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A regional cost-benefit analysis of replacing motorized modes by a shared automated electric vehicle service

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ABSTRACT

Shared automated electric vehicles (SAEVs) have the potential to transform regional transportation, particularly in low-density areas where accessibility and resource optimization are challenging. However, their integrated economic impact on operators, users, environment, and society have been little explored. This paper presents a cost-benefit analysis methodology, incorporating a flow-based integer programming model, to assess the viability of SAEV services in a regional inter-urban context. The case study is based on mobility data from the Aveiro and Coimbra regions (Portugal). We evaluate the replacement of all motorized intermunicipal trips with various SAEV configurations, including automated cars (with and without pooling), automated minibuses, and a mixed fleet (cars and minibuses). Results indicate that SAEV providers can achieve profitability with fares ranging from €0.08 to €0.36 per kilometer. Even at these rates, SAEV services generate economic benefits for users, particularly pooled car-based services, as private car expenses dominate current mobility costs. Additionally, all SAEV configurations contribute to cost reductions related to air pollution, noise, global warming potential, and road accidents, with pooled services offering the greatest savings. A series of SAEV transition scenarios using a fleet of pooled cars also demonstrated benefits for all stakeholders, albeit lower than those from fully replacing motorized trips. A second sensitivity analysis confirms that reducing vehicle acquisition costs is key to lowering fares and increasing user savings. This paper represents one of the first evaluations of large-scale SAEV services for intermunicipal trips with significant distances between urban centers, contributing insights into smart and sustainable transportation solutions for such contexts.

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Cost-benefit analysis; flow-based integer programming; intermunicipal trips; service cost; shared automated electric vehicles

1. Introduction

The extensive reliance on private motor vehicles exerts significant pressure on the current transportation system, leading to adverse effects such as traffic congestion, climate change, air pollution, and road crashes (Ashik et al., 2022). The application of a smart combination of vehicle efficiency improvements, alternative fuels, and flexible mobility services can be a way to fulfill current mobility needs while addressing the problem of carbon intensity associated to private passenger-car travel (Tikoudis et al., 2021). Integrating driverless technology into this triad framework can provide additional benefits, such as in-vehicle productivity, mobility for non-drivers, and increased safety (Fagnant & Kockelman, 2015), and expecting reductions in energy consumption and greenhouse gases (GHG) emissions (Rahman & Thill, 2023; Wang et al., 2018). The evolving mobility-on-demand paradigm featuring automated vehicles (AVs), known as the shared automated electric vehicle (SAEV) system, encompasses all the above benefits (Morfeldt & Johansson, 2022).

SAEV systems are a competitive technology for urban mobility (Sumitkumar & Al-Sumaiti, 2024). However, this conclusion was retrieved from a collection of research works with different analysis agendas not focused on extensively studying the costs and benefits of SAEV services across diverse perspectives (e.g. user, operator, society, environment), which is normally associated with Cost-Benefit analysis (CBA). This method can be applied to answer unaddressed questions regarding the implementation of SAEV systems, namely:

- Does replacing all existent transportation modes with a SAEV mobility service contribute to overall gains (considering the life cycle cost of vehicles)?
- What are the costs and benefits for the different stakeholders' perspective (users, operator, environment, society) associated to this replacement?

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This work proposes a CBA methodology to evaluate the potential of SAEV mobility services within a regional inter-urban context, aimed to explore futuristic scenarios where motorized trips are gradually replaced by a SAEV service. It uses mobility data from a survey and optimization results. Survey data characterizes the current situation, serving as a benchmark for comparison, while optimization results, derived from a flow-based integer programming model (Santos & Correia, 2021), define the design parameters and operational movements of future SAEV systems.

The main objective is to determine whether the proposed SAEV mobility replacement scenarios exhibit benefits not only for the SAEV operator and users, but also for the environment and society. The analysis pays attention to the impacts on air pollution, noise, as well as the societal costs associated with traffic congestion and road crashes, while also considering the lifecycle Global Warming Potential (GWP) (EC, 2020b).

The proposed SAEV mobility scenarios encompass different fleet compositions: (i) a fleet of single-seat vehicles; (ii) a fleet of 4-seat cars (with pooling); (iii) a fleet of minibuses; and (iv) a mixed fleet of cars and minibuses. The methodology is applied to two regions in central Portugal. This study also includes two sensitivity analyses. The first analysis examines a series of transition scenarios, focusing on the best-performing scenario under varying SAEV deployment ratios of 5%, 10%, 20%, and 30%. The second analysis focuses on cost structure related to electric vehicles and AV technology, vehicle and battery lifetimes, electric vehicle (EV) usage rates in the benchmark scenario, low-cost electricity options, and the evaluation of policy measures including tax exemption and subsidies for SAEV fleet acquisition.

The innovate nature of the paper lies on the fact that it is one of the first studies to propose and apply a methodology that estimates and compares the potential of partially and completely replacing all existent modes by a large-scale SAEV service for the intermunicipal trips within two regions characterized by low-density areas and significant distances between urban centers. This methodology holds relevance in understanding the perspectives and challenges of these services from different stakeholders, a key aspect highlighted in recent studies (Duan et al., 2025). It also provides a foundation for a decision-support analysis framework with some numerical values to reflect about.

2. Literature review

SAEV mobility services are seen as potential solutions for improving access to electric AVs, which is expected to be an expensive technology (Narayanan et al., 2020). The aggregation of automation, shared mobility, and electrification offers a viable solution to overcome the current electrification challenges (e.g. charging speeds, limited charging station availability, range anxiety), and mitigate the higher fares associated with conventional vehicle services (Bauer et al., 2018; Fagnant & Kockelman, 2014; Luk et al., 2017; Prencipe et al., 2022) and improve urban transportation systems (Zhu et al., 2023).

SAEVs have the potential to reduce the per-kilometer GHG emissions when compared to both conventional vehicles and projected hybrid electric vehicles (HEVs), even if total vehicle kilometer traveled (VKT), average speed, and vehicle size increases substantially (Greenblatt & Saxena, 2015). Furthermore, replacing privately-owned vehicles with SAEV services utilizing four-seat capacity vehicles can yield reductions in life cycle environmental impacts (Vilaça et al., 2022).

To assess the competitiveness of future SAEVs service operations, it is crucial to comprehensively understand their cost structures across diverse scenarios. CBA is a method used to evaluate investments by comparing the monetary value of benefits with costs over the lifetime of a project, involving all relevant stakeholders (EC, 2014). While CBA is commonly employed for evaluating transportation projects, shared mobility services, including SAEV systems, have received comparatively less attention, as listed in Table S1 of the Supporting Information.

The majority of studies involving SAV and SAEV services have used simulation (Bauer et al., 2018; Chen et al., 2016; Fagnant & Kockelman, 2014, 2018; Fagnant et al., 2016; Loeb & Kockelman, 2019; Vilaça et al., 2024; Wang et al., 2019) or optimization approaches (Guo et al., 2022; Liang et al., 2020; Liang et al., 2016; Narayanan et al., 2022; Paudel & Das, 2023; Santos et al., 2023; Santos & Correia, 2021; Wang et al., 2025).

Cost structures have been used to produce simple financial analysis for the perspectives of the operator and travelers (Bösch et al., 2018; Chen et al., 2016; Fagnant & Kockelman, 2018; Loeb & Kockelman, 2019; Santos et al., 2023). Chen et al. (2016) examined the costs of electrified SAVs versus gasoline-powered fleets in a medium-sized metropolitan area under various vehicle-range and charging scenarios while Loeb and Kockelman (2019) compared different SAEV services based on different combinations of charging speeds, vehicle range and cost estimates. The hybrid electric vehicle (HEV) fleet layout exhibited lower operation costs than the SAEV configurations, for gasoline prices up to $10 per gallon or long-range SAEV acquisition costs higher than $16,000 per unit (Loeb & Kockelman, 2019). Some studies have expanded their cost structures to encompass user-centric metrics, such as wait penalty and reject times, alongside operator considerations (Fagnant & Kockelman, 2018; Liang et al., 2020). Narayanan et al. (2022) demonstrated that SAEV systems outperformed both car-sharing and mixed systems in terms of travel time, congestion levels, total vehicle kilometers traveled, and vehicle requirements. Their analysis also considered user travel time and the costs associated with empty SAV trips. Bösch et al. (2018) analyzed cost structures for various SAEV fleet configurations (cars, midsized, vans, minibuses, and buses), expressed by urban and regional services. Another study by Santos and Correia (2021) included different SAEV fleet compositions (cars, minibuses, and a mixed fleet comprised of cars and minibuses) to examine the feasibility of using such a service for interurban trips. This work was later enhanced by adding a third dimension to the space-time network, considering vehicle energy flows, however, the focus remained on the operator's perspective (Santos et al., 2023).

Environmental benefits of SAV services have been demonstrated in studies conducted by Bauer et al. (2018) and Fagnant et al. (2016) for regional trips. Österle et al. (2022) also highlighted environmental and safety advantages of SAVs, albeit focusing on services utilizing trucks and vans for urban and suburban trips.

3. Methodology

The framework of the proposed methodology is shown in Figure 1. First, data from mobility surveys is used to describe the current transportation situation (S0). Various metrics are collected to characterize the existing transportation modes, including the number of vehicles, traveled distance, and number of trips per mode. Afterwards, a flow-based integer programming (IP) optimization model is applied to determine the optimal SAEV fleet and operational movements for the same demand data (as in the mobility survey data), assuming that all motorized intermunicipal trips are being replaced by a SAEV service. This flow-based integer programming model is similar to the one proposed by Santos and Correia (2021) for an SAV system. Finally, SAEV scenarios are applied to the IP model to define the correspondent optimal outputs needed as an input for the CBA.

3.1. Study assumptions

Some assumptions related to the optimization model and the cost structure of the CBA are adopted for this exploratory research.

Users always accept the vehicle provided to them (i.e. users' mode choice behavior is not simulated) and the fare charged per kilometer traveled is constant throughout the day, thus ignoring dynamic price strategies. The main goal is to evaluate the financial operation relative to an extreme scenario where SAEV mobility service satisfies all requested intermunicipal trips. Although recent applications that incorporate mode choice models into optimization procedures have been developed, this would require more data, adding computational complexity to estimate a suitable mode choice model for the proposed service (Pacheco et al., 2021).

Each SAEV carries the passenger from their origin to their destination, which includes intra-region and inter-region trips. Incorporating trip patterns and relocations into the optimization model enables the estimation of operations with effective vehicle positioning, minimizing response times. The trip modeling approach was identical to that conducted in our previous studies (Santos et al., 2023; Santos & Correia, 2021). The detours for the pooling trips are determined using the procedure described in Santos and Correia (2021). The intra-municipal trips are not covered by the SAEV system, as they are well served by local public transportation companies.

The fleet size corresponds to the number of vehicles needed to fulfill all trips, without accounting for slack to cover incidents or vehicle malfunctions. The cost of the SAEV fleet for the operator is expressed as depreciation costs and is based on the trip characteristics and odometer distance. It corresponds to the ratio between the vehicle's traveled distance (with passengers and relocations) and the lifetime of vehicles (Bauer et al., 2018). Fleet is renewed after vehicles reach their projected lifetime (Chen et al., 2016).

Battery replacement costs are computed as the ratio between the vehicle's traveled distance (including passengers and relocations) and the lifespan of the batteries (Bauer et al., 2018). The battery can be replaced during the SAEV's service span, in line with past studies (Bauer et al., 2018; Chen et al., 2016; Vilaça et al., 2022).

Costs associated with driving to recharge are considered negligible since vehicles can readily locate fuel or charging stations near their idle positions, and both battery capacity and charging speeds are enough to not have an impact on the movement of clients and relocations (Santos & Correia, 2021).

Environmental and society impacts were expressed by means of the main external costs for each category and per vehicle-kilometer (Österle et al., 2022; Vasconcelos et al., 2017) based on 2014 reference values (EC, 2020b) and adjusted to 2024 figures, accounting for annual inflation rates. This approach was used because it easily allows to compute costs based on vehicle and fuel type information, and aggregated by service types (urban versus regional) and country (EC, 2020b). Air pollution, noise, and traffic congestion marginal cost factors for SAEVs are assumed to align with those for current EVs due to limited data specifically applicable to AVs (EC, 2020b). Costs associated with transportation infrastructure effects on habitat damage are omitted due to challenges in accurately quantifying such effects (Silva et al., 2022).

GWP impacts quantify the amount of greenhouse gases produced with a direct or indirect effect on global warming. Those impacts include vehicle production and assembly, fuel/electricity production, vehicle use and maintenance, and disposal of vehicles and batteries (EC, 2020a).

SAEV safety benefits are estimated by comparing crash external costs under Vision 2040 against the present scenario, depicting road safety improvements for all road users. Several studies dealt with the percentage of road crashes that could be eliminated by AV technology (Mueller et al., 2020). We adopt the assumption that SAEV mobility service reduces crashes by 70% (compared to today) (Österle et al., 2022).

3.2. Flow-based IP model

The design of the SAEV system is performed using a flow-based integer programming model similar to the one proposed by Santos and Correia (2021) for a SAV system. This optimization model is built upon a two-dimensional space-time network $I \times T$, in which the space is divided into zones ($i \in I$), each one represented by a centroid, and the time

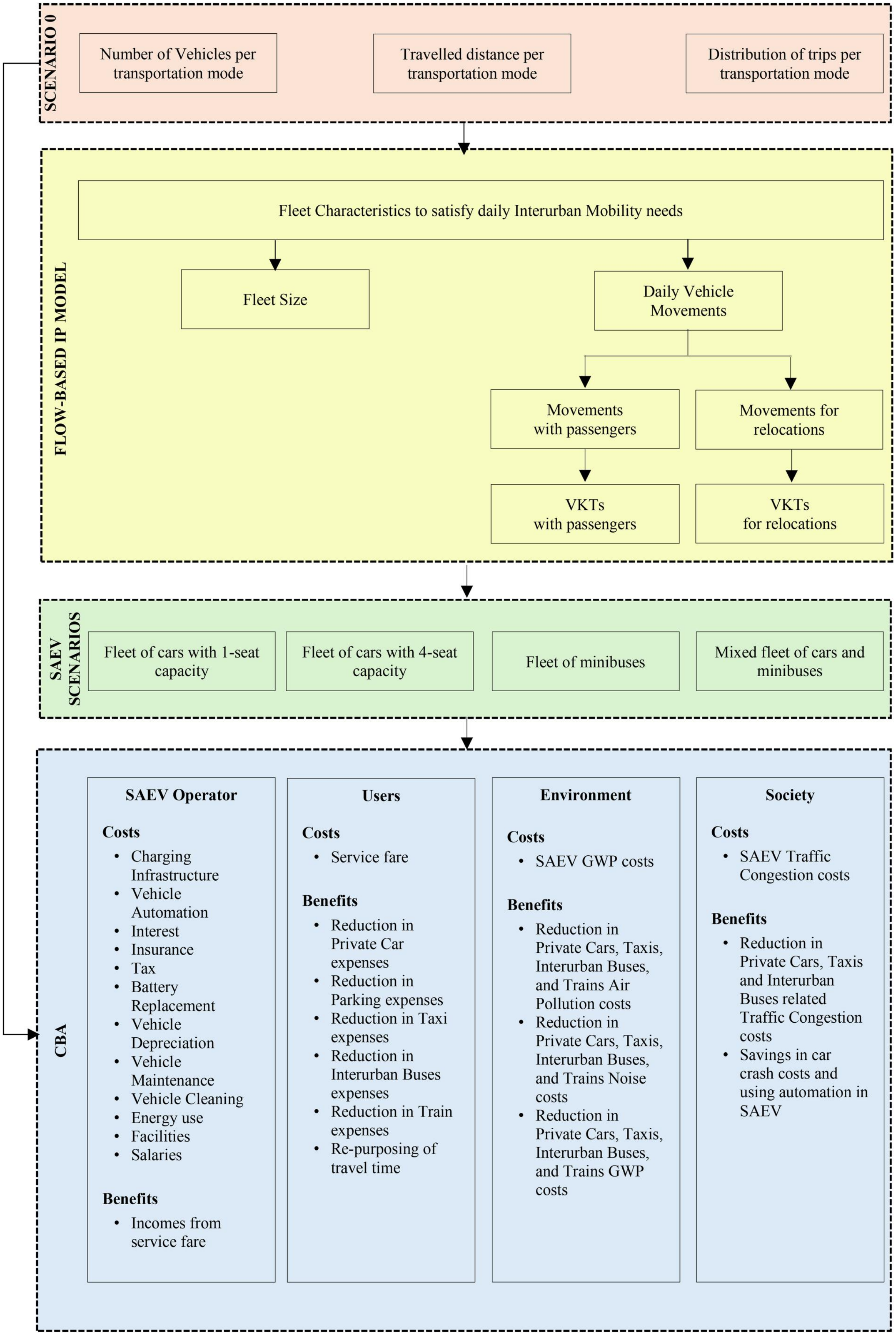

Figure 1. Methodological framework.

divided into time instants ($t \in T$) — the distance between two consecutive time instants is a timestep. This network structure enables the aggregation of vehicle movement into flows instead of considering each vehicle individually, allowing large-scale problems to be optimally solved (Santos & Correia, 2021). Additionally, it differentiates movements throughout the day, providing an overview of daily operations, which is essential for accounting for associated benefits and costs. The discretization of time and space associated with the use of the time-space network needs to be in balance with the detail needed and the size of the optimization problem. A set of vehicle types, B, distinguishes the different vehicle categories $b \in B$ considered by the model (e.g. car and minibus). A vehicle type is mathematically defined by a set of characteristics that include seat capacity, travel time, driving cost, and fixed daily usage cost. The vehicle flows in the time-space network are represented by arcs ($a \in A$) with coordinates (i, j, t_1, t_2), being i, $j \in I$ and t_1, $t_2 \in T$. Subsets of arcs are defined for each vehicle type $b \in B$, each one including the following arc types:

1. Flow of vehicles of type $b \in B$ moving with a user (subset $A_u^b \subset A$) from zone i to j ($i \neq j$) starting at time t_1 and finishing at $t_2 = t_1 + u_{ij}^b$, being u_{ij}^b the travel time using vehicle type b to transport users from i to j;
2. Flow of vehicles of type $b \in B$ relocating (subset $A_r^b \subset A$) from zone i to j ($i \neq j$) starting at time t_1 and finishing at $t_2 = t_1 + r_{ij}^b$, being r_{ij}^b the travel time to relocate from i to j;
3. Flow of idle vehicles (subset $A_s^b \subset A$), related to the stopped vehicles of type $b \in B$ at zone i from time t_1 to t_2 (in this case $i = j$).

The subset of arcs A^b results from the union of the previously presented subsets, $A_u^b \cup A_r^b \cup A_s^b$. The nodes $n \in N$ represent the time-space instances (v, t), $v \in I$ and $t \in T$, of the extremities of the arcs ($a \in A$).

The decision variables are:

- f_b (a) represents the number of vehicles of type $b \in B$ flowing in arc a;
- F_b represents the number of vehicles of type $b \in B$ in the SAEV fleet.

The model parameters are:

- c_b (a) is the cost associated with a vehicle of type $b \in B$ for using arc a. It includes energy cost and infrastructure fees (e.g., tolls, congestion fees) for arcs associated with the movement with users ($a \in A_u^b$) and relocations ($a \in A_r^b$). It can also accommodate parking costs for stopped vehicles ($a \in A_s^b$);
- k_b is the daily cost of using a vehicle type $b \in B$ which includes registration fee, depreciation, and vehicle operating costs including cleaning and maintenance;
- m_b is an integer number representing the capacity in number of seats of vehicle type $b \in B$;
- $d(i,j,t)$ is the demand in number of users at zone i and time t that intend to go to j, being $i,j \in$ I and $t > 0$.

The IP model is then formulated using Equation 1–6.

$$\min\ (\Pi) = \sum\nolimits_{b\in B}\sum\nolimits_{a\in A^b} f_b(a) \times c_b(a) + \sum\nolimits_{b\in B} k_b \times F_b \tag{1}$$

s.t.

$$\sum\nolimits_{a\in A^b|(j=v \quad t_2=t)} f_b(a) = \sum\nolimits_{a\in A^b|(i=v \quad t_1=t)} f_b(a), \forall b \in B, \forall (v,t) \in N \quad t > 0 \tag{2}$$

$$d(i,j,t) \le \sum\nolimits_{b\in B} m_b \times f_b(a)_{\left(a\epsilon A_u^b|t_1=t\right)}, \forall i,j \in I \quad i \neq j, \forall t \in T \tag{3}$$

$$\sum\nolimits_{a\in A^b|t_1=0} f_b(a) = F_b, \forall b \in B \tag{4}$$

$$f_b(a)_{\left(a\epsilon (A_u^b \cup A_r^b)|t_1=0\right)} = 0, \forall b \in B \tag{5}$$

$$f_b(a) \in \mathbb{N} \cup \{0\}, \forall b \in B, \forall a \in A \tag{6}$$

$$F_b \in \mathbb{N} \cup \{0\}, \forall b \in B \tag{7}$$

The objective is to minimize the cost of running the SAEV system (as expressed in Equation 1), which derives from the daily usage and movement of vehicles. Equation 2 ensures the conservation of flows at each node of the time-space network for each vehicle type $b \in B$. Equation 3 guarantees that the aggregated capacity of vehicles departing from i to j at time t is enough to serve the demand requests. Equation 4 defines the total number of vehicles in the fleet per vehicle type $b \in B$. Equation 5 assures that only idle arcs starting at $t = 0$ can assume non-zero values. These idle arcs (with $t_1 = 0$ and $t_2 = 1$) are auxiliary and needed to determine the fleet size and initial position of vehicles by using Equation 4. Lastly, Equations 6 and 7 enforce that the decision variables are non-negative integers. The FICO Xpress Solver was employed to perform numerical experiments and find the optimal solution that satisfies the problem constraints. For specific details on model performance, see Santos and Correia (2021).

3.3. Cost-benefit analysis framework

The CBA-based framework is developed to assess the replacement of all modes by a SAEV mobility service, considering the viewpoints of the various stakeholders. As the guidelines for transportation-related projects provided by the European Commission (EC) do not specifically address SAEV system services (EC, 2014), a new CBA procedure has been devised. This procedure combines the EC approach with other CBA approaches from studies (Chen et al., 2016; Österle et al., 2022; Vasconcelos et al., 2017). It encompasses the following steps.

First, to identify the case study and establish alternative SAEV service scenarios (cars, minibuses, mixed fleet of cars and minibuses).

Second, to calculate the service fare per vehicle occupant and kilometer (P_{SAEV}) that corresponds to the production cost plus a profit margin (r) for the SAEV operator (different for each scenario), the Value Added Tax (VAT), and a payment transaction fee (p) related to bank charges and commissions, as expressed by Equation 8.

$$P_{SAEV} = \frac{\sum \text{Costs}_{SAEV}}{365 \times s_{SAEV} \times (d_{SAEV} \times F_{SAEV})} \times \frac{(1 + VAT)}{((1 - r) \times (1 - p))} \tag{8}$$

Where:

$\sum \text{Costs}_{SAEV}$ – Annual costs of the SAEV service [€];

s_{SAEV} – Average number of occupied seats per vehicle;

d_{SAEV} – Daily distance travelled by SAEV moving clients per vehicle [km];

F_{SAEV} – Number of vehicles (fleet size) used daily in the SAEV service.

Third, to determine the costs and benefits associated with each scenario and for the different stakeholders. The perspectives considered in this CBA approach are thus the following: *operator* (fixed, variable and other costs, and fare revenues); *users* (service price, savings on changing transportation mode, and user benefits due to re-purposing of travel time), *environment* (external costs related to air pollution, noise and GWP); and *society* (external costs related to traffic congestion and the reduction in car crashes due to a decrease of human-driven car trips). The calculation details of the above-mentioned costs are shown in Section 2 of the Supporting Information.

Fourth, to quantify costs and benefits of a target year (365 days) and convert each cost and benefit into a common monetary value (such as Euro).

4. Case study

This methodology is applied to the Regions of Aveiro and Coimbra, located in the center of Portugal. These regions are merged for the analysis, forming a larger area comprised of 30 municipalities and covering 6,026 km^2 (Figure 2). The combined region has a population of 811,001 inhabitants, which is roughly 8% of the Portuguese population (see details in Section 3 of the Supporting Information) (Pordata, 2023). The population is spread out across the territory, except for the cities of Aveiro and Coimbra, with most municipalities classified as thinly populated areas with population densities lower than 300 inh.km^{-2}. The distances between municipality centers range from 6 km to 184 km, being the average value equal to 65.8 km.

The region has a few railway lines with different characteristics and purposes, including urban, regional, and long-distance travel. The characteristics of the area lead to low feasibility of building metro or light rail systems, resulting in a heavy reliance on the usage of private cars which are used by 75% of the local population, for work and education trips (Pordata, 2023). Therefore, the case study area proves to be a suitable location for studying the economic viability of an intermunicipal SAEV mobility service.

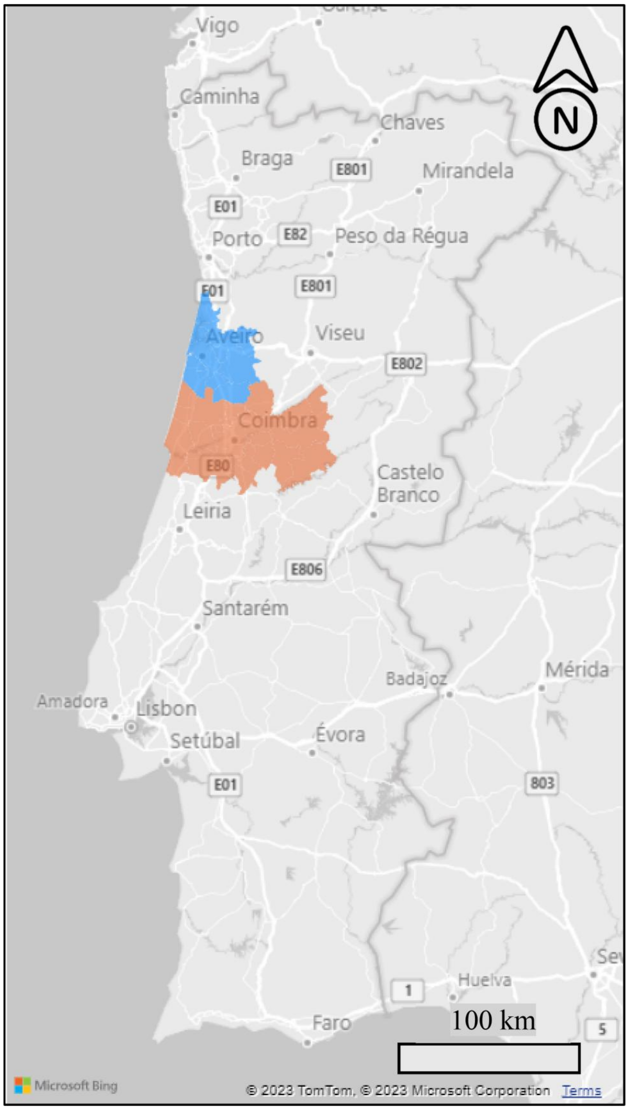

Figure 2. Geographic location of Aveiro Region (in blue color) and Coimbra Region (in orange color). Image source: Microsoft Corporation.

The data on trips within the Coimbra region and between Coimbra and Aveiro regions were retrieved from a survey conducted in 2009 by TIS.pt (2009) while the trips inside the Aveiro region were generated based on the information included in the intermunicipal plan of mobility and transportation of the Aveiro Region (CIRA, 2012) and on the transportation report of the municipal director plan done by the Aveiro municipality (CMA, 2019). Although candidate locations lack updated mobility data our study utilized the most recent available sources. The analysis of demographic data also confirmed low variation in population figures from 2011 to 2021; especially −0.3% and −3.4% for Aveiro and Coimbra regions, respectively. The full characterization of the trip generation methodology can be found in Section 4 of the Supporting Information. The total number of daily intermunicipal trips inside the case study area is 255,635 (46% inside the Aveiro region, 47% inside the Coimbra region and 7% inter regions). This corresponds to an aggregated daily distance of approximately 84,000 km.

Crash data for the studied region were gathered for a 10-year time period from 2014 to 2024 (ANSR, 2021). The database comprised a total of 49,796 crash observations, with approximately 1.2%, 4.7% and 94.1% resulting in fatalities, serious injuries and light injuries, respectively. The frequency and crashes per severity level for each region are included in Table S3 in the Supporting Information.

4.1. SAEV service scenarios

Four different SAEV service scenarios, each having a distinct fleet configuration, were tested in this work (see Table 1). This set of scenarios (S1–S4) assumes a complete replacement of motorized intermunicipal trips currently made by private cars, taxis, buses, and trains with a specific SAEV service. The SAEV fleet size and vehicle movements needed to serve the intermunicipal travel demand were determined using the flow-based integer programming model described in Section 3.2. The number of daily trips within the region remains constant across all scenarios.

The benchmark scenario (S0) represents the current mobility situation in the region, with its characteristics retrieved from survey data (e.g. modal shares, trip distances). The daily number of private cars in this current situation (75,578) is based on the assumption that all intermunicipal trips are commuting trips with an average vehicle occupancy of 1.3 passengers (Tomás et al., 2021). The mobility information about taxis, interurban buses and trains are retrieved from local and national transportation companies (AMT, 2017; CP, 2023; TRANSDEV, 2023).

Table 1. Scenario definition.

Notation	Scenario characteristics
S0	Current mobility situation (benchmark)
S1	SAEV service with a fleet of cars that can accommodate only 1 passenger (without pooling)
S2	SAEV service with a fleet of cars with capacity for 4 passengers (with pooling)
S3	SAEV service with a fleet of minibus with capacity for 16 passengers
S4	SAEV service with a mixed fleet of cars (4 passengers) and minibuses (16 passengers)

4.2. CBA input data

The SAEV service fares (P_{SAEV}) are estimated using input values listed in Table 2. These are calculated for an expected profit margin (r) of 5%, and take into account the Portuguese VAT of 23% and payment transaction fee (p) of 0.2% (EU, 2023).

The charging infrastructure cost assumes that the SAEV operator pays for both the installation and maintenance of the charging stations, and for the energy used. The total cost per year of a single-port charger is based on a 22 kW alternating current (AC) charger type. It was assumed that one charging port is required per 3 vehicles in the SAEV system fleet (Santos et al., 2023).

The cost of one car unit is assumed to be 30,610€ for companies (Renault, 2024), which is based on a fully electric but not driverless vehicle Renault Zoe E-Tech with an autonomy range of 315 km in real driving conditions (EVD, 2024) and an expected vehicle lifetime of 300,000 km (Bösch et al., 2018; Chen et al., 2016). The lifetime adopted for the battery equipping this vehicle model is 150,000 km, which is similar to the battery lifetime specified by previous authors (Loeb & Kockelman, 2019; Vilaça et al., 2022). Currently, vehicles last longer than their batteries, leading to battery replacement or reconditioning before the vehicle is disposed. The adopted vehicle lifetime is closer to the highest ones found in other research studies (370,000–482,000 km) (Bauer et al., 2018; Chen et al., 2016).

The reference for the minibus is the IVECO daily electric. This electrified model has a seating capacity of 16 passengers, a maximum range of 280 km, and costs 92,000 € (Ansell, 2019). The adopted values of vehicle and battery lifetimes were the same as cars.

The interest fee amount for companies was determined assuming an annuity loan with an annual percentage rate of charge of 4.46%, and a 3-year credit period (BdP, 2022). These prices do not include government rebates, which might vary in the medium-term.

Concerning the electricity costs, we use the kWh price of the empty period (21–8 h) provided by Portuguese company EDP, assuming that all fleet vehicles charge during the night when the kWh is cheaper (ERSE, 2025).

Table 2. Summary of cost structure for the SAEV operator.

Variable	Definition	Car Fleet	Minibus Fleet	Based Source
ci_{SAEV}	Charging infrastructure costs per unit-year	15,300 €	15,300 €	(Santos et al., 2023)
a_{SAEV}	Automation costs per vehicle-year	9,600 €	9,600 €	(Bauer et al., 2018; Chen et al., 2016)
i_{SAEV}	Interest costs per vehicle-year	1,100 €	3,510	(BdP, 2022)
iu_{SAEV}	Insurance costs per vehicle-year	630 €	1,500 €	(Bösch et al., 2018)
t_{SAEV}	Tax costs per vehicle-year	0 €	0 €	(Mobi-E, 2023)
bl_{SAEV}	Lifespan of an electric battery	150,000 km	150,000 km	(Loeb & Kockelman, 2019)
bu_{SAEV}	Unitary cost of an electric battery[a]	100 €.kWh^{-1}	100 €.kWh^{-1}	(Goldman Sachs, 2024; Orangi et al., 2024)
B_{SAEV}	Capacity of the electric battery	52 kWh	91 kWh	(Ansell, 2019; EVD, 2024)
de_{SAEV}	SAEV vehicle depreciation cost per vehicle-kilometer	10.20 €–cent.vkm^{-1}	30.70 €–cent.vkm^{-1}	(Ansell, 2019; Chen et al., 2016; EVD, 2024)
m_{SAEV}	SAEV vehicle maintenance cost per vehicle-kilometer	2.52 €–cent.vkm^{-1}	13.54 €–cent.vkm^{-1}	(Bösch et al., 2018)
c_{SAEV}	SAEV vehicle cleaning cost per vehicle-kilometer	2.15 €–cent.vkm^{-1}	5.29 €–cent.vkm^{-1}	(Bösch et al., 2018; Loeb & Kockelman, 2019)
Ec	Electricity costs	0.0917 €.kWh^{-1}	0.0917 €.kWh^{-1}	(ERSE, 2025)
V_p	Vehicle performance	16.5 kWh.100 km^{-1}	33 kWh.100 km^{-1}	(Ansell, 2019; EVD, 2024)
R_O	Monthly rent per each office space	15,000 €	15,000 €	(IDEALISTA, 2024)
S	Gross salary plus food subsidy of the SAEV staff	322,000 €	322,000 €	(Vasconcelos et al., 2017)

[a] Based on the 2024 values.

We considered the existence of two office installations, one in Aveiro and another in Coimbra, both with 3000 m^2 (IDEALISTA, 2024). The company staff includes 155 employees with one co-chief executive officer, 4 chief officers, and 150 normal employees, with 14 monthly salaries expenses of 6,000€, 4,000€ and 2,000€, respectively, (Vasconcelos et al., 2017) and 23.75% of the social security tax (SS, 2023).

The main data used to determine users' impacts is summarized in Table S4 in the Supporting Information. The cost of the different vehicle technologies includes fixed expenses per vehicle such as maintenance, taxes, insurance, parking and tolls, as well as depreciation costs (LeasePlan, 2022). Four types of vehicle technologies for private cars are considered: gasoline and diesel, hybrid, and electric. The emission values per distance were measured from various passenger cars using a Portable Emission Measurement System (Delgado et al., 2018; Fernandes et al., 2019, 2021, 2022, 2024). The 2022 local fleet composition is used to calculate the average representative costs for private cars, which consists of 37.5% gasoline passenger vehicles, 59.1% diesel passenger vehicles, 1.3% HEVs, 0.9% plug-in electric vehicles, and 1.2% EVs (EMISIA, 2023).

Regarding users' parking expenses, the percentage of paid parking was assumed to be around 11% with an average cost of $0.57€.h^{-1}$ (CIRA, 2012). In the studied regions, taxi prices are regulated, with a fixed flag of 3.95€ plus $0.75€.km^{-1}$ (NUMBEO, 2023). The fares for interurban buses and rail services were derived from regional and national public companies taking into account the monthly pass in each origin-destination (O-D) (CP, 2023; TRANSDEV, 2023). The daily re-purposing of travel time was set as 0.83€ per trip for automation level 5 for arterial routes (Szimba & Hartmann, 2020). We assumed that passengers were permitted to engage in other activities during their journeys in taxis, transit buses, and trains.

Additional input data to quantify the environmental and societal impacts are shown in Table S4. Diesel powertrain is considered for both taxis and buses (EMISIA, 2023). The values of GWP for private cars, interurban buses, and trains are obtained from the literature (EC, 2020a**;** EEA, 2021). Their values were adjusted to the reference year 2024 by incorporating the inflation rates since 2015 (Pordata, 2024). The adopted inflation-adjusted CO_2 price for Portugal is 121 $€.tonCO_{2eq}{}^{-1}$ (EC, 2020b). Since GWP values for trains are expressed in mass of CO_2 equivalent per passenger-kilometer traveled ($gCO_2eq.pkm^{-1}$), these values are multiplied by the number of trips done in each O-D pair served by trains. The selected GWP impact values are 154 $gCO_2eq.vkm^{-1}$ for cars (Vilaça et al., 2022) and 216 $gCO_2eq.vkm^{-1}$ for minibuses (Ferreira et al., 2023) of the SAEV service.

The marginal traffic congestion costs per vehicle type and traveled distance are based on the values for interurban areas (EC, 2020b). The inflation-adjusted (Pordata, 2024) accident external costs (in average) for crashes by severity level for the studied locations are 2,710,150€(*SCF*), 411,620€(*SCSI),* and 31,800€(*SCLI)* (EC, 2020b).

5. Results

This section contemplates the impact assessment of replacing all modes by a SAEV service on vehicle usage and user travel time (Section 5.1), on service fare (Section 5.2) and the economy (Section 5.3). It finishes with a sensitivity analysis of partial SAEV replacement scenarios (Section 5.4) policy and market-related parameters (Section 5.5).

5.1. Impacts of introducing a SAEV service on vehicle usage and user travel time

Comparing the SAEV service scenarios with scenario S0, our estimates show that each vehicle in the SAEV fleet would be able to replace an average of 3, 8, 21 and 20 private cars for scenarios S1, S2, S3 and S4, respectively (see Figure 3). These values are comparable to the private car replacement potential per SAEV vehicle found in the literature, ranging between 4 and 11 for SAEV services using a fleet of cars (Chen et al., 2016; Fagnant et al., 2016; Fagnant & Kockelman, 2014, 2018; Loeb & Kockelman, 2019; Santos & Correia, 2021), and 17–18 for services with minibus fleets, or mixed fleets (Santos & Correia, 2021). The reduction in the private vehicle fleet is a result of the improvement in vehicle usage associated with the SAEV service. While the average idle time of private cars verified currently is 94% (Santos & Correia, 2021), it decreases to 76% (or less) for SAEV scenarios.

The vehicle occupancy rate for the SAEV service with a 4-seat car fleet (scenario S2) has a value of 83%, while the one using a minibus fleet (scenario S3) has a value of 57%. For the mixed fleet (scenario S4), the vehicle occupancy rate of the SAEV car and SAEV minibus is 70% and 89%, respectively. However, this has a consequence on passenger travel time values due to the extra pick-up and delivery movements (Figure 3). Accordingly, the travel time experienced by SAEV passengers tends to be higher (73–74 min for S2, S3 and S4), than the travel times experienced by private car users ($\sim$ 30 min for scenario S0).

It should be noted that the travel time calculation for the scenario S0 considers the intermunicipal trips performed by all modes and is based on the O-D trip coordinates of a synthetic population, whereas the SAEV scenarios involve discretization of space resulting in trips between centroids. These simplifications limit the direct comparison of travel times between SAEV scenarios and the current situation.

Relocation movements within the SAEV system are residual, with vehicles spending 0.6–1.8% of the day relocating (see Section 6 of the Supporting Information). This means that vehicles mostly move with the population, leaving the vehicles where the population is at each moment. Companies can see this as an opportunity to use their fleet also for shorter (intra-municipal) trips.

The daily distances traveled per vehicle for each SAEV scenario exceeds the vehicles' battery range, though the average daily vehicle time for moving passengers and relocation is less than 11 h, there is enough time to fully recharge the batteries. The charging happens during the night hours when passenger demand is negligible, resulting in lower energy costs according to the adopted electricity price plan (ERSE, 2025).

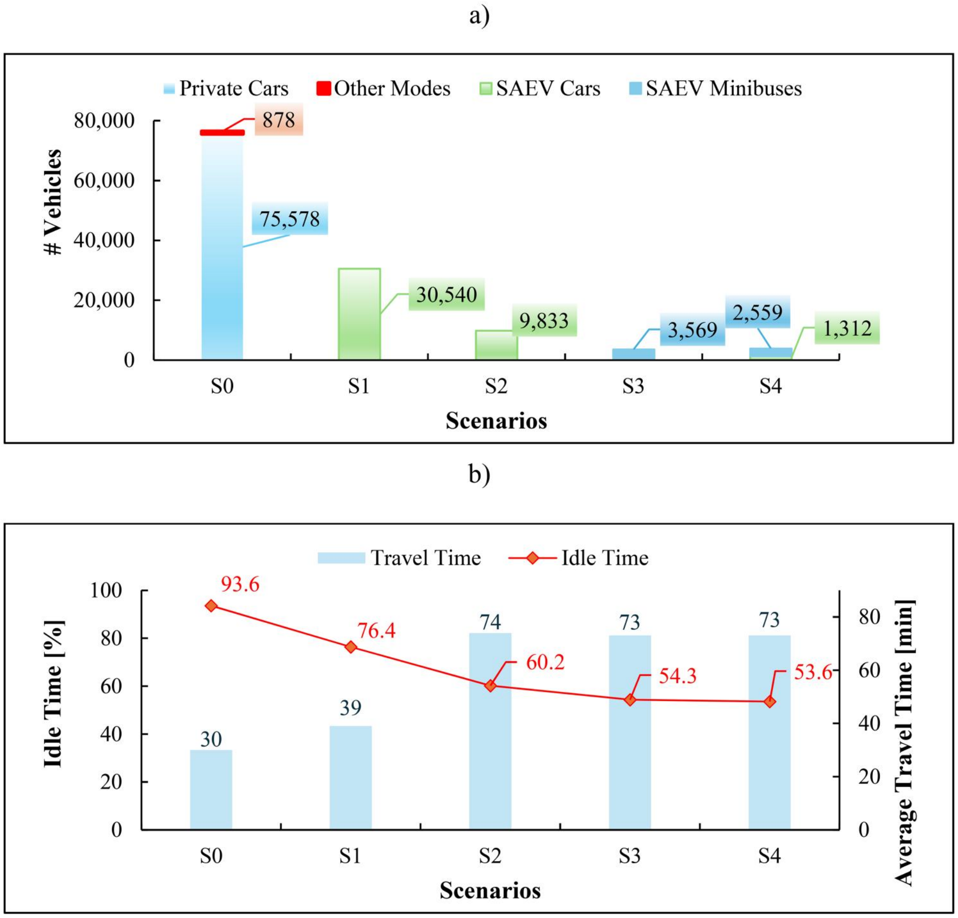

Figure 3. Comparison of scenarios: (a) number of vehicles; and (b) percentage of idle time and average passenger travel time.

Table 3. Comparison of the vehicle use per SAEV scenario.

Description	Units	S1 SAEV car 1-seat	S2 SAEV car 4-seats	S3 SAEV minibus 16-seat	S4 SAEV mixed car + minibus
Average Vehicle Occupancy	# passengers	1.0	3.3	9.1	10.4
Daily traveling distance by the fleet with passengers and relocations	vkm/day	1.10×10^7	5.83×10^6	2.41×10^6	2.64×10^6
Daily traveling distance per vehicle with passengers	km/day	338.02	578.61	666.67	670.97
Daily traveling distance per vehicle with passengers and relocations	km/day	360.44	592.42	674.69	680.85
Yearly traveling distance per vehicle with passengers and relocations	km/year	1.20×10^5	1.97×10^5	2.24×10^5	4.58×10^5
Daily time with passengers per vehicle	#hours/day	5.23	9.31	10.81	10.85
Daily time in relocations per vehicle	#hours/day	0.43	0.23	0.15	0.30

The annual distances per vehicle for scenarios S2–S4 exceed 150,000 km (Table 3), meaning that the lifetime of vehicle batteries is quickly reached. Therefore, the cost of battery replacement is included in the annual costs of the SAEV service of the CBA framework.

5.2. Impacts of the different SAEV configurations on service fare

The SAEV car service with 1-seat (scenario S1) is the most expensive to operate with a total operation cost per passenger kilometer-traveled equal to 0.28€, for which, to obtain a 5% profit margin, that is revenues of 0.29€ per passenger kilometer-traveled, the service fare needs to be equal to 0.36€ per passenger-kilometer (Table 5). The fare for this scenario (S1), the highest of the scenarios tested, is slightly higher than the 0.32€ per passenger-kilometer estimated by Bösch et al. (2018) for a regional SAEV service without polling, using more expensive cars and a higher VAT, and in line with the 0.22–0.45€.km^{-1} found by Loeb and Kockelman (2019) for standard SAEV with an occupancy rate lower than 50%.

The mixed fleet of cars and minibuses (scenario S4) delivers the cheapest service fare price for users (0.08€.km^{-1}.passenger^{-1}), which is mostly due to the higher average vehicle occupancy of the S4 scenario (Table 3). This estimated fare is lower than the one used by Santos and Correia (2021) in which a SAEV fleet of cars and minibuses could reach profit for serving more than 5% of the region's demand with a service fare per passenger of 0.10€.km^{-1}, a similar value to the one charged by the bus company (these authors did not explicitly account for facility and salary costs in their study).

The service configurations that use cars with pooling (scenario S2) and minibuses (scenario S3) have an estimated service fare price value of 0.09 €.km^{-1}.passenger^{-1}. This value aligns with the range of prices considered by Narayanan et al. (2020) for SAV services with pooling (0.09–0.87€.km^{-1}), but it is lower than the 0.21€.km^{-1} obtained by Bösch et al. (2018) for regional services with midsized vehicles.

The most important cost component is the "variable costs," representing approximately 62%, 74%, 88%, and 86% of the total costs in scenarios S1, S2, S3, and S4, respectively (Figure 4). A closer examination reveals that depreciation accounted for the highest portion of the SAEV operator costs, ranging from 39% (scenario S1) to 49% (scenario S3). Vehicle automation is the second contributor in the cost structure of the SAEV services with cars (S1–S2). Additionally, both maintenance and cleaning costs are relevant in cost structure representing together more than 18% of operator costs in all scenarios, which aligns with the percentages obtained by other CBA studies (Bösch et al., 2018). This significance stems from the expectation that users of these services might exhibit more reckless behavior in the vehicle due to the absence of a driver (Bösch et al., 2018; Loeb & Kockelman, 2019). The additional battery replacement costs only represented around 4-5% of the operator costs for the services with pooling S2–S4.

5.3. Economic impacts of replacing all modes by a SAEV service

The cost and benefit components for users, environment, and society of the CBA structure are presented. Their detailed numbers can be found in Table S6 of the Supporting Information. The widely recommended Net Present Value (NPV) and Benefit–Cost Ratio (BCR) indicators are also provided for each stakeholder to evaluate the economic viability of each service configuration (Österle et al., 2022).

The deployment of SAEV services with pooling (scenarios S2–S4) demonstrates economic attractiveness for users, yielding an NPV of €574 million and a BCR of 1.76 for the mixed fleet of cars and minibuses (scenario S4), and €680 million and 2.04 for the car service with pooling (scenario S2), as depicted in Figure 5. Such potential benefits are due to the notable reduction in private car expenses that represent 80% of users' costs (including repurposing of travel time savings) with current mobility choice options. Our calculations include fixed expenses such as insurance, taxes, or interests, resulting in a cost of €0.84 per passenger kilometer for a conventional private car, considering the daily usage patterns of the studied region. Scenario S1 did not result in benefits for users (BCR lower than 1), which is explained by the higher service fare associated with this SAEV service configuration (Table 4).

All SAEV service scenarios generally result in lower environmental impacts than the benchmark (scenario S0). This is especially true in scenarios using minibus fleet (S3) and mixed fleet (S4) where annually environmental costs would be reduced by 69 million € per year, leading to 4€ in benefits per 1€ of costs, though not so different than a scenario with 4-seat cars (S2) that leads to 52 million € per year of savings. The SAEV service with cars without pooling (scenario S1) represents the worst environmental scenario due to the higher GWP costs, with a 33% increase over the GWP costs generated by the scenario S0 (Table S6). The intensive use of SAEVs primarily contributes to GWP costs during the use phase, encompassing energy consumption, maintenance, vehicle and battery wear, and non-exhaust emissions (Ferreira et al., 2023; Vilaça et al., 2022).

Additionally, there is a positive impact on society, due to the ability of AV technology to decrease road accidents which countervails the increase in vehicle-kilometer traveled as they bundle passenger trips (traffic congestion costs). The mixed fleet scenario (S4) leads to the highest reduction in society costs, with an NPV of 263 million € per year and a BCR of 1.83, being the 4-seat car fleet the second-best configuration, with savings of 212 million € per year and a BCR of 1.63. Österle et al. (2022) found similar trends in SAEV societal benefits, but they did not estimate traffic congestion costs.

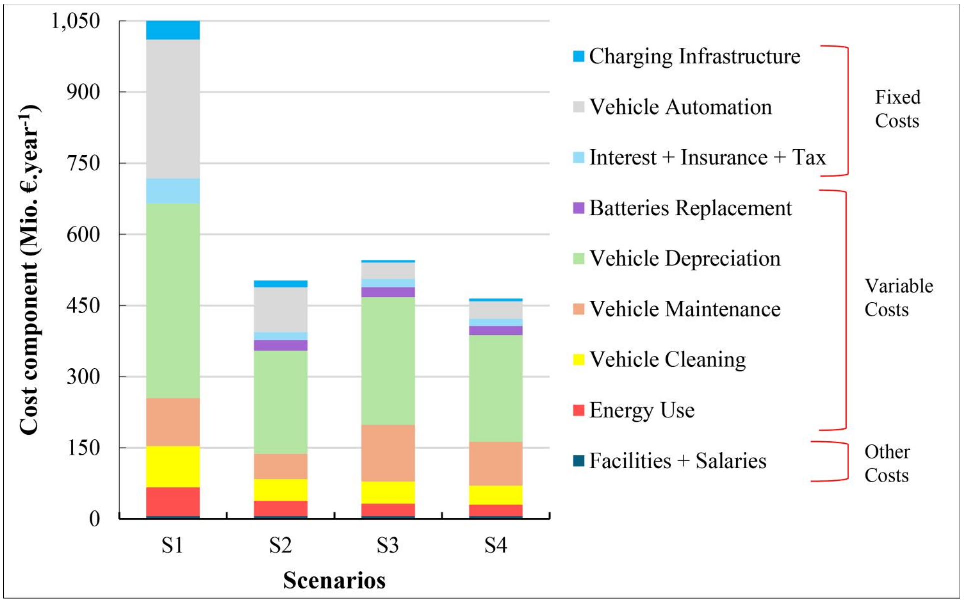

Figure 4. Collapse of SAEV operator total costs per component.

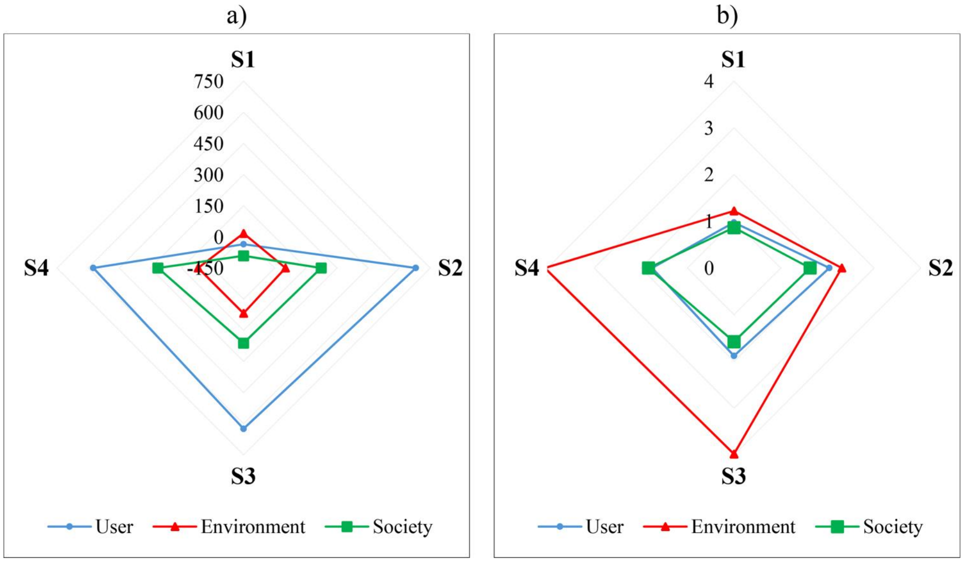

Figure 5. CBA core results by scenario: (a) NPV (values in millions); and (b) BCR.

Table 4. Cost and service prices kilometer traveled and passenger by SAEV scenario.

Description*	Units	S1 SAEV car 1-seat	S2 SAEV car 4-seats	S3 SAEV minibus 16-seat	S4 SAEV mixed car + minibus
Fixed Costs	€.km^{-1}.passenger^{-1}	0.103	0.018	0.007	0.006
Variable Costs	€.km^{-1}.passenger^{-1}	0.175	0.054	0.061	0.042
Other Costs	€.km^{-1}.passenger^{-1}	0.002	0.001	0.001	0.001
Total Costs	€.km^{-1}.passenger^{-1}	0.280	0.073	0.069	0.048
Total Benefits (fare revenues)	€.km^{-1}.passenger^{-1}	0.294	0.076	0.072	0.051
Service Fare (P_{SAEV})	€.km^{-1}.passenger^{-1}	0.363	0.094	0.090	0.077

*As in Section 2.

Table 5. Overview of scenarios according to BCR quality and total NPV.

Stakeholder	S1 SAEV car 1-seat	S2 SAEV car 4-seats	S3 SAEV minibus 16-seat	S4 SAEV mixed car + minibus
Users	*	****	***	**
Environment	*	**	***	****
Society	*	***	**	****
Total NPV (**Mio.€ /year**)	−111	956	905	907

****= the best BCR;
*= the worst BCR

Overall, the highest savings are reached by replacing all current mobility solutions with a SAEV service using 4-seat cars in its fleet, which saves 956 million € per year (see Table 5). In contrast, the SAEV service without pooling is estimated to have an overall negative balance. While these findings may seem optimistic, there is substantial uncertainty about future costs and benefits. Therefore, a further sensitivity analysis of the most relevant parameters afecting the CBA structure is required.

5.4. Transition SAEV scenarios

This section analyses four scenarios involving the partial replacement of trips with an SAEV service. The reference for this analysis is the SAEV with cars and pooling (scenario S2), a configuration that has the best BCR for users and the best total NPV considering the sum of users, society, and environment contributions (see Table 5). The tested scenarios involve SAEV services replacing 5% (A1), 10% (A2), 20% (A3), and 30% (A4) of trips previously made using existing mobility options. Detailed results on the implementation of gradual SAEV adoption, in terms of vehicle usage and cost components, are presented in Sections 8 and 9, respectively in the Supporting Information.

Figure 6 shows that the proposed scenarios led to an increase in service costs of up to 14% compared to S2 (Table 4). Their service prices were equal to or greater than €0.12 per passenger-kilometer. These results can be explained by two main facts. First, these transition scenarios were characterized by vehicle occupancy rates ranging from 55% in scenario A1 to 74% in scenario A4 (Supplemental Table S7), which are lower than the 83% occupancy observed in S2, as noted in Section 5.1. It is worth highlighting that these occupancy rates fall within the range (50–75% per vehicle) tested by Narayanan et al. (2022) for SAEV services with 10% and 20% penetration rates. Second, some transition scenarios (A2 and A3) required higher traveling distances by vehicle than did S2, which in turn increased variable costs per passenger (see Supplemental Table S7).

The analysis of vehicle usage and travel time further confirmed higher relocation times compared to a fully fleet of

SAEV cars with pooling (S2), although idle times remained relatively similar ranging from 53% to 67%, depending on the transition scenario.

Despite their relatively lower economic performance, these gradual scenarios remain attractive to users, particularly scenario A4, which generates a NPV of €220 million per year and a BCR above 2 (Figure 7). The same holds on for environment component, where the S2 gradual scenarios yield NPV values ranging from €2 million A1 to €13 million per year at A4, with BCR values between 1.5 and 2.4 at A2 and A4, respectively. Interestingly, all transition scenarios generated societal benefits based on BCR; however, the ratios were close to 1 in scenarios with low SAEV penetration rates (5% and 10%). This point was primarily due to higher costs associated with crashes, as a significant portion of the vehicle fleet remains composed of conventional vehicles. In general, the implementation of proposed transition scenarios generated lower benefits compared to a fully deployed SAEV system with pooling, suggesting that the latter is the most effective mobility solution for the studied regions.

5.5. Policy and market-related analysis

This set of sensitivity analyses also test the robustness of scenario S2 estimates by assessing the influence of market evolution (analysis B1 to B5) and policy measures (analysis B6) on service fares, as well as their broader impacts on users and the environment (see Table 6 and Figure 8).

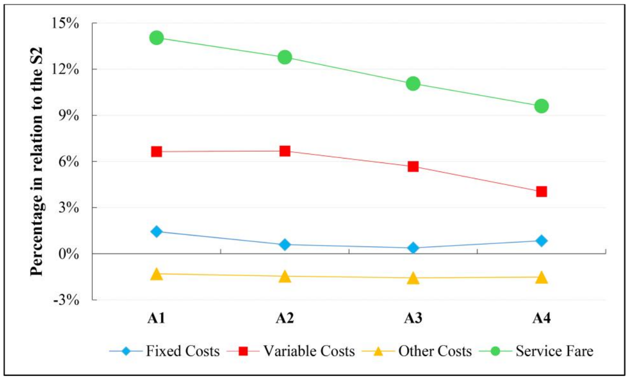

Figure 6. Comparison of cost and service prices kilometer traveled and passenger by S2 transition scenario.

The two first sensitivity analyses, B1 and B2, test the influence of the price of electric vehicles with automation technology. The proposed acquisition costs of such vehicles (30,610€) as well as the automation cost (9,600€ per year), have a high level of uncertainty due to the expected evolution of electric and automation technology prices with market maturity. Vehicle automation technology will play a key role in production costs for these fleets, meaning that certain cost estimates will need adjustment as technology costs evolve over time. The Eno Center for Transportation (ENO, 2013) reports that the automation technology kit to equip vehicles will have an estimated cost of $25,000 to $50,000 per vehicle, but this value could come down to $3500–$10,000 after 5–10 years on the market (Loeb & Kockelman, 2019). In Analysis A1 and A2 we tested the use of lower and higher costs for vehicle acquisition (21,000€ and 38,000€, which are comparable to the values used by Chen et al. (2016) and Loeb and Kockelman (2019)) and automation (3,500€ and 25,000€ per year).

It is currently understood that the vehicle lasts longer than its battery, requiring battery replacement or reconditioning around the middle lifetime of the vehicle. Analysis B3 examines shorter vehicle and battery lifetimes with values of 200,000 km and 125,000 km, respectively (Vilaça et al., 2022).

In the sensitivity analysis B4 we change the private car fleet of the scenario S0 by increasing the number of electric cars circulating in the region to a hypothetical future situation where half of private cars and all taxis are fully electric. The sensitivity analysis B5 goes further and considers a benchmark with all vehicles (private cars, taxis, interurban bus, and trains) being electric, and lower electricity prices. From 2030 onwards, it is expected that the market could face a drop in electricity prices with lower values compared with today (Huangluolun et al., 2024), which in turn benefit both SAEV operator and users. The magnitudes of benefits

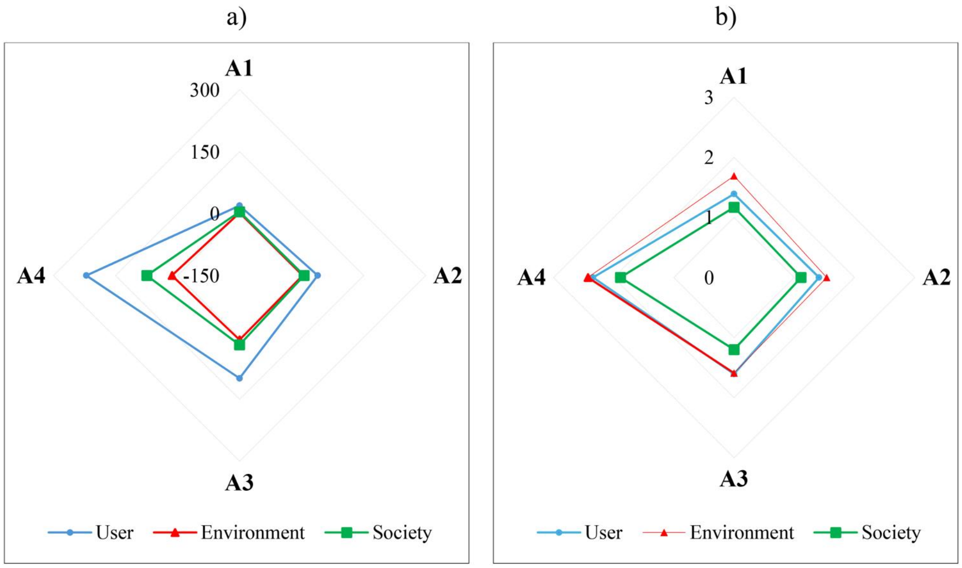

Figure 7. CBA core results by S2 transition scenario: (a) NPV (values in millions); and (b) BCR.

Table 6. Summary of the results from the policy and market-related analysis.

Sensitivity Scenario	Explanation	Changes to cost model	Service Price (€.km^{-1})
S2	Result from the first CBA assessment (see Table 4)	None	0.094
B1	Cheap vehicles and AV technology	Vehicle acquisition costs of 21,000 € (Peugeot, 2024) $a_{SAEV} = 3{,}500$ € $i_{SAEV} = 800$ € / $B_{SAEV} = 40$ kWh / $de_{SAEV} = 0.070$ €.vkm^{-1} / $V_p = 14.8$ kWh.100 km^{-1} (Peugeot, 2024)	0.068
B2	Expensive vehicles and AV technology	Vehicle acquisition costs of 38,000 € (Tesla, 2024) $a_{SAEV} = 25{,}000$ € $i_{SAEV} = 1{,}450$ € / $B_{SAEV} = 80$ kWh / $de_{SAEV} = 0.127$ €.vkm^{-1} / $V_p = 14.7$ kWh.100 km^{-1} (Tesla, 2024)	0.135
B3	Same values for vehicle and battery acquisition, but their lifetimes are less than expected	Vehicle lifetime of 200,000 km $bl_{SAEV} = 125{,}000$ km $de_{SAEV} = 0.153$ €.vkm^{-1}	0.117
B4	Half of the current fleet of private cars and all taxi fleet is electrified	$F_{PC} = 810$ € (LeasePlan, 2022) (25% of ICEs, 25% of HEVs and 50% of EVs) GWP of electric private cars and taxis of 145 gCO$_2$eq.vkm^{-1} (EC, 2020a; Pordata, 2024)	(same as for S2)
B5	All current fleet (private cars, taxis, interurban buses, and trains) is electrified and lower electric tariffs	$F_{PC} = 657$ € (LeasePlan, 2022) GWP of electric private cars and taxis of 145 gCO$_2$eq.vkm^{-1} (EC, 2020a; Pordata, 2024) GWP of electric interurban buses of 580 gCO$_2$eq.vkm^{-1} (EC, 2020a; Pordata, 2024) $E_c = 0.06$ €.kWh^{-1} (Santos et al., 2023)	0.092
B6	Subsidies to the vehicle fleet acquisition and tax benefits	150 vehicles with acquisition costs of 24,610 € (Mobi-E, 2023) VAT = 13% $de_{SAEV} = 0.101$ €.vkm^{-1}	0.087

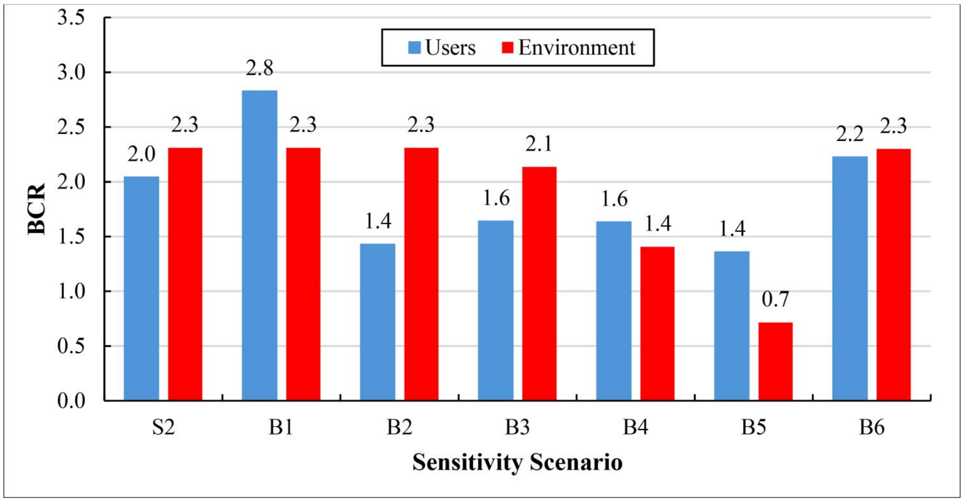

Figure 8. Comparison of BCR of users and environment by sensitivity scenario using a SAEV fleet of private cars with pooling (S2).

if all private cars become electrified are constrained by electricity supply sources that can lead to higher GWP, and the possible migration of government taxes from petrol fuel to electricity.

Analysis B6 assesses the impact of the measures provided by the Portuguese government, which includes incentives of 6,000€ and a VAT of 13%, for the acquisition of EV vehicles to the SAEV fleet, up to a maximum of 150 vehicles or 900,000€ (Mobi-E, 2023).

Figure 6 shows that studied sensitivity analysis have benefits for users as expressed by BCR values higher than 1. Sensitivity analysis B1 and B6 increase user benefits when compared to scenario S2, both have identical BCR environmental performance than scenario S2. Therefore, having cheaper units of AVs is key. The lower vehicle price of analysis B1 would reduce service fare by 21% in relation to the baseline scenario (S2), while in analysis A6 the political measures allow a reduction of 8% in the service fare.

The other sensitivity analysis (B2-B6) resulted in worse performance than S2. Having a more expensive vehicle (B2) leads to a high service fare (≈35%), but not as high as when lifetimes of both vehicles and batteries are reduced (B3), which yielded a rise in fare of 48%. If the current private car fleet was fully electric (B5), then the environmental costs from a SAEV with cars and pooling would outweigh the environmental benefits from replacing today's car fleet, as demonstrated by the BCR of 0.7.

6. Study limitations

The evaluation done in this exploratory study is one of the first comprehensive methods for estimating the costs of future SAEV services for intermunicipal trips. It incorporates several points that past works have partially overlooked, including the analysis of a regional size area with less-dense geographies, different SAEV fleet configurations, specific operator cost components (e.g.: cleaning, overhead), quantification of user's benefits from replacing the current adopted mode with SAEV, and externalities caused by replacing all current modes with an SAEV service (e.g. global warming potential, traffic congestion and road crashes) (Bauer et al., 2018; Bösch et al., 2018; Chen et al., 2016; Fagnant et al., 2016; Fagnant & Kockelman, 2014, 2018; Liang et al., 2016; 2020; Loeb & Kockelman, 2019; Österle et al., 2022; Santos et al., 2023; Santos & Correia, 2021). Despite the interesting results provided, some drawbacks need to be highlighted.

To simplify the model, we assume that the service fare per-kilometer remains constant throughout the day, neglecting the usage of pricing strategies based on the demand period (e.g. off-peak hours, peak hours, and night hours) and distances between municipalities (e.g. shorter versus longer trips). Also, our focus on the CBA approach is directed toward intermunicipal trips. The testing of dynamic pricing strategies and the inclusion of intra-municipal trips in the analysis with the highest costs and/or benefits could be part of future work.

Relatively to lifecycle estimation, we consider that all vehicles reach their lifetime at the same time, ignoring the fact that some vehicles could be replaced before others. An extensive analysis based on different groups of vehicles categorized by vehicle use could be included to add more authenticity to the SAEV operation cost calculations.

The number of vehicle types considered for the SAEV service (car and minibus) is somehow limited. A SAEV service with an even more heterogeneous fleet (i.e. vehicles with varied sizes, prices, battery power, range, and seat capacities) could enable reductions in costs, energy use and environmental impacts. However, it would lose the benefits of the large-scale effect, such as similar maintenance procedures, the same replacing parts, charging speed, and service quality. A discussion of these tradeoffs should be done in future work developments.

There is a risk that the overhead costs are misaligned with the future ones of an SAEV company, due to the uncertainties relative to the internal organization management of the company and the economic country environment. Uncertainty is also associated with the cost effects of emerging technologies. Although the adopted costs associated to EVs are well documented, the automation ones are based on values reported by previous research studies and can be unrealistic or outdated. The is a need for sensitivity analysis to explore the effects of these uncertainties on the study findings.

7. Conclusions

This study proposed a methodology to evaluate the economic implications of replacing all motorized modes serving the intermunicipal trips with a shared automated electric vehicle (SAEV) service. The approach employed a Cost-Benefit Analysis prepared to evaluate the impact on the operator, the users, the environment, and society. A flow-based Integer Programming model was included to determine the optimal size and operation movements of the SAEV system. Data from mobility surveys allowed to characterize the demand (around 250 thousand trips), current mode choices, and trip characteristics. Different fleet configurations were tested for the SAEV service: a single-seat capacity car fleet, a 4-seat capacity car fleet (with pooling), a 16-seat capacity minibus fleet, and a mixed fleet comprised of cars (with 4-seat capacity) and minibuses (with 16-seat capacity).

The results revealed that each SAEV service vehicle has the potential to replace 3–20 private cars, depending on the service configuration. This is due to the increase in vehicle usage of replacing private cars with a shared vehicle service from 6% (value of the usage of private cars in the current situation) to 24% (usage value of a single occupant SAEV service) or 46% (usage value for a SAEV service with minibus fleet or mixed fleet).

It was also found that the SAEV fleet configurations can be operated with a fare ranging from 0.08 to 0.36 € per kilometer, assuring a profit margin of 5% for the operator. The configuration using a mixed fleet has a smaller fare, while the single passenger configuration is the most expensive one. The remaining SAEV configurations, with a fleet of cars allowing pooling and the one with a minibus fleet, can be operated with a service fare of 0.09€ per kilometer for the same profit margin. The variable costs, associated with the use of vehicles in the fleet, are the component that has the most impact on the operator's expenses across all SAEV fleet configurations, highly influencing the fare needed to reach the targeted profit margin.

Having an SAEV service replacing all other modes for interurban trips led to interesting results for users, the environment and society. The solution that leads to the highest total savings for the three stakeholders (956 million € per year) is the SAEV service using a fleet of 4-seat cars allowing pooling. This is the best SAEV solution for users with total savings of 680 million € per year. This means that, on average, each user can save 2€ per each 1€ spent on the SAEV service (due to reduction in other modes expenses, namely the ones associated with private car ownership and usage).

Two sensitivity analysis were performed, using this best SAEV service solution (with cars allowing pooling) as a reference. The first one focused on gradually replacing the current trips with the SAEV system. While these transition scenarios provided positive benefits for users, the environment, and society, they underperformed compared to the full trip-replacement SAEV service with pooled cars , because such transition services required higher service prices per passenger.

The second one tested the influence of market evolution (namely the characteristics and prices of vehicles, batteries and driverless technology) and policy measures (subsidies for the acquisition of vehicles) on service fares, as well as their broader impacts on users and the environment. This analysis confirmed that reducing vehicle prices is key to reducing service fares and, consequently, increasing the savings for users.

The proposed methodological framework also offers flexibility to incorporate additional parameters and be adapted to other regions. However, it is important to consider that the findings are applicable only to regions sharing similarities in terms of travel distances, fleet compositions, demand levels, available transportation modes (both public and private), and energy sources. It should be noted that this research is exploratory in nature, as the proposed service has not yet been implemented on a large-scale.

Many improvements can be made in further research works, for example: examining dynamic pricing strategies based on time period and trip characteristics; the use of a demand model to reflect the influence of prices and travel times in users' choices for scenarios where the SAEV represents just an additional available mode of the region's transportation system; the consideration of other SAEV scenarios with different vehicle types (e.g. vans) and even more heterogenous fleets (e.g. different power, vehicle-range); and updating the parameters in the cost structure, namely the ones related to automation technology and respective maintenance, as it becomes commercially available and prices more accurate.

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