Chapter 4
Economic Assessment of Services with Intelligent Autonomous Vehicles: EASI-AV

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Abstract
While most of the current research on autonomous public transport focuses on improving operational and technical aspects, as well as tackling policy and user behavioral factors, the integration of autonomous buses into public networks is mainly dependent on costs and breakeven points (both for operators and local governments). Research quantifying costs and return on investment specifically in academic settings are sparse. This chapter aims to introduce a simulation tool: EASI-AV, designed as a decision-making tool to support public policies on the decision of implementing innovative mobility services. EASI-AV proposes to 1) assess the global economic impacts of deploying fleets of AVCTs in comparison with traditional public transport modes, and 2) help local authorities to build scenarios integrating autonomous buses into their public network and imagine new business models. The simulation is based on the Total Cost of Ownership (TCO) approach and includes 4 aspects that may be used independently: the fleet size dimensioning, the TCO calculation with internal costs and local externalities, the business model simulation, and the global impact assessment in comparison with other transport modes. EASI-AV was tested with real data from pilot sites, and the results prove it to be fully relevant.

Key-words
Autonomous Vehicles; Autonomous Shuttles; Public Transport; Economic impact assessment; Total Cost of Ownership (TCO).

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4.1. Introduction

National and city governments are expected to redesign public transport in order to better cope with the increase in urbanization as well as the growing negative externalities of mobility such as congestion, pollution and noise. Furthermore, policy makers are quite aware that public transport is a key element for the economic development of a region and the quality of life of its citizens and voters.

Meanwhile, 15 major cities around the world are starting to ban cars. The idea of a car-free city is not without its challenges, since cars remain a preferred method of transportation for many urban commuters. Therefore, public authorities need to define new strategies for the development of efficient public transport based on different importance criteria for their regions, such as their topography, citizens' needs and desires, economic barriers, environmental concerns, historical development, etc. On the other hand, new transport technologies and services are emerging with promising alternatives for supporting regional public transport development strategies.

As stated by Attias (2017), this revolution of urban areas will likely occur by the arrival of autonomous collective vehicles like buses or shuttles, thus building a new paradigm of urban mobility and smart cities. If successfully deployed, Autonomous Vehicles for Collective Transport (AVCTs) can provide flexible and cost-efficient solutions for serving both peak and off-peak demand by driving parallel and, as feeders to mass transit trunk lines (Ainsalu et al., 2018, Merat, Madigan & Nordhoff, 2017).

In fact, estimates presented by RethinkX (2017) show that by 2030, 95% of the passenger miles traveled will be served by shared fleets of on-demand autonomous electric vehicles, in a new business model of Mobility-as-a-Service (MaaS). Furthermore, as pointed out by ARK Invest (2017), this future market offering will cost consumers $0.35 cents per mile (roughly half of the all-in cost car owners pay to drive today), and thereby it should exceed 10 trillion dollars in sales by the early 2030s.

Urban centers could strongly benefit from the introduction of AVCTs (Ainsalu et al., 2018). For the authors, besides being the first- and last-mile connection to mass transit, AVCTs could compete with automobiles by price and be more effective than traditional public transport buses (by taking 15 instead of 150 passengers), being on-demand instead of on-schedule, and moving on flexible routes instead of fixed ones.

Much of the effort dedicated to the implementation of AVCTs focused on improving their operational and technical aspects, as well as policy and behavioral factors that will allow successful deployment and user/societal uptake (Gandia et al., 2018; Merat, Madigan & Nordhoff, 2017), however, their market penetration rate is dependent on costs (direct and indirect) and return on investment (Ongel et al., 2019), with that, research quantifying the costs and benefits of AVCTs, specifically in academic settings are sparse. As pointed out by (Henderson et al.,

2017) most of the research has focused on the cost impact of autonomy on taxis and other ride sourcing services for vehicles up to 5 passengers.

In this sense, the present chapter aims to fill this gap by introducing a simulation tool to assess the economic impacts of deploying fleets of autonomous vehicles for collective transport and different implementation scenarios. Our ambition with this decision support tool is to provide an objective and quantitative toll to evaluate public policy scenarios on implementing innovative public transport services like autonomous collective vehicles.

Our tool, kindly named as **EASI-AV** proposes an **Economic Assessment of Services with Intelligent Autonomous Vehicles.**

EASI-AV is able to provide: the fleet dimensioning, calculate the total cost of ownership, and the costs of local externalities of the service. EASI-AV was designed with the objective of helping policy makers in cities, regions, or even Public Transport Operators (PTOs) and others that may be interested in implementing services with AVCTs (like companies or university and hospital campuses). EASI-AV has been tested on pilot cases in Luxembourg, Lyon, Geneva, and Copenhagen and the results show that the algorithms are coherent and yield good results.

This chapter is structured as follows. Section 4.2 brings the literature review by presenting an overview of AVCTs economic impact assessment for the applicative domain. The tool, EASI-AV, is presented in section 4.3. In Section 4.4, we exemplify its application with empirical data from a pilot site, next on section 4.5 the implications of the method as well as the limitations of our proposition are discussed. Section 4.6 concludes on the study.

This chapter is a parallel study alongside the AVENUE project. The Autonomous Vehicles to Evolve to a New Urban Experience project (AVENUE), is an EU funded project which aims to design and carry out full-scale demonstrations of urban transport automation by deploying, for the first time worldwide, fleets of AVCTs on mixed-traffic conditions. Providing innovative services, like door-to-door and multimodal transportations, in low to medium demand areas of 4 European demonstrator cities: Geneva, Lyon, Copenhagen, and Luxembourg (AVENUE, 2018).

4.2. Theoretical framework: autonomous mobility impact assessment

4.2.1. Autonomous Vehicles for Collective Transport (AVCTs)

As stated by Mira-Bonnardel and Attias (2019), the most revolutionary impact of Autonomous Vehicles (AVs) will probably be on collective public transport with the introduction of on-demand mobility that will deeply the urban commute and its business models (see chapter 1 for further an in depth view). Therefore, AVs manufacturers have been leaning into intermediate sized electric buses with an average capacity of 15 passengers, that allows them to serve either fixed or on-demand routes offering microtransit services, or acting as a complement to high capacity transit systems by covering the first- and last-mile parts of the commute (Ongel et al., 2019; Harris, 2018).

Thereby, AVCTs have progressed through conceptual design, fundamental research, and technological development, and are now facing commercial applications (Zhang; Jenelius; Badia, 2019). Current AVCTs fall into the levels 3 and 4 of vehicular automation as proposed by SAE (2016), and are already being tested in various parts of the world both on dedicated lanes and, on mixed traffic always respecting traffic rules and local policies: with maximum speeds between 15 and 25km/h and with a human operator on board for fallback whether automation fails, as required by current regulation.

With this, a significant group of new companies have been implementing pilot projects with AVCTs (Mira-Bonnardel & Attias, 2018; Clausen, 2017), and in order to better understand the panorama of these pilot projects, Antonialli (2020) conducted an extensive worldwide benchmark identifying a total of 176 projects (among finished, on-going and, yet-to-start) that unfold in 142 cities, spread over 32 countries, being enabled by 20 different autonomous shuttles manufacturers.

Results have shown an European lead on both the number of experimentations (101 projects – 57.39%) and manufacturers (9 out of the 20), with highlights to the French startups Navya and Easymile, which are the global leaders when it comes to manufacturing and deployment of AVCTs worldwide (Antonialli, 2020). In addition, by analyzing the prevailing business models of the experimentations, the author concluded that AVCTs are offered by PTOs as a transport solution to citizens of a given city/region/area to either serve as first- and last mile commute (50.28%) or microtransit (49.72%).

A second in-depth study carried out by Mira-Bonnardel, Antonialli and Attias (2020), analyzed more deeply three main European Projects with AVCTs (CityMobil2, Sohjoa, and Gateway) with the aim of identifying their most relevant social and economic results. Their main academic findings showed varied and extensive results on consumers' behavior, acceptance and willingness to use, as well as studies with the aim of advancing technical aspects of the service and the legal barriers to overcome. However, as the authors stated, robust results on economic aspects were not addressed or were not disclosed on the projects' publications. The few results found were mainly concerned with users' willingness to pay, and the potential to reduce fares (mainly due to the lack of a human driver).

Although results shown by Antonialli (2020) and Mira-Bonnardel, Antonialli and Attias (2020) made it clear that the experiments with AVCTs did not address or disclose comprehensive results on the economic assessment of deployments, there has been important academic advances (not directly linked to the aforementioned experimentations) addressing the costs and benefits of implementing AVCTs. The next subsection further details the theoretical premises on economic assessment for AVCTs.

4.2.2. Economic impact assessment of AVCTs.

With AVCTs expected to be an accepted technology by 2030 (Litman, 2018), their market penetration rate is dependent on costs. By not requiring a driver and with expected lower energy consumption due to smoother driving, AVCTs may have lower operating costs than their human-driven counterparts (Fagnant; Kockelman, 2015), however, the current imbedded autonomy pack constitutes the major cost components – with LIDARs, sensors, cameras, processing unit, V2X equipment ranging from around 25,000 to 30,000 dollars, not to mention that AVCTs are generally equipped with an electric battery and powertrain, which also increases costs, and reduces the overall lifecycle of the product to currently around 5 years (Ongel et al., 2019).

On the other hand, it is expected that the prices of the automation pack as well as battery prices will go down with time and hence AVCTs may become cost effective compared to conventional vehicles in the long term (Catapult, 2018; KPMG, 2018; Bansal; Kockelman, 2017).

In this sense, cities and PTOs should consider the costs and benefits of implementing a public transport service using AVCTs over traditional services and, several recent studies have sought to provide answers to these demands.

Kalakuntla (2017) carried out a prospective comparative study of costs and benefits of fleets of AVCTs versus traditional regular diesel buses for the city of Austin (Texas, USA) with the aim of guiding Public Transport Operators (PTOs) on whether AVCTs are feasible or not. The author concluded that AVCTs can save PTOs' from capital & operational costs, reduce the environmental effects and increase the quality of life of the people.

The study carried out by Henderson et al. (2017) aimed at finding useful and efficient ways to use AVCTs in the campus of the Ohio State University (USA), the authors conducted an analysis to compare the current fleet of traditional vehicles used on campus to the costs of purchasing and maintaining a fleet of AVCTs (in their case the shuttle Olli from Local Motors). It was concluded that the autonomous shuttle exceeded the fleet of traditional vehicles in several categories – cheaper cost/mile, fewer carbon emissions/mile (0.91 lbs), and lower annual maintenance costs ($600/yr) – however, the autonomous shuttle was currently not cost-effective due to its high initial price relative to traditional shuttles.

Bösch et al. (2018) carried out a substantial cost-based analysis comprised of a bottom-up calculation of the cost structures (including besides the fixed costs, the overhead costs of shared services) for different types of AVs in various operation models, such as: dynamic ride-sharing, taxi, shared vehicles fleets and, AVCTs. The authors stated that their methodology allows determination of different cost components' importance and differentiation of vehicle automation effects on individual cost components. Their results showed that more than half of AVs fleets' operating costs will be service and management costs. Furthermore, they've concluded that autonomous driving technology will allow taxi services and buses to be operated at substantially lower costs, even more cheaply than private cars.

At last, the study from Ongel et al. (2019) aimed at determining the Total Cost of Ownership (TCO) of AVCTs and comparing them to regular internal combustion engine buses and mini-buses. Their TCO analysis included three major cost components: acquisition costs, operating costs, and end-of-life costs. Their simulations have shown that although the acquisition costs of AVCTs are higher than those of conventional buses, they can reduce the TCO per passenger-km up to 75% and 60% compared to conventional mini-buses and regular buses, respectively.

Although bringing several promising and interesting results regarding the economic feasibility of services with AVCTs, none of the aforementioned studies proposed a holistic methodology for dimensioning and assessing the economic impact of AVCTs services which could be easily applied by decision makers – such as city and regional governments and other interested stakeholders – in the economic evaluation and decision of whether or not implementing services with AVCTs.

Therefore, we designed a simulation tool EASI-AV that helps to assess the economic impact of AVCTs integration into public transport networks and to simulate different scenarios by allowing the users to play with cost variables as well as revenue variables. In the next section we explain how EASI-AV has been designed and how it works.

4.3. The EASI-AV simulation tool

4.3.1. EASY-AV design methodology

The **E**conomic **A**ssessment of **S**ervices with **I**ntelligent **A**utonomous **V**ehicles (EASI-AV) tool was developed as a support tool to assist decision makers in cities, as well as transport operators, and other organizations to estimate the economic assessment of implementing a service with AVCTs.

EASI-AV has been developed within the European project AVENUE. We worked with the transport operators in charge of the collective transport network and responsible for the demonstrators in the four cities in the project (Copenhagen, Geneva, Lyon, and Luxembourg). We collected their data on the autonomous service as well as on traditional services to test the tool and check the reliability of its algorithms.

The EASI-AV tool was firstly designed using a spreadsheet software and manual data entry with automated calculation. By the time this chapter was published, the EASY-AV tool was being designed as a web application including automated data collection (such as geolocation and traffic data). Once finished, the EASI-AV application is due to be on open access on the AVENUE project website.

4.3.2. EASY-AV structure

The EASI-AV tool provides different types of assessments in a comparative manner (between the shuttle and different transport modes), such as the Total Cost of Ownership (TCO) - including investment costs and operational costs, the Local Impact of externalities as well as the Global Impact assessment - with business model and breakeven assessment.

As shown on Figure 4.1 and on the paragraphs that follow, the EASI-AV is composed of 5 different parts that may be carried out sequentially or independently according to the needs of the user.

Part 1: Service contextualization
- Territorial typology (urban, peri-urban, rural);
- Zoning (residential, commercial, industrial);
- Population density.

Step 2: Fleet size dimensioning
- Service operation modes: fixed road or on-demand mobility;
- Calculation modes: supply-push or demand-pull.

Step 3: TCO evaluation
- Vehicle's life cycle and staff dimensioning (economies of scale);
- Investments and operation costs;
- KPIs metrics (cost per passenger/km – cost per vehicle/km).

Step 4: Local externalities assessment
- Monetization of local external costs (accidents, air pollution, noise and, congestion);
- KPIs metrics (cost per passenger/km – cost per vehicle/km).

Step 5: Global impact evaluation and scenarios
- Business model simulations;
- Break even assessment.

Figure 4.1. EASI-AV analyses portfolio

4.3.2.1. Part 1 - Service contextualization

This part consists in qualitatively defining the local context envisioned for the new services with AVCTs. Contextualizing the service helps to build more accurate scenarios and allows decision makers to have a holistic view of the service context to be implemented. EASI-AV helps to properly frame the territorial typology (urban, peri-urban, rural), the zoning (residential, commercial, industrial or mixed areas), define the public transport supply (if there is already existing public transporting the area) and the area's population density as well as surface area and extension of roads. Data for contextualization can be either entered by the user or automatically extracted online.

4.3.2.2. Part 2 - Fleet size dimensioning

As detailed on Table 4.1, EASI-AV proposes four alternatives for the fleet size calculation, that are guided by two main drivers: 1) service type (supply-push or demand-pull), and 2) road environment (fixed-roads or on-demand). EASY-AV allows the fleet size to be calculated for all combinations of service type / road environment.

Once the category is selected, decision makers enter data on selected cells if they work with the spreadsheet tool or ask for data collection online if they work on the web application. In section 4.4.2, we develop how the four combinations are introduced in mobility scenarios.

	Service type 1 Demand-pull (S1)	**Service type 2 Supply-push (S2)**
Road environment 1 Fixed road (R1)	R1S1	R1S2
Road environment 2 On-demand (R2)	R2S1	R2S2

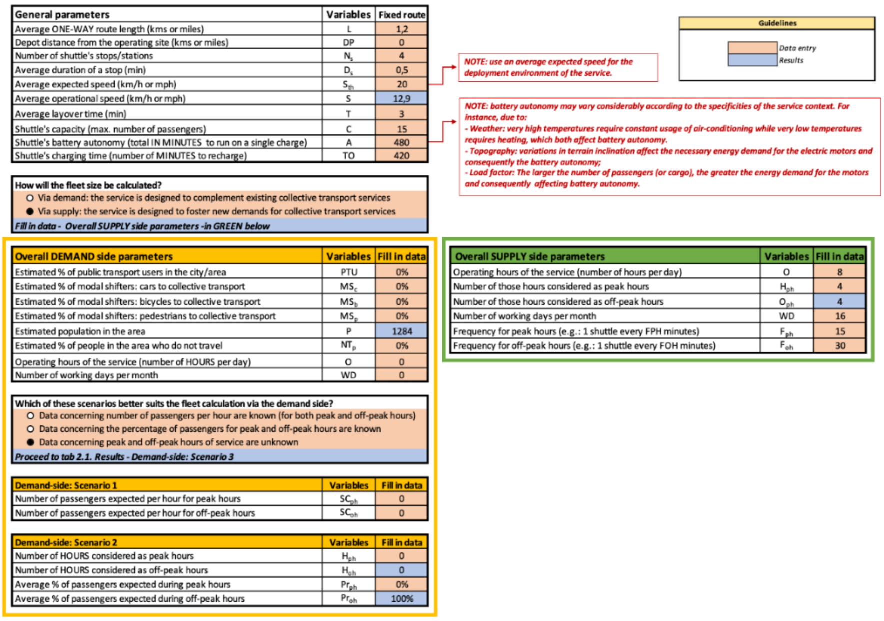
Table 4.1. Fleet size calculation options array

For road environment 1, the fleet size dimensioning is based on traditional fleet size calculations. Besides the usual general parameters characterizing the territory (route length, average speed, layover time, capacity, etc.) and specific parameters characterizing local mobility uses (percentage of public transport users in the area or numbers of operating hours per day), we considered some other specific for parameters as a way of leading to a finer calculation, such as the average operational speed (taking into account the idle time on each stop), as well as the battery autonomy and its charging time (which allows us to make a time differential to integrate in the calculation for how long a vehicle will be out of service to recharge). Simple algorithms compute these data and propose an optimum fleet size.

Road environment 2 is more complex since the algorithms have to evaluate how many kilometers the vehicle may drive across the serviced area to comply with any users' demand for any direction at any time. Key elements of calculation in that option are the passenger waiting time (i.e. how long should a requester wait before a vehicle arrives), and the maximum distance between the requester and the vehicle at the time of the request. After computing these elements in addition to all elements taken into account for option 1, EASI-AV proposes an optimum fleet size.

For Service type 1 (demand-pull), EASI-AV proposes calculations via demand side, that is: for the cases where the demand for mobility is known. Three calculation scenarios are proposed depending on the degree of knowledge of data concerning the existing transport demand (the number of passengers or the expected percentage of passengers during the peak and off-peak hours, etc.). The objective is to offer a flexible, modular tool depending on the transport demand and/or the future transport service offer.

ForsService type 2 (supply-push), the tool offers calculations via supply, where demand on public transport is unknown or the service will be offered as a new transport offering in a supply-pushed strategy. Figure 4.2 illustrates the spreadsheet data entry for R1S1 and R1S2.



General parameters	Variables	Fixed route
Average ONE-WAY route length (kms or miles)	L	1,2
Depot distance from the operating site (kms or miles)	DP	0
Number of shuttle's stops/stations	N_s	4
Average duration of a stop (min)	D_s	0,5
Average expected speed (km/h or mph)	S_{th}	20
Average operational speed (km/h or mph)	S	12,9
Average layover time (min)	T	3
Shuttle's capacity (max. number of passengers)	C	15
Shuttle's battery autonomy (total IN MINUTES to run on a single charge)	A	480
Shuttle's charging time (number of MINUTES to recharge)	TO	420

NOTE: use an average expected speed for the deployment environment of the service.

NOTE: battery autonomy may vary considerably according to the specificities of the service context. For instance, due to:
- Weather: very high temperatures require constant usage of air-conditioning while very low temperatures requires heating, which both affect battery autonomy.
- Topography: variations in terrain inclination affect the necessary energy demand for the electric motors and consequently the battery autonomy;
- Load factor: The larger the number of passengers (or cargo), the greater the energy demand for the motors and consequently affecting battery autonomy.

Guidelines

🟧 *Data entry*
🟦 *Results*

How will the fleet size be calculated?
○ Via demand: the service is designed to complement existing collective transport services
● Via supply: the service is designed to foster new demands for collective transport services
Fill in data - Overall SUPPLY side parameters -in GREEN below

Overall DEMAND side parameters	Variables	Fill in data
Estimated % of public transport users in the city/area	PTU	0%
Estimated % of modal shifters: cars to collective transport	MS_c	0%
Estimated % of modal shifters: bicycles to collective transport	MS_b	0%
Estimated % of modal shifters: pedestrians to collective transport	MS_p	0%
Estimated population in the area	P	1284
Estimated % of people in the area who do not travel	NT_p	0%
Operating hours of the service (number of HOURS per day)	O	0
Number of working days per month	WD	0

Which of these scenarios better suits the fleet calculation via the demand side?
○ Data concerning number of passengers per hour are known (for both peak and off-peak hours)
○ Data concerning the percentage of passengers for peak and off-peak hours are known
● Data concerning peak and off-peak hours of service are unknown
Proceed to tab 2.1. Results - Demand-side: Scenario 3

Demand-side: Scenario 1	Variables	Fill in data
Number of passengers expected per hour for peak hours	SC_{ph}	0
Number of passengers expected per hour for off-peak hours	SC_{oh}	0

Demand-side: Scenario 2	Variables	Fill in data
Number of HOURS considered as peak hours	H_{ph}	0
Number of HOURS considered as off-peak hours	H_{oh}	0
Average % of passengers expected during peak hours	Pr_{ph}	0%
Average % of passengers expected during off-peak hours	Pr_{oh}	100%

Overall SUPPLY side parameters	Variables	Fill in data
Operating hours of the service (number of hours per day)	O	8
Number of those hours considered as peak hours	H_{ph}	4
Number of those hours considered as off-peak hours	O_{ph}	4
Number of working days per month	WD	16
Frequency for peak hours (e.g.: 1 shuttle every FPH minutes)	F_{ph}	15
Frequency for off-peak hours (e.g.: 1 shuttle every FOH minutes)	F_{oh}	30

Figure 4.2. Fleet size calculation data entry for R1S1 and R1S2

4.3.2.3. Part 3 – TCO evaluation

The TCO evaluation part may be used as the follow up of part 2 (fleet size dimensioning), or if the fleet size is already known, it may be started with entering the current fleet size the users seek to evaluate.

For this part, questions about the lifetime of the vehicles as well as the number of on-board safety drivers and off-board supervisors are asked. The former will allow the calculation of the depreciation while the last two will allow a better characterization of the operating costs and possible economies of scale in terms of personnel.

The main internal costs are investment costs (or capital expenditures - CAPEX) and operations expenditures (OPEX), both have to be determined. Once all costs are registered, EASY-AV calculates the costs per passenger/km and per vehicle/km as well as other indicators. These ratios will be used afterwards for a detailed comparison between other transport modes.

To help the user, we created a list of the most relevant Capex and Opex cost sources that are explained on a specific side-document and via drop-down menus for the web application. In order to integrate economies of scale, the user can choose if the cost applies to a single vehicle or to the entire fleet (for example feasibility study is not a cost per vehicle whereas acquisition costs is a cost per unit).

In some cases, it is possible that the people who are filling out the tool do not know the exact cost values for the autonomous shuttle, being a new (and until now scarcely implemented technology), data about costs and financial values may not be easily accessible and foreseeable for everyone. For these cases, we provide the option of using the standard costs (determined based on the average results obtained in the AVENUE project). All that needs to be done is choose the button to use generic costs.

4.3.2.4. Part 4 - Local Externalities assessment

At both local and global scales, public actions are considered in terms of sustainability. In this regard, the transport sector is no exception (Bulteau, 2016). The objective of policy-makers is to reduce negative externalities of transport for the community, such as congestion, environmental pollution, and accidents. This is why the economic assessment has to take into account externalities generated by the transport service implemented in the territory.

In the EASI-AV tool, several sources of external costs for the cities are considered: congestion, accidents, air pollution (NOx and fine particles), and noise. The monetarized values of these externalities come from the Handbook of the externalities of transport (CE, 2019) being adjusted for inflation for the year 2020 and adapted to fit AVCTs. To get the results for externalities valuation, all that needs to be done is select the country of where the shuttle will be deployed . Everything else is automatically calculated. A comparative analysis is provided between the external costs generated by the fleet size of shuttles and different modes of transport (see Figure 4.5).

It is worth noting that since this assessment is based on secondary data from the Handbook of externalities of transport, the analysis is only available for the European countries listed in the handbook.

4.3.2.5. Part 5 - Global impact evaluation and scenarios

The implementation of autonomous vehicles may open the way for new business use cases and new business models. Different funding sources may be explored along with the traditional subsidies and ticketing because autonomous fleets may be more flexible and more customizable than a traditional fleet. EASI-AV can help to monetize all business scenarios and bring a comparative analysis with alternative mobility modes.

For instance, scenarios may be combined with passenger ticketing at peak hours as well as with goods delivery financed by freight forwarding companies during off-peak hours. They can also differentiate week-days with subsidized workers traveling and weekends with paid tourists (sightseeing). In addition, passengers may be willing to pay more than the standard ticket price for customized on-demand offers while for fixed-routes, the trip may have the same price of the local ticket, included on monthly or weekly passes, or even be free of charge for the local population commuting to a mass transit mode.

Because use cases and their revenue models are still to be envisioned, EASI-AV proposes different revenue scenarios varying from ticketing, subsidies, financing from companies, from tour operators, and from other different public sources (such as ministry of health, etc.). In the tool, decision makers are asked to give an estimated value of the percentage of the annual operation costs that are covered by each revenue source.

Since the objective of EASI-AV is to evaluate the impact of the introduction of autonomous vehicles, decision makers get to use the comparative approach between AVCT and any other public transport mode they would like to choose to be their baseline vehicle for comparison.

The tool also gives results for the TCO comparison set of main indicators for both the AVCTs and the chosen baseline vehicle (such as: cost per passenger/km, cost per vehicle/km, one-way cost per passenger/km and one-way cost per vehicle/km, etc.).

4.3.3. EASI-AV application on a test pilot in Luxembourg

In this section, we present the tool in action exemplified with real data from a pilot site in the neighborhood of Pfaffenthal in Luxembourg city.

4.3.3.1. Part 1 - Service contextualization

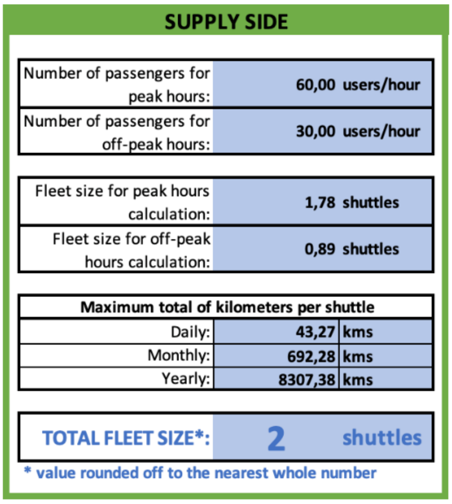
The Pfaffenthal area of 0.38 km2 has a total population of 1.284 inhabitants, and is not served by the city’s traditional public transport network. In June 2018, as part of the European Commission funded project AVENUE (AVENUE, 2018), the local transport operator (Sales-Lentz) implemented in the area a 1.2 km fixed-looped route (with 4 stops) serviced by two Navya ARMA shuttles to run free of charge to passengers every Tuesday, Thursday from 12h00 to 20h00 and every weekend and public holidays from 10h00 to 21h00.

Regarding the data entry, it is worth emphasizing that data characterizing the context can be filled in manually by the users on the spreadsheet, while for the web application, extraction algorithms can collect data concerning surface and population when the user enters identification geographic points.

4.3.3.2. Part 2 - Fleet size dimensioning

EASI-AV was applied to Pfaffenthal configuration (R1S2 from Table 4.1) and the calculated results corroborates the real number of two shuttles implemented by Sales-Lentz in their trials, proving the accuracy of the tool (a similar validation was also carried out in the AVENUE testing sites in Lyon, Geneva and Copenhagen).

Besides the total expected fleet size, the results shown on Figure 4.3 also give some other interesting metrics and KPIs for decision makers (such as: number of passengers for peak and off-peak hours, frequency of shuttles, maximum total of kilometers per shuttle, and so on).



SUPPLY SIDE

Number of passengers for peak hours:	60,00 users/hour
Number of passengers for off-peak hours:	30,00 users/hour

Fleet size for peak hours calculation:	1,78 shuttles
Fleet size for off-peak hours calculation:	0,89 shuttles

Maximum total of kilometers per shuttle		
Daily:	43,27	kms
Monthly:	692,28	kms
Yearly:	8307,38	kms

TOTAL FLEET SIZE*: 2 shuttles

* value rounded off to the nearest whole number

Figure 4.3. Fleet size calculation results for Pfaffenthal via the R1S2 configuration

4.3.3.3. Part 3 – TCO evaluation

As exemplified with data for the Pfaffenthal pilot site, many indicators are given as results, such as the total CAPEX and OPEX both for the single vehicle and for the fleet. Due to confidentiality, we cannot present all financial data from the experimentation site but Figure 4.4 gives an overview of the results by summarizing the main sources of CAPEX, OPEX as well as the revenue sources percentage needed to cover the yearly OPEX for both the baseline vehicle and for the shuttle.

The most important CAPEX source for both the shuttle as well as for the baseline bus was vehicle acquisition (87.73% and 98.91% respectively). Regarding OPEX, the most relevant cost source for the baseline vehicle is costs with personnel (that is: drivers' salaries), representing more than half of the total OPEX (66.51%), corroborating the results found by Bösch et al. (2018). For the current stage of deployments with AVCTs, costs with personnel are also representative (32%), in a sense that the legislation still requires a safety driver onboard the vehicles. However, the most relevant operational cost for the shuttles is depreciation (41%), as stated by Ongel et al., (2019) this is due to the fact that the current life cycle of these vehicles are significantly shorter, averaging 5 years versus the 15 for traditional buses. This is mainly due to the fast pace of technology evolution of sensors, cameras and the aging of the battery.

Regarding the revenues, as of March 1st 2020, the government of Luxembourg made free all public transport in the country (CNN, 2020), thereby for traditional buses 100% of the transport is subsidized while for the shuttle, by being a pilot site partially funded by the AVENUE project, part of the funding come from subsidies (around 70%) and part of it comes from the EC (around 30%).

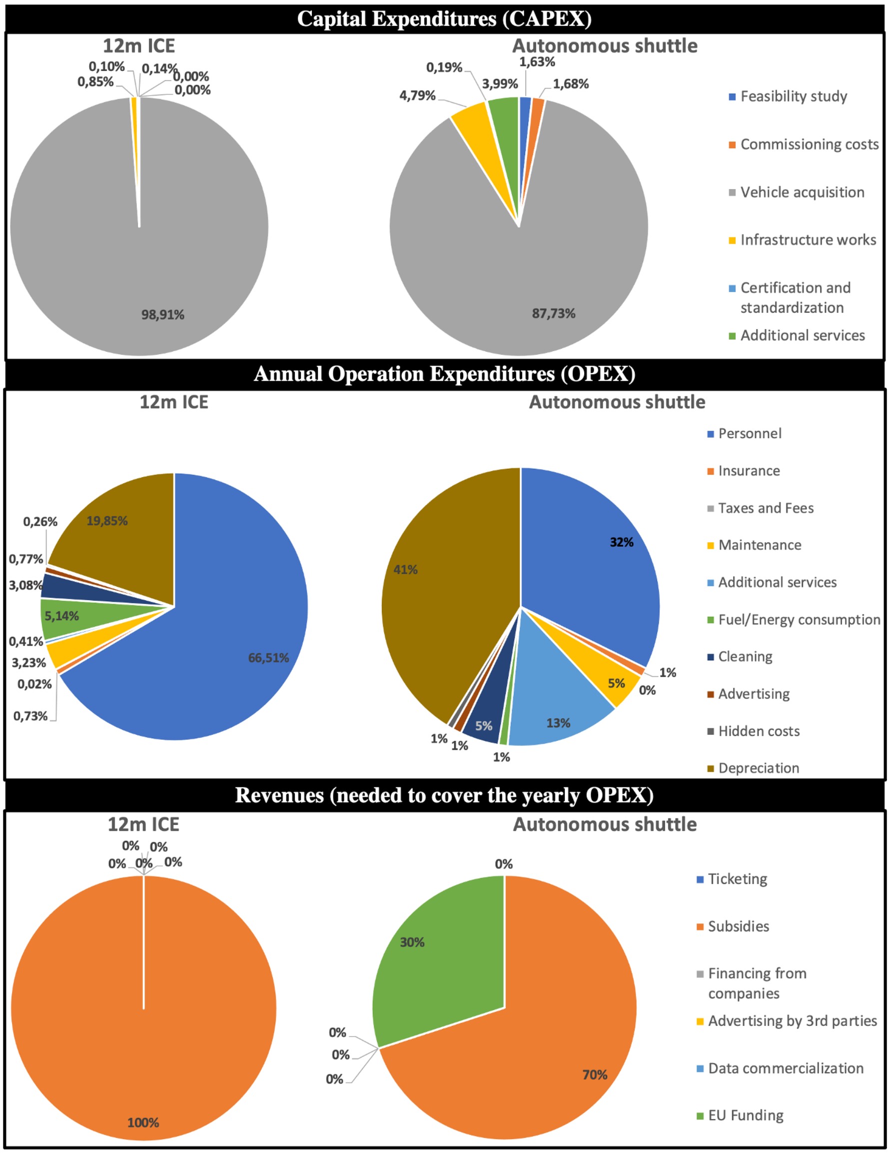


Figure 4.4. Summary of TCO results for Pfaffenthal pilot site.

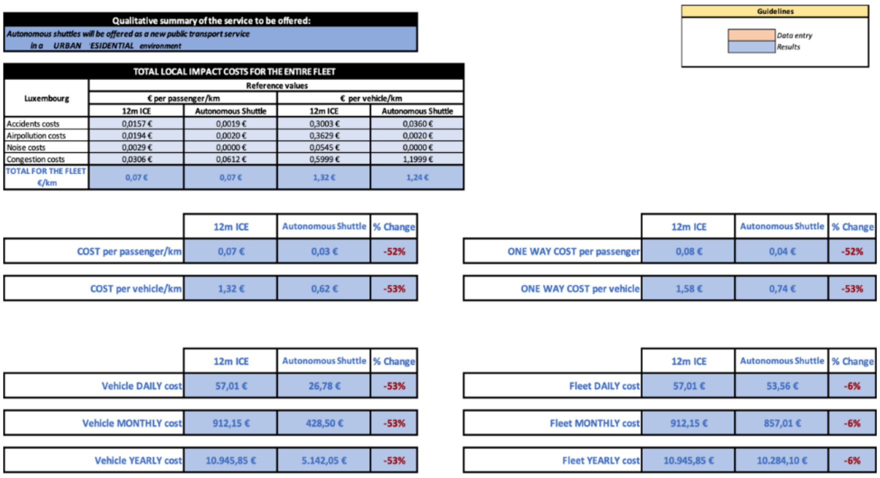
Taking all these elements into account, it can be seen that today the CAPEX needed for deploying services with AVCTs is not much higher than those needed for a traditional bus (in the case of Pfaffenthal pilot site, it is only 7% more for the entire fleet).

On the other hand, the annual operating costs for AVCTs are still higher (37% for the fleet and 26% for a single vehicle) when compared to the baseline, thereby, our tool corroborates the findings of Henderson et al. (2017) since autonomous shuttle are indeed currently not cost-effective relative to traditional buses. Thereby taking into account the TCO calculation, results from Pfaffenthal estimates a current cost per passenger/km of 3.59 € versus 1.57 € for the baseline bus.

However, as technology and legislation evolves, it is expected that in the coming years the life cycle of shuttles will increase (hence reducing the depreciation costs) and an onboard safety driver will no longer be needed (thereby drastically reducing the costs with personnel), which assures that our tool is also aligned with the results of the prospective studies carried out by Fagnant and Kockelman (2015), Bösch et al. (2018) and, Ongel et al. (2019).

4.3.3.4. Part 4 - Local externalities assessment

As shown on the results of Figure 4.5, EASI-AV provides a cost per passenger/km and a cost per vehicle/km for each externality studied and therefore the total cost of the externalities for the shuttle fleet and the modes of transport taken in comparison. This results in several cost indicators such as the vehicle daily, monthly and yearly external costs for example. By being electric, the results for the shuttles in Pfaffenthal show a drastic reduction in the local external costs for the service.



Qualitative summary of the service to be offered:
Autonomous shuttles will be offered as a new public transport service
in a URBAN ESIDENTIAL environment

Guidelines
🟧 *Data entry*
🟦 *Results*

TOTAL LOCAL IMPACT COSTS FOR THE ENTIRE FLEET				
Luxembourg	Reference values			
	€ per passenger/km		€ per vehicle/km	
	12m ICE	Autonomous Shuttle	12m ICE	Autonomous Shuttle
Accidents costs	0,0157 €	0,0019 €	0,3003 €	0,0360 €
Airpollution costs	0,0194 €	0,0020 €	0,3629 €	0,0020 €
Noise costs	0,0029 €	0,0000 €	0,0545 €	0,0000 €
Congestion costs	0,0306 €	0,0612 €	0,5999 €	1,1999 €
TOTAL FOR THE FLEET €/km	0,07 €	0,07 €	1,32 €	1,24 €

	12m ICE	Autonomous Shuttle	% Change
COST per passenger/km	0,07 €	0,03 €	-52%
COST per vehicle/km	1,32 €	0,62 €	-53%

	12m ICE	Autonomous Shuttle	% Change
ONE WAY COST per passenger	0,08 €	0,04 €	-52%
ONE WAY COST per vehicle	1,58 €	0,74 €	-53%

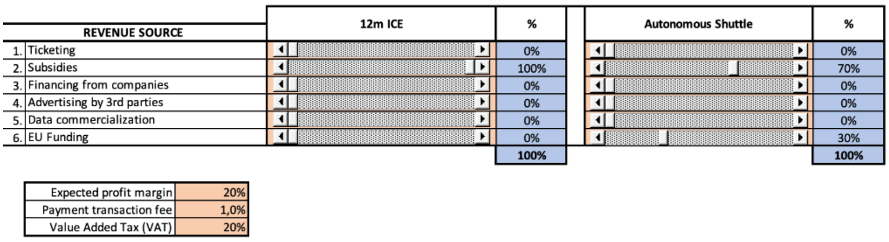
	12m ICE	Autonomous Shuttle	% Change
Vehicle DAILY cost	57,01 €	26,78 €	-53%
Vehicle MONTHLY cost	912,15 €	428,50 €	-53%
Vehicle YEARLY cost	10.945,85 €	5.142,05 €	-53%

	12m ICE	Autonomous Shuttle	% Change
Fleet DAILY cost	57,01 €	53,56 €	-6%
Fleet MONTHLY cost	912,15 €	857,01 €	-6%
Fleet YEARLY cost	10.945,85 €	10.284,10 €	-6%

Figure 4.5. Local externalities analysis results

4.3.3.5. Part 5 - Global impact evaluation and scenarios

The four previous parts conduct a picture of a global impact assessment for decision making concerning the implementation of autonomous mobility. In Luxembourg, Figure 4.6 shows that the revenue model is not diversified yet but the tool is ready to let decision makers re-imagine the business model future of their autonomous fleet.



	REVENUE SOURCE	12m ICE	%	Autonomous Shuttle	%
1.	Ticketing		0%		0%
2.	Subsidies		100%		70%
3.	Financing from companies		0%		0%
4.	Advertising by 3rd parties		0%		0%
5.	Data commercialization		0%		0%
6.	EU Funding		0%		30%
			100%		100%

Expected profit margin	20%
Payment transaction fee	1,0%
Value Added Tax (VAT)	20%

Figure 4.6. Examples of revenue sources data entry.

Revenue data are used to calculate financial ratios like the breakeven point or the net present value; those ratios quantify the cost-benefit analysis and contribute to the decision making process for investors as well as for policy makers (if different).

Since investors or policy makers need to choose how to implement multimodality, EASI-AV systematically gives tables and indicators to compare the impact of autonomous services with other collective transport modes options.

4.4. Economic impact evaluation: a holistic view

4.4.1. The scope of economic impact evaluation

The future public transport in urban and suburban areas should be safe, rapid, economic, ecological and personalized. Technology progress of robomobility supports the development of new services that could transform the simple ride into a high level user experience, taking into account the diversity of passenger needs, offering personalized services and serving areas that are not economically covered today. Consequently, speaking about robomobility arises the question: is the use of autonomous vehicles economically, socially and environmentally interesting?

Nonetheless the question of robomobility is still cemented in the triad Technology / Regulation / Uses. For instance, the KPMG (2018) study proposes the Autonomous Vehicles Readiness Index by assessing 4 key areas of preparedness for twenty nations: infrastructure, technology, regulatory and user acceptance. No analysis was accorded to the economic impact of autonomous driving.

Public transport includes various services that provide shared mobility to the general public by means of buses, trains, ferries, subways, etc.) and play an important and unique role in the overall shaping of the urban public transport, by providing affordable and efficient basic mobility for urban travel.

Changes in itineraries and planning can have diverse impacts (benefits and costs) on the complete public transport ecosystem and can change the urban planning landscape. Therefore, any mobility project should include an in depth study of the economic impacts of the introduction of the new disruptive services or public transport; by analyzing benefits and costs not only from the point of view of service operation, but also quantify the indirect effects and the externalities like, parking cost savings, or efficient land development benefits, change of modal transfer, working hour gains, gains in waiting time, energy savings, carbon footprint, noise, air pollution, etc.

Since public transport is shaped by a complex ecosystem, the evaluation of the economic impact has to be done in a holistic way, taking into account not only direct costs, but also quantify the indirect benefits such as vehicle ownership, parking cost savings, or efficient land development benefits, resulting from the public service personalization as on-demand trips. The economic analysis of the used autonomous electric vehicles must examine business viability as well as economic impacts for users and cities.

EASI-AV covers the scope since it integrates internal cost-benefit analysis of the service including investment and operation costs as well as a cost-benefit analysis of the environmental impact of the service (externalities).

By offering a global economic comparison between an autonomous service and any other mobility mode, EASI-AV helps policy makers to decide on the one hand how and with which characteristics an autonomous transport service can be deployed, and, on the other side, what would be the effect of this deployment.

4.4.2. Scenarios assessment

The economic impact evaluation must also help shape the future of mobility by proposing evaluated scenarios. Prospecting the future is a mandatory process for decision makers; scenarios represent the fuel for strategic investment decisions. Mobility models, and especially collective mobility models, are mostly built on proactive and transformative public strategies.

The design of scenarios aims at strengthening strategic thinking models of decision makers and reducing the negative effect of cognitive biases. Scenario for urban mobility is not simply a forecast of the most probable outcome, but rather it creates a set of plausible futures challenging the prevailing mind-set and status quo.

There are two kinds of scenarios: 1) international scenarios prospecting the future of mobility based on macro trends leveraged by global technology and society changes, and 2) local scenarios prospecting innovation propensity to success based on micro trends and leveraged by local initiatives. EASI-AV targets the latter type of scenarios by proposing scenarios viability evaluation.

Through economic impact evaluation, policy makers can test and evaluate different levels of personalized services, calculating costs and benefits for different stakeholders such as public transport operators, collectivity, the leading organization, or passengers.

EASI-AV provides a framework to evaluate sustainability footprint of robomobility with value creation for different stakeholders (city, PTO, passengers and any organisation willing to introduce an autonomous mobility service). EASI-AV helps to calculate the viability of new business models. EASI-AV will not propose new concrete passenger use cases but it gives the framework to evaluate the economic viability of the deployment of a specific mobility adapted to these cases and its global impact.

Furthermore, the tool will help to evaluate new service business models that will transform the “simple” ride into a user experience, taking into account the diversity of passenger needs, offering them with personalized services. A survey we conducted in 2019 (Mira-Bonnardel, 2020) on uses of autonomous vehicles by a local population allowed us to picture daily scenarios combining different options/services (Table 4.2).

Time Slots	Options	Use Cases
6 am - 9 am Predetermined journeys	R1S1	Transportation with predetermined stops for regular commuters, fixed time mobility (employees and schoolchildren)
9 am – 5 pm Journeys on request	R2S2	Transportation of goods (last mile) in city centers for retailers and individuals, with booking and connection to track the delivery process in real time
		Transportation for targeted needs (people with reduced mobility, leisure centers, care centers, specific goods, etc.)
		Transportation for disabled people at set times
		Transportation for city tours and outings
5 pm - 8 pm Predetermined journeys	R1S1	Transportation with predetermined stops for regular commuters, fixed time mobility (employees and schoolchildren)
8 pm - 6 am Journeys on request	R2S1	Night transportation for specific and emergency requests (like injured or sick people, delivery, deliveries for hospitals, tourist trips, etc.). Specific requests should be privately funded (individuals, travel agencies, retailer associations, etc.).

Table 4.2. Examples of daily usage scenarios for AVCTs

Each time slot comes with its own business model with relevant partners; customers or needs. Thereby, the overall organization, revenue model, communication channels, logistic et fleet management must be adapted.

EASI-AV ambitions to help valorize globally the economic side of any scenario combination and in doing that, helps decision-makers to choose with knowledge of economic impact.

4.4.3. Current limits of EASI-AV

EASI-AV is still a work in progress. The web application is under development and will likely be on open access by the end of 2022.

With public transport being a complex ecosystem including not only transport operators, passengers and policy makers but a lot of different stakeholders such as software providers, mobility platforms, vehicle manufacturers, insurance companies, telecoms companies, infrastructure construction companies, maintenance companies, data provider companies. Each stakeholder may facilitate or hinder the deployment of autonomous collective transport. Therefore, they should be able to analyze scenarios for their own economic standpoint.

In that way EASI-AV is still limited, since it is designed as a decision making tool for local authorities (a city government or a regional government), national policy makers, companies or universities needing to offer a mobility service on their campus. It is not designed for all stakeholders of the mobility ecosystem.

The other limitation of EASI-AV lies in the fact that it does not take into consideration the social impact of robomobility on unemployment. Sooner or later regulation may no longer require any safety driver in the vehicles, but instead remote supervisors to monitor a fleet of 5 to 10 vehicles. This change will automatically impact drivers' level of employment and local unemployment rates. Since Schumpeter's creative revolution, we know that this consequence will be only temporary until drivers get trained for other competencies. Yet this impact should be taken into account as a social effect (so should security against vandalism and other sources of violence, or other local social side-effects). Our aim for the future is to expand EASI-AV in that direction.

4.5. Conclusion

The large-scale deployment of autonomous collective vehicles, combined with on-line services, user profiling and dynamic itinerary optimization, will have a snow-ball disruption-effect on today's public transport model. The disappearance of drivers will allow transport operators to deploy more vehicles, leading to reducing the size of the vehicles, which in its turn will allow vehicles to divert from the predefined itineraries and start offering on-demand door-to-door services (based on on-line dynamic reservations and optimization), transforming public transport into transit service personalization.

This transformation will require a high level of investment. Anticipating the economic impact of investments is a usual task for any decision-maker or investors. Surprisingly this seems not to be the case for autonomous mobility investment at least very few elements have been published on this topic. Within the European AVENUE project, we have worked with transport operators and local cities governments to build a tool enabling the economic calculation for the implementation of autonomous vehicles into their transport network and the valorization of deployment scenarios. This tool: EASI-AV, was successfully tested on the experimentation site in Luxembourg city and proved to be a real support tool for decision-making in mobility strategy.

Further analysis and programming work need to be conducted before it allows to valorize the global socio-economic impact of robomobility. The authors work on it and the web-app should be posted open access online by the end of 2022.

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References

Ainsalu, J. et al. (2018). State of the art of automated buses. Sustainability, 10(3118), 2-34.

Antonialli, F. (2020). Autonomous Shuttles for Collective Transport: a worldwide benchmark. International Journal of Automotive Technology and Management, Genèva, 2020. In press.

ARK Invest (2017). Mobility-as-a-service: why self-driving cars could change everything. Available online: www.research.ark-invest.com/hubfs/1_Download_Files_ARK-Invest/White_Papers/Self-Driving-Cars_ARK-Invest-WP.pdf (accessed 14 April 2020).

Attias, D. (2017). The automobile world in a state of change: from the automobile to the concept of auto-mobility. In: Attias, D. (2017). The Automobile Revolution: Towards a New Electro-Mobility Paradigm. (1st ed.). Gewerbestrasse (Switzerland): Springer International Publishing.

AVENUE (2018). Objectives of the Avenue Project. Available online: Retrieved on www.h2020-avenue.eu/content/objectives-avenue-project (accessed on 14 April 2020).

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

Bösch, P. M., Becker, F., Becker, H., Axuausen, K. W. (2018). Cost-based analysis of autonomous mobility services. Transport Policy, 64, 76-91.

Bulteau, J. (2016) Revisiting the bottleneck congestion model by considering environmental costs and a modal policy, International Journal of SustainableTransportation, 10:3, 180-192.

Bulteau, J., Feuillet, T., Le Boennec, R. (2018) Spatial Heterogeneity of Sustainable Transportation Offer Values: A Comparative Analysis of Nantes Urban and Periurban/Rural Areas (France). Urban Sciences, 2, 14.

Caragliu, A., Bo, C. D., Nijkamp, P. (2011). Smart Cities in Europe. Journal of Urban Technology, 18(2), 65-82.

Catapult Transport Systems (2017). Market Forecast for Connected and Autonomous Vehicles. Available online:

www.assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/642813/15780_TSC_Market_Forecast_for_CAV_Report_FINAL.pdf (accessed on 13 April 2020).

Clausen, C. (2017). Niche management of Autonomous Vehicles for positive environmental outcomes in Copenhagen: Evaluating the feasibility of purposive measures through scenario analysis. Master's thesis, Lund University, Lund, Sweden.

Fagnant, D. J., Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transportation Research Part A: Policy & Practice, 7, 167–181.

Gandia, R. M., Antonialli, F., Cavazza, B. H., Neto, A. M., Lima, D. A. D., Sugano, J. Y., Nicolaï, I. & Zambalde, A. L. (2018). Autonomous vehicles: scientometric and bibliometric review. Transport Reviews, 38, 1-20.

Harris, R. (2018). Shuttle diplomacy: The path to deployment. Available online: www.publishing.ninja/V4/page/4572/245/270/1 (accessed 14 April 2020).

Henderson, H., Veder, A., Li, L., Johnson, M. (2017). Feasibility of Electric Autonomous Vehicles on Ohio State University Campus. Available online: www.kb.osu.edu/bitstream/handle/1811/81632/1/ENRAEDE4567_ElectricAutonomousVehicles_au2017.pdf (accessed 14 April 2020).

Jones, P., Marshall, S., & Boujenko, N. (2008). Creating more people-friendly urban streets through 'link and place' street planning and design. IATSS Research, 32(1), 14-25.

Kalakuntla, S. P. (2017). Adopting autonomous bus to a transit agency: a cost-benefit analysis. Available online: www.academia.edu/34636124/ADOPTING_AUTONOMOUS_BUS_TO_A_TRANSIT_AGENCY_A_COST-BENEFIT_ANALYSIS (accessed 14 April 2020).

KPMG (215).Connected and Autonomous Vehicle - The UK Economic Opportunity. 2015. Available online: www.smmt.co.uk/wp-content/uploads/sites/2/CRT036586F-Connected-and-Autonomous-Vehicles-%E2%80%93-The-UK-Economic-Opportu...1.pdf (accessed on 13 April 2020).

Litman, T. (2018). Autonomous vehicle implementation predictions. Implications for Transport Planning. 2018. Available online: www.vtpi.org (accessed on 13 April 2020).

Merat, N., Madigan, R., Nordhoff, S. (2017). Human factors, user requirements, and user acceptance of ride-sharing in automated vehicles. Available online: www.google.com.br/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=2ahUKEwi97onnuPXhAhWjAmMBHV0vANoQFjABegQIBBAC&url=https%3A%2F%2Fwww.itf-oecd.org%2Ffile%2F16355%2Fdownload%3Ftoken%3DwzML3Ngi&usg=AOvVaw3u20zlsLVA-aIGHQmK0810 (accessed 14 April 2020).

Mira-Bonnardel, S., Antonialli, F., Attias, D. (2020). Autonomous Vehicles toward a revolution in collective transport. In: Autonomous Vehicle and Smart Traffic, (In Press). London (England): IntechOpen.

Mira-Bonnardel, S., Attias, D. (2018). The autonomous vehicle for urban collective transport: disrupting business models embedded in the smart city revolution. Proceedings of International Colloquium of Gerpisa: Who drives the change? New and traditional players in the global automotive sector. São Paulo, 26.

Mira-Bonnardel, S., Attias, D. (2019). Autonomous vehicle for flexible public transportation systems: towards a shared on demand mobility. Proceedings of International Colloquium of Gerpisa:Paradigm Shift? The automotive industry in transition. Paris, 27.

Ongel, A., Loewer, E., Roemer, F., Sethuraman, G., Chang, F., Lienkamp, M. (2019). Economic assessment of Autonomous Electric Microtransit Vehicles. Sustainability, 11(648), 1-18.

Pancost, R. D. (2016). Cities lead on climate change. Nature Geoscience, 9, 264–266.

Rethink (2017). Disruption, Implications and Choices Rethinking Transportation 2020-2030 The Disruption of Transportation and the Collapse of the Internal-Combustion Vehicle and Oil Industries. Available online: www.static1.squarespace.com/static/585c3439be65942f022bbf9b/t/591a2e4be6f2e1c13df930c5/1494888038959/RethinkX+Report_051517.pdf (accessed on 14 April 2020).

Rosenzweig, C., Solecki, W., Hammer, S.A., & Mehrotra, S. (2010). Cities lead the way in climate-change action. Nature, 467, 909-911.

SAE (2016). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles J3016_201609, Available online: www.sae.org/standards/content/j3016_201609/ (accessed 14 April 2020).

Zhang, W., Jenelius, E., Badia, H. (2019). Efficiency of Semi-Autonomous and Fully Autonomous bus services in trunk-and-branches networks. Journal of Advanced Transportation, 1-18.