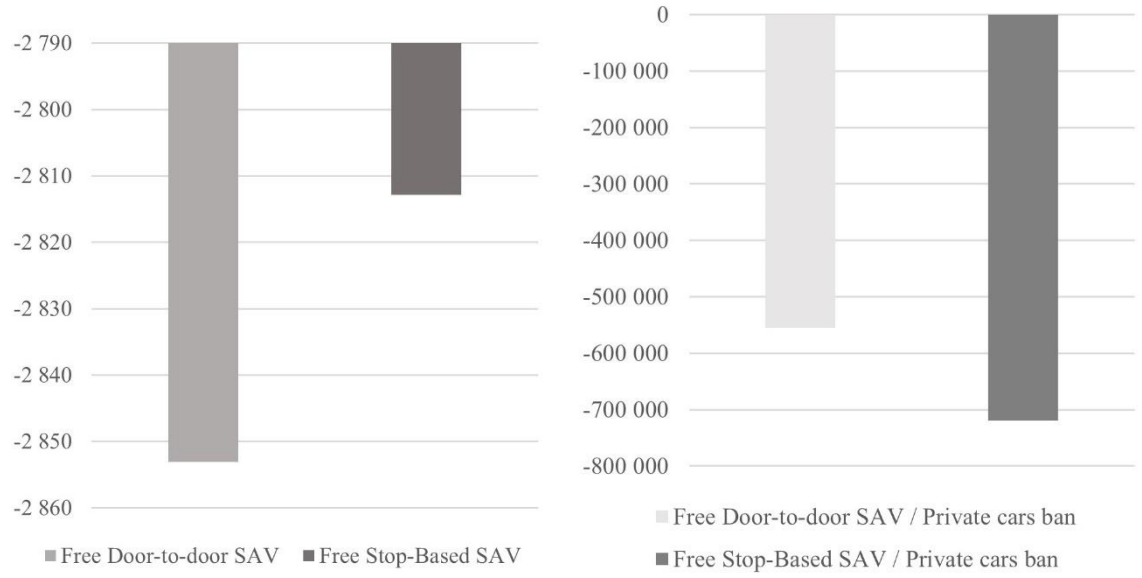


Figure 8 Consumer surplus (10 years term, millions € differences with basecase)
NB: for scale reasons, the variation of consumer surplus are represented in two figures.

The CS loss found for the two car ban scenarios is 200 times larger than for the first two scenarios (Figure 8). The loss on 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 3) 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 [7], [10], [73] 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. [10] chose to reduce the VoT from 75% to 93% which largely offsets the slight modal shift effect from trains to AVs. [7] reduced the VoT by 50% which counterbalance the increase of VMT (+10%), congestion and travel time. [73] 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, [34] 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. [9] 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 9) 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.

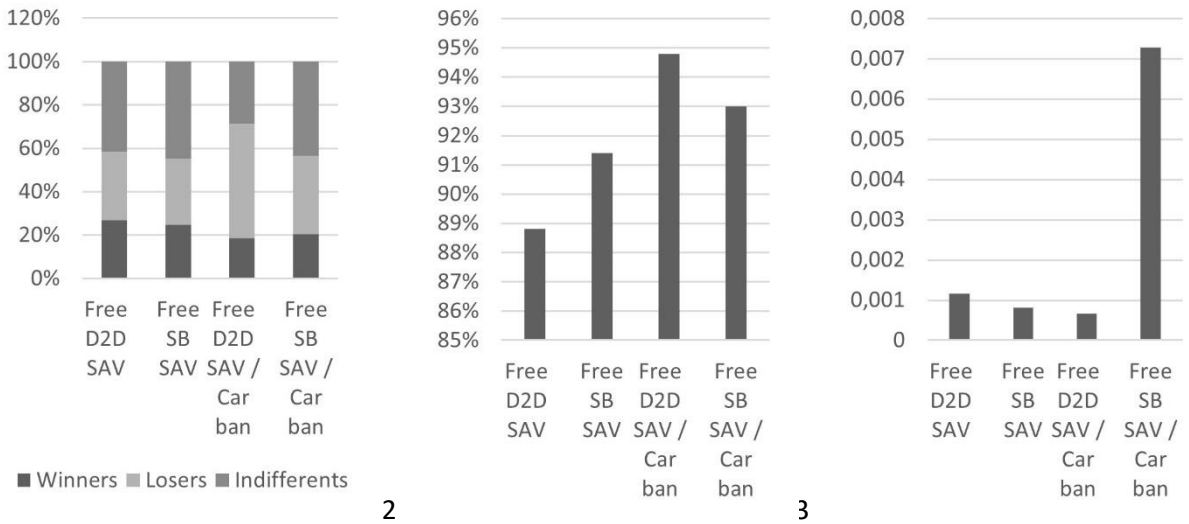


Figure 9 Equity KPIs Winners versus Losers (left), the 10% measure (middle) and Gini index (right)

Operator profits

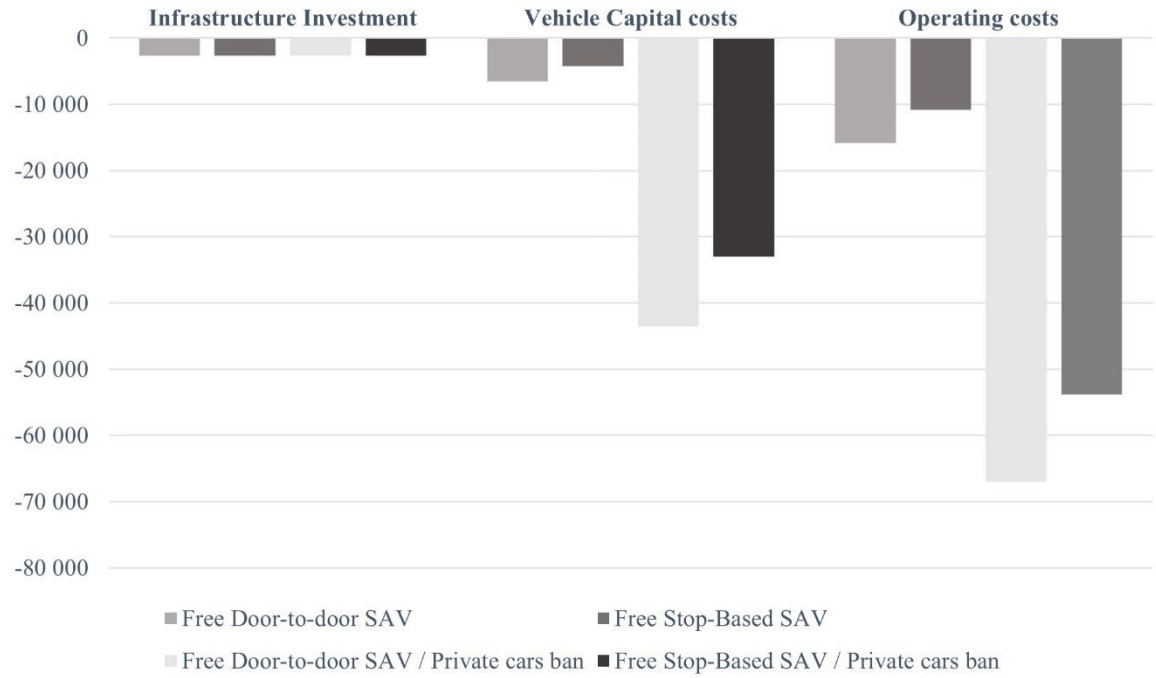


Figure 10 Financial surplus (10 years term, millions € differences with basecase)

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 10). 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 A.1). 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.

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 11). The AV efficiency (less emissions and less accident per kilometers) do not compensate. [74] 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 [75] 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.

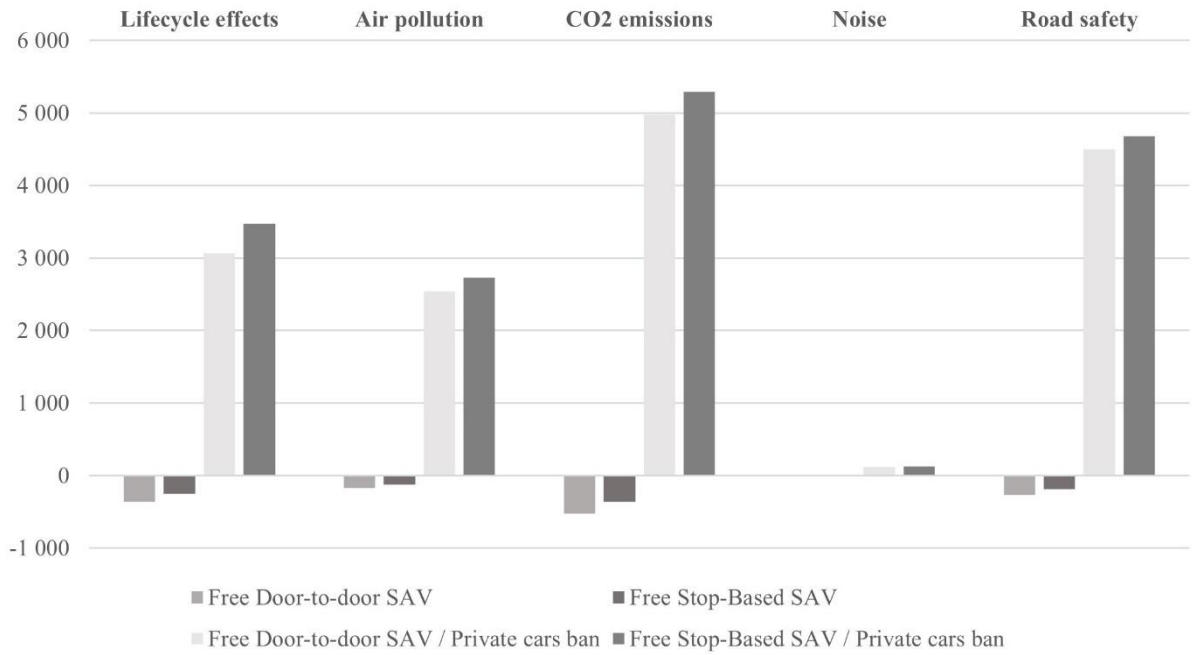


Figure 11 Externalities impact (10 years term, millions € differences with basecase)

These results are consistent with the literature [7], [10], [34] in which externalities can also be found to decrease with the AVs introduction. [9], 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. [34] 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.

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 12). These results are consistent with [76]. The gain for few users does not tradeoff 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).

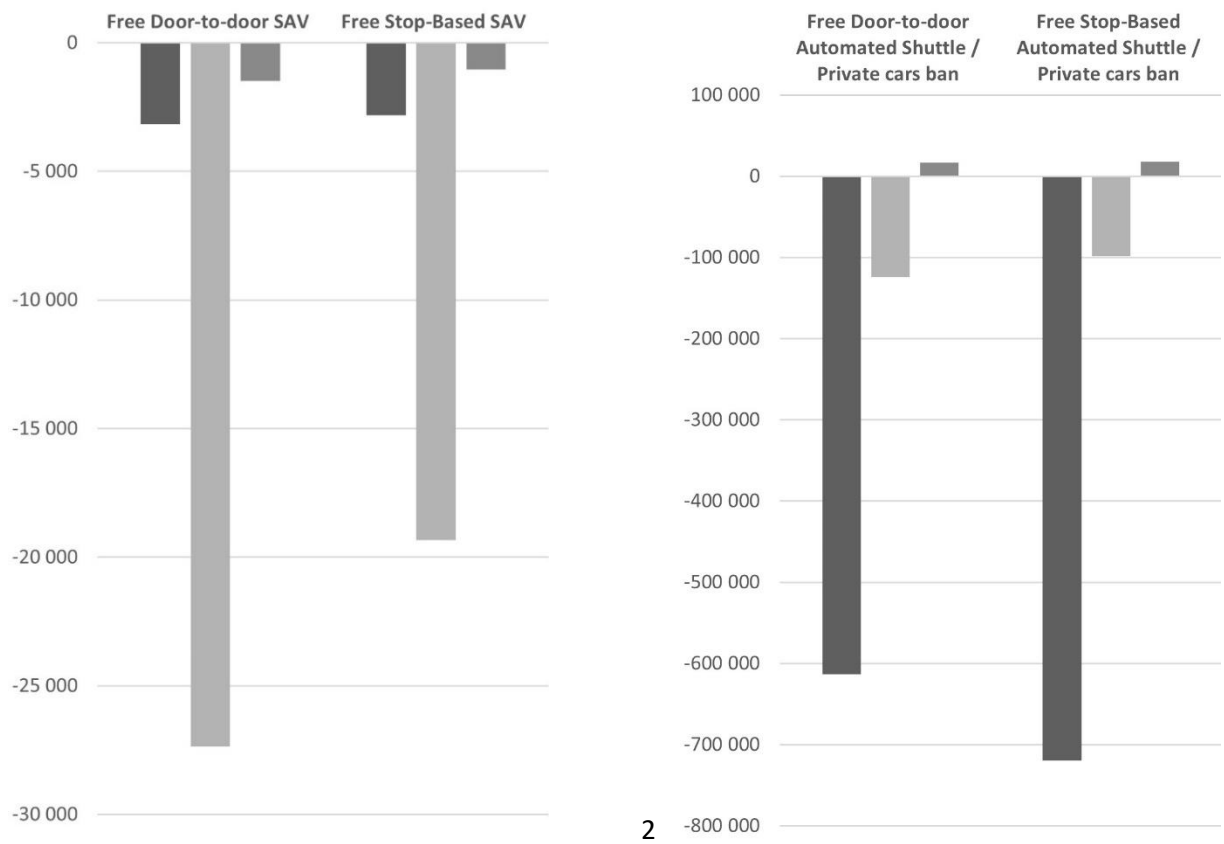


Figure 12 Net Present Value (10 years term, compared to basecase, millions €)

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 [7], [10], [73]. The difference of items considered in others financial evaluation of AVs which did not include infrastructure costs or supervision costs [9]. In the other hand, the externalities results seems to be consistent with the literature. As mentioned in [77], 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*".

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 as 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 use case 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. [78] 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.

The next step for the AV economic evaluation would be to propose a territorial comparison with a less densely inhabited areas such a suburban territory. The equity analysis should be spatialized and it should help to identify which sun-groups of the population would gain or lose for AV introduction.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: All; data collection: TC; analysis and interpretation of results: All; draft manuscript preparation: FC&TC. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

[1] McKinsey Center for Future Mobility, “The future of mobility is at our doorstep,” McKinsey, 2020.

[2] M. Balac, S. Hörl, and K. Axhausen, “Fleet Sizing for Pooled (Automated) Vehicle Fleets,” *Transportation Research Record Journal of the Transportation Research Board*, Jul. 2020, doi: 10.1177/0361198120927388.

[3] P. M. Bösch, F. Ciari, and K. W. Axhausen, “Autonomous vehicle fleet sizes required to serve different levels of demand,” *Transportation Research Record*, vol. 2542, no. 4, pp. 111–119, 2016, doi: 10.3929/ethz-b-000104743.

[4] G. Ben-Dor, E. Ben-Elia, and I. Benenson, “Determining an Optimal Fleet Size for a Reliable Shared Automated Vehicle Ride-Sharing Service,” *Procedia Computer Science*, vol. 151, pp. 878–883, Jan. 2019, doi: 10.1016/j.procs.2019.04.121.

[5] F. Carreyre, N. Coulombel, J. Berrada, and L. Bouillaut, “Economic evaluation of autonomous passenger transportation services: a systematic review and meta-analysis of simulation studies,” *Revue d’économie industrielle*, no. 178–179, Art. no. 178–179, Sep. 2022.

[6] T. Ahmed, M. Hyland, N. J. S. Sarma, S. Mitra, and A. Ghaffar, “Quantifying the employment accessibility benefits of shared automated vehicle mobility services: Consumer welfare approach using logsums,” *Transportation Research Part A: Policy and Practice*, vol. 141, pp. 221–247, Nov. 2020, doi: 10.1016/j.tra.2020.09.002.

[7] K. Kockelman *et al.*, “An assessment of autonomous vehicles : traffic impacts and infrastructure needs,” FHWA/TX-17/0-6847-1, Mar. 2017. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/31990

[8] “40+ Corporations Working On Autonomous Vehicles,” 2020. [Online]. Available: https://www.cbinsights.com/research/autonomous-driverless-vehicles-corporations-list/

[9] I. Kaddoura, J. Bischoff, and K. Nagel, “Towards welfare optimal operation of innovative mobility concepts: External cost pricing in a world of shared autonomous vehicles,” *Transportation Research Part A: Policy and Practice*, vol. 136, pp. 48–63, Jun. 2020, doi: 10.1016/j.tra.2020.03.032.

[10] P. Andersson and P. Ivehammar, “Benefits and Costs of Autonomous Trucks and Cars,” *Journal of Transportation Technologies*, vol. 9, no. 2, pp. 121–145, Mar. 2019, doi: 10.4236/jtts.2019.92008.

[11] J. Berrada, “Technical-economic analysis of services based on autonomous vehicles,” Paris-Est, 2019.

[12] S. Mira Bonnardel, F. Antonialli, and D. Attias, “Autonomous Vehicles toward a Revolution in Collective Transport,” in *Autonomous Vehicle and Smart Traffic*, S. Ersoy and T. Waqar, Eds. IntechOpen, 2020, pp. 21–32. doi: 10.5772/intechopen.89941.

[13] G. de Rus, M. Socorro, J. Campos, D. Graham, J. Valido, and P.-O. Johansson, *Methodology for the cost-benefit analysis of transport projects and policies.* 2020.

[14] G. de Rus, *Introduction to Cost–Benefit Analysis: Looking for Reasonable Shortcuts*. Edward Elgar Publishing, 2021.

[15] C. Koopmans and N. Mouter, “Chapter One - Cost-benefit analysis,” in *Advances in Transport Policy and Planning*, vol. 6, Academic Press, 2020, pp. 1–42. doi: 10.1016/bs.atpp.2020.07.005.

[16] A. Horni, K. Nagel, TU Berlin, and K. W. Axhausen, *The Multi-Agent Transport Simulation MATSim*. Ubiquity Press, 2016. doi: 10.5334/baw.

[17] M. Maciejewski and K. Nagel, “Simulation and dynamic optimization of taxi services in MATSim,” *Transportation Science*, p. 34, 2013.

[18] J. Bischoff and M. Maciejewski, “Simulation of City-wide Replacement of Private Cars with Autonomous Taxis in Berlin,” *Procedia Computer Science*, vol. 83, pp. 237–244, Jan. 2016, doi: 10.1016/j.procs.2016.04.121.

[19] R. W. Boadway, “The Welfare Foundations of Cost-Benefit Analysis,” *The Economic Journal*, vol. 84, no. 336, pp. 926–939, 1974, doi: 10.2307/2230574.

[20] A. E. Boardman, D. H. Greenberg, A. R. Vining, and D. L. Weimer, *Cost-Benefit Analysis: Concepts and Practice*. Cambridge University Press, 2017.
[21] OECD, *Cost-Benefit Analysis and the Environment: Further Developments and Policy Use*. OECD, 2018. doi: 10.1787/9789264085169-en.
[22] D. Asplund and J. Eliasson, "Does uncertainty make cost-benefit analyses pointless?," *Transportation Research Part A: Policy and Practice*, vol. 92, pp. 195–205, Oct. 2016, doi: 10.1016/j.tra.2016.08.002.
[23] M. Börjesson and J. Eliasson, "Should values of time be differentiated?," *Transport Reviews*, vol. 39, no. 3, pp. 357–375, May 2019, doi: 10.1080/01441647.2018.1480543.
[24] P. Beria, I. Maltese, and I. Mariotti, "Multicriteria versus Cost Benefit Analysis: a comparative perspective in the assessment of sustainable mobility," *Eur. Transp. Res. Rev.*, vol. 4, no. 3, Art. no. 3, Sep. 2012, doi: 10.1007/s12544-012-0074-9.
[25] Congress, *Flood Control Act of 1936*. U.S. Government Publishing Office, 2018. Accessed: Aug. 01, 2022. [Online]. Available: https://www.govinfo.gov/app/details/https%3A%2F%2Fwww.govinfo.gov%2Fapp%2Fdetails%2FCOMPS-9543
[26] E. Quinet, "L'évaluation socioéconomique des investissements publics," Commissariat général à la stratégie et à la prospective, 2013. [Online]. Available: https://www.strategie.gouv.fr/espace-presse/levaluation-socioeconomique-investissements-publics
[27] "Document: Cost Benefit Analysis Guidelines," *Millennium Challenge Corporation*. https://www.mcc.gov/resources/doc/cost-benefit-analysis-guidelines (accessed May 30, 2022).
[28] "Cost Benefit Analysis Guidance," *CEO Water Mandate*, 2014. https://ceowatermandate.org/resources/cost-benefit-analysis-guidance/
[29] A. Gühnemann, "International Comparison of Transport Appraisal Practice - Annex 2 Germany Country Report," Apr. 2013.
[30] G. de Jong, A. Daly, M. Pieters, and T. van der Hoorn, "The logsum as an evaluation measure: Review of the literature and new results," *Transportation Research Part A: Policy and Practice*, vol. 41, no. 9, pp. 874–889, Nov. 2007, doi: 10.1016/j.tra.2006.10.002.
[31] B. Kickhöfer, K. Nagel, and K. Nagel, "Microeconomic Interpretation of MATSim for Benefit-Cost Analysis," in *The Multi-Agent Transport Simulation MATSim*, ETH Zürich, TU Berlin, A. Horni, ETH Zürich, and TU Berlin, Eds. Ubiquity Press, 2016, pp. 353–364. doi: 10.5334/baw.51.
[32] B. Kickhöfer, "Economic Policy Appraisal and Heterogeneous Users," 2014. doi: 10.14279/depositonce-4089.
[33] T. U. Saeed, "Road Infrastructure Readiness for Autonomous Vehicles," 2019. doi: 10.25394/PGS.8949011.v1.
[34] S. Xue, "Minimum Physical Infrastructure Standard for the Operation of Automated Driving Part D: Economic Analysis of Investment Options," p. 61, 2022.
[35] G. S. Bauer, J. B. Greenblatt, and B. F. Gerke, "Cost, Energy, and Environmental Impact of Automated Electric Taxi Fleets in Manhattan," *Environ. Sci. Technol.*, vol. 52, no. 8, pp. 4920–4928, Apr. 2018, doi: 10.1021/acs.est.7b04732.
[36] H. Becker *et al.*, "Impact of vehicle automation and electric propulsion on production costs for mobility services worldwide," *Transportation Research Part A: Policy and Practice*, vol. 138, pp. 105–126, Aug. 2020, doi: 10.1016/j.tra.2020.04.021.
[37] A. Ongel, E. Loewer, F. Roemer, G. Sethuraman, F. Chang, and M. Lienkamp, "Economic Assessment of Autonomous Electric Microtransit Vehicles," *Sustainability*, vol. 11, no. 3, p. 648, Jan. 2019, doi: 10.3390/su11030648.

[38] N. Quarles and K. Kockelman, "How will self-driving vehicles affect U.S. megaregion traffic ? The case of the Texas triangle," Jan. 2018, Accessed: Jan. 22, 2019. [Online]. Available: https://www.caee.utexas.edu/prof/kockelman/public_html/TRB19TXMegaregionAVs.pdf

[39] A. Tirachini and C. Antoniou, "The economics of automated public transport: Effects on operator cost, travel time, fare and subsidy," *Economics of Transportation*, vol. 21, no. C, 2020, [Online]. Available: https://econpapers.repec.org/article/eeeecotra/v_3a21_3ay_3a2020_3ai_3ac_3as2212012219300802.htm

[40] Z. Wadud, "Fully automated vehicles: A cost of ownership analysis to inform early adoption," *Transportation Research Part A: Policy and Practice*, vol. 101, pp. 163–176, Jul. 2017, doi: 10.1016/j.tra.2017.05.005.

[41] Z. Wadud and G. Mattioli, "Fully automated vehicles: A cost-based analysis of the share of ownership and mobility services, and its socio-economic determinants," *Transportation Research Part A: Policy and Practice*, vol. 151, pp. 228–244, Sep. 2021, doi: 10.1016/j.tra.2021.06.024.

[42] C. Leroy, "Le prix de vente des voitures neuves évince une partie de la clientèle," *Journal Auto*, Dec. 08, 2021. https://journalauto.com/data-center/le-prix-de-vente-des-voitures-neuves-evince-une-partie-de-la-clientele/

[43] P. M. Bösch, F. Becker, H. Becker, and K. W. Axhausen, "Cost-based analysis of autonomous mobility services," *Transport Policy*, vol. 64, pp. 76–91, May 2018, doi: 10.1016/j.tranpol.2017.09.005.

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

[45] R. Abe, "Introducing autonomous buses and taxis: Quantifying the potential benefits in Japanese transportation systems," *Transportation Research Part A: Policy and Practice*, vol. 126, pp. 94–113, Aug. 2019, doi: 10.1016/j.tra.2019.06.003.

[46] J. Scoliege, "Conception d'un centre de supervision pour véhicules autonomes : Apport de l'ergonomie prospective," ARPEGE - Doctoriales 2021, 2021. Accessed: Mar. 29, 2022. [Online]. Available: https://arpege-recherche.org/activites/doctoriales/doctoriales-2021/Doctoriales%202021-Pr%C3%A9sentation%20SCOLIEGE.pdf

[47] A. Nunes and K. D. Hernandez, "Autonomous taxis & public health: High cost or high opportunity cost?," *Transportation Research Part A: Policy and Practice*, vol. 138, pp. 28–36, Aug. 2020, doi: 10.1016/j.tra.2020.05.011.

[48] A. Quinet, "La valeur de l'action pour le climat," France Stratégie, 2019. [Online]. Available: https://www.strategie.gouv.fr/publications/de-laction-climat

[49] R. Buehler, "Daily Travel and Carbon Dioxide Emissions from Passenger Transport: Comparison of Germany and the United States," *Transportation Research Record*, vol. 2454, no. 1, pp. 36–44, Jan. 2014, doi: 10.3141/2454-05.

[50] P. Jochem, S. Babrowski, and W. Fichtner, "Assessing CO2 emissions of electric vehicles in Germany in 2030," *Transportation Research Part A: Policy and Practice*, vol. 78, pp. 68–83, Aug. 2015, doi: 10.1016/j.tra.2015.05.007.

[51] J. Jöhrens, D. Räder, J. Kräck, L. Mathieu, R. Blanck, and P. Kasten, "Plug-in hybrid electric cars: Market development, technical analysis and CO_2 emission scenarios for Germany," p. 94, 2020.

[52] F. Liu, F. Zhao, Z. Liu, and H. Hao, "Can autonomous vehicle reduce greenhouse gas emissions? A country-level evaluation," *Energy Policy*, vol. 132, pp. 462–473, Sep. 2019, doi: 10.1016/j.enpol.2019.06.013.

[53] N. J. Kemp, G. A. Keoleian, X. He, and A. Kasliwal, “Life cycle greenhouse gas impacts of a connected and automated SUV and van,” *Transportation Research Part D: Transport and Environment*, vol. 83, p. 102375, Jun. 2020, doi: 10.1016/j.trd.2020.102375.

[54] M. Held and M. Schücking, “Life cycle assessment of electric vehicles in shuttle traffic - field test results of the project RheinMobil,” 2017.

[55] S. Taszka and S. Domergue, “Analyse coûts bénéfices des véhicules électriques,” CGDD, 2017. [Online]. Available: https://www.ecologie.gouv.fr/sites/default/files/Th%C3%A9ma%20-%20Analyse%20co%C3%BBts%20b%C3%A9n%C3%A9fices%20des%20v%C3%A9hicules%20%C3%A9lectriques.pdf

[56] S. M. Patella, F. Aletta, and L. Mannini, “Assessing the impact of Autonomous Vehicles on urban noise pollution,” *Noise Mapping*, vol. 6, no. 1, pp. 72–82, Jan. 2019, doi: 10.1515/noise-2019-0006.

[57] A. Papadoulis, M. Quddus, and M. Imprialou, “Evaluating the safety impact of connected and autonomous vehicles on motorways,” *Accident Analysis & Prevention*, vol. 124, pp. 12–22, Mar. 2019, doi: 10.1016/j.aap.2018.12.019.

[58] S. Kitajima, K. Shimono, J. Tajima, J. Antona-Makoshi, and N. Uchida, “Multi-agent traffic simulations to estimate the impact of automated technologies on safety,” *Traffic Injury Prevention*, vol. 20, no. sup1, pp. S58–S64, Jun. 2019, doi: 10.1080/15389588.2019.1625335.

[59] I. Mahdinia, R. Arvin, A. J. Khattak, and A. Ghiasi, “Safety, Energy, and Emissions Impacts of Adaptive Cruise Control and Cooperative Adaptive Cruise Control,” *Transportation Research Record*, vol. 2674, no. 6, pp. 253–267, Jun. 2020, doi: 10.1177/0361198120918572.

[60] P. Tafidis, H. Farah, T. Brijs, and A. Pirdavani, “Safety implications of higher levels of automated vehicles: a scoping review,” *Transport Reviews*, vol. 0, no. 0, pp. 1–23, Aug. 2021, doi: 10.1080/01441647.2021.1971794.

[61] ONISR, “Bilan 2019 de la sécurité routière,” Observatoire national Interministériel de la sécurité routière, 2019. Accessed: Dec. 20, 2021. [Online]. Available: https://www.onisr.securite-routiere.gouv.fr/etat-de-l-insecurite-routiere/bilans-annuels-de-la-securite-routiere/bilan-2019-de-la-securite-routiere

[62] N. Mouter, “A critical assessment of discounting policies for transport Cost-Benefit Analysis in five European practices,” *European Journal of Transport and Infrastructure Research*, vol. 18, no. 4, Art. no. 4, Sep. 2018, doi: 10.18757/ejtir.2018.18.4.3256.

[63] “Cadrage du scénario de référence,” 2019. Accessed: Mar. 10, 2023. [Online]. Available: https://www.ecologie.gouv.fr/sites/default/files/II%20-%20Sc%C3%A9nario%20de%20r%C3%A9f%C3%A9rence.pdf

[64] D. Ziemke, I. Kaddoura, and K. Nagel, “The MATSim Open Berlin Scenario: A multimodal agent-based transport simulation scenario based on synthetic demand modeling and open data,” *Procedia Computer Science*, vol. 151, pp. 870–877, Jan. 2019, doi: 10.1016/j.procs.2019.04.120.

[65] “Here’s Why Waymo is Leading the Self-Driving Car Race,” *DDS Wireless*. https://ddswireless.com/blog/heres-why-waymo-is-leading-the-self-driving-car-race/

[66] S. Evans and W. Walker, “Waymo One Robotaxi First Ride: Way Mo’ Better Than Driving?,” *MotorTrend*, Apr. 08, 2022. [Online]. Available: https://www.motortrend.com/reviews/waymo-one-autonomous-vehicle-first-ride/

[67] K. A. Marczuk *et al.*, “Autonomous Mobility on Demand in SimMobility: Case Study of the Central Business District in Singapore,” presented at the 7th International Conference on Cybernetics and Intelligent Systems (CIS) and IEEE Conference on Robotics, Automation and Mechatronics (RAM), 2015, 2015. doi: 10.1109/ICCIS.2015.7274567.

[68] M. Heilig, T. Hilgert, N. Mallig, M. Kagerbauer, and P. Vortisch, “Potentials of Autonomous Vehicles in a Changing Private Transportation System – a Case Study in the Stuttgart Region,” *Transportation Research Procedia*, vol. 26, pp. 13–21, Jan. 2017, doi: 10.1016/j.trpro.2017.07.004.

[69] F. Javanshour, H. Dia, and G. Duncan, "Exploring the performance of autonomous mobility on-demand systems under demand uncertainty," *Transportmetrica A: Transport Science*, vol. 15, no. 2, pp. 698–721, Nov. 2019, doi: 10.1080/23249935.2018.1528485.
[70] K. M. Gurumurthy and K. M. Kockelman, "Dynamic ride-sharing impacts of greater trip demand and aggregation at stops in shared autonomous vehicle systems," *Transportation Research Part A: Policy and Practice*, vol. 160, pp. 114–125, Jun. 2022, doi: 10.1016/j.tra.2022.03.032.
[71] S. Hörl, F. Becker, and K. W. Axhausen, "Simulation of price, customer behaviour and system impact for a cost-covering automated taxi system in Zurich," *Transportation Research Part C: Emerging Technologies*, vol. 123, p. 102974, Feb. 2021, doi: 10.1016/j.trc.2021.102974.
[72] L. Börjeson, M. Höjer, K.-H. Dreborg, T. Ekvall, and G. Finnveden, "Scenario types and techniques: Towards a user's guide," *Futures*, vol. 38, no. 7, pp. 723–739, Sep. 2006, doi: 10.1016/j.futures.2005.12.002.
[73] M. Shatanawi and F. Mészáros, "Implications of the Emergence of Autonomous Vehicles and Shared Autonomous Vehicles: A Budapest Perspective," *Sustainability*, vol. 14, no. 17, Art. no. 17, Jan. 2022, doi: 10.3390/su141710952.
[74] S. Narayanan, E. Chaniotakis, and C. Antoniou, "Chapter One - Factors affecting traffic flow efficiency implications of connected and autonomous vehicles: A review and policy recommendations," in *Advances in Transport Policy and Planning*, vol. 5, D. Milakis, N. Thomopoulos, and B. van Wee, Eds. Academic Press, 2020, pp. 1–50. doi: 10.1016/bs.atpp.2020.02.004.
[75] Z. Le Hong and N. Zimmerman, "Air quality and greenhouse gas implications of autonomous vehicles in Vancouver, Canada," *Transportation Research Part D: Transport and Environment*, vol. 90, p. 102676, Jan. 2021, doi: 10.1016/j.trd.2020.102676.
[76] J. Berrada and A. Poulhès, "Economic and socioeconomic assessment of replacing conventional public transit with demand responsive transit services in low-to-medium density areas," *Transportation Research Part A: Policy and Practice*, vol. 150, pp. 317–334, Aug. 2021, doi: 10.1016/j.tra.2021.06.008.
[77] J. A. Annema, "Chapter Six - Policy implications of the potential carbon dioxide (CO2) emission and energy impacts of highly automated vehicles," in *Advances in Transport Policy and Planning*, vol. 5, D. Milakis, N. Thomopoulos, and B. van Wee, Eds. Academic Press, 2020, pp. 149–162. Accessed: Dec. 17, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2543000920300093
[78] S. Hörl, C. Ruch, F. Becker, E. Frazzoli, and K. W. Axhausen, "Fleet operational policies for automated mobility: A simulation assessment for Zurich," *Transportation Research Part C: Emerging Technologies*, vol. 102, pp. 20–31, May 2019, doi: 10.1016/j.trc.2019.02.020.

APPENDIX

TABLE A.1 Infrastructure Cost Sensibility Analysis (per kilometer)

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 €

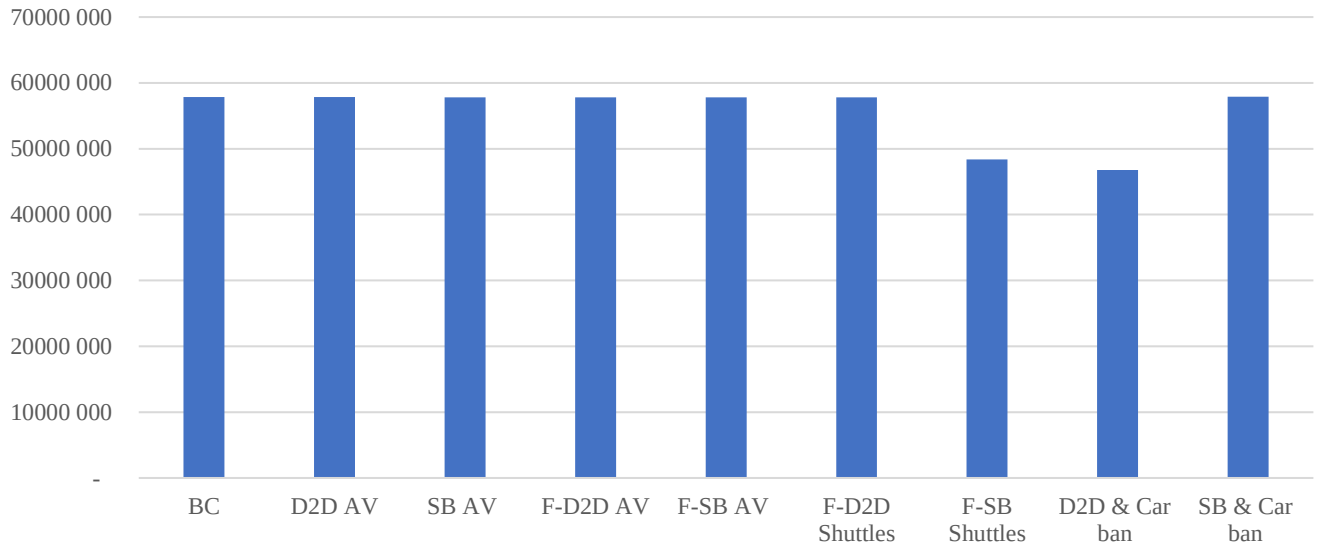

Figure A1 Agents Aggregated Scores