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Automated vehicles and the urban parking paradigm: Environmental implications and Citizen preference

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ABSTRACT

This study examines parking decisions in a future populated by automated vehicles (AVs), focusing on their energy implications. Using a multinomial logit model, preferences among cruising, garage parking, sending the AV home, and on-street parking in Santander, Spain, were evaluated. Home sending emerged as the favourite (52%) for its convenience, while garage parking was chosen by 36%, valued for security and environmental benefits. Cruising was least popular (6%), deterred by environmental concerns. Integrating survey data with traffic simulations, the research uncovered that cruising, despite its low preference, accounted for 16% of energy consumption due to empty trips. Surprisingly, sending AVs home, despite being the most popular, led to significant energy use, although it maintained a good consumption ratio. Garage parking, especially when located on city outskirts, was also inefficient. The study highlights the urgent need for strategies to mitigate inefficient parking behaviours, thereby enhancing the sustainability of AV-driven mobility.

1. Introduction

Numerous articles, both scientific and non-scientific, frequently begin by mentioning the rapid pace of urbanization and the predictions regarding future urban population growth (Davis, 1955; Desa, 2018; Gu, 2019). Papers focusing on transportation often highlight the escalating issues of congestion, urban sprawl, poor air quality, and a shortage of parking spaces (Alonso Raposo et al., 2019; Banister and Lichfield, 1995; dell'Olio et al., 2019; Rodríguez et al., 2022). However, there is a recent trend in cities to prioritize more sustainable modes of transport, which has sparked an ongoing debate about the use of public space for parking, pitting car users against other citizens who advocate for more sustainable space utilization (Alonso Raposo et al., 2019; Bertolini, 2020; Campisi et al., 2022). Activists and city planners recognize the untapped potential of parking spaces in urban areas, proposing alternative uses that benefit the community. For instance, Barcelona's super-blocks have transformed parking spots into pedestrian and cycling paths, green spaces, playgrounds, and picnic areas. This approach has been shown to prevent 667 premature deaths, reduce air and noise pollution, mitigate heat, and simultaneously increase the market value of real estate in the area (Mueller et al., 2020).

Although the decision to repurpose parking spaces currently faces resistance from car users and may appear radical, it is expected to

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become more accepted in the future, especially as self-parking cars become more prevalent (Faisal et al., 2019). Researchers have already explored how automated vehicles (AVs) could revolutionize parking, predicting that their ability to park themselves could dramatically alter land use in cities. Unless there is a significant shift in vehicle ownership rates with the advent of shared automated vehicles (SAVs), suburban areas are likely to see little change, with AVs parked in the same manner as regular cars are today. However, in densely populated areas collective garages are expected to emerge, providing residents with convenient parking spots near their homes. Automation of transport could also have additional effects on journeys with central destinations, such as leisure, shopping, or work, where AVs could drop off passengers and then proceed to allocated parking spaces or collective garages located on the outskirts of the city, where land is less valuable in terms of both monetary and social worth (Duarte and Ratti, 2018; Heinrichs, 2016). The recent Automated Valet Parking system deployed at the Stuttgart airport as a result by a collaboration between Mercedes-Benz Bosch and the parking garage operator (Stuttgart airport set to welcome fully automated and driverless parking, n.d.), is just the proof concept on what can be a common approach also in city centres in the years to come.

With the automation of vehicles, another phenomenon emerges: "cruising" (Shoup, 2006). Distinct from traditional parking strategies, as the vehicle does not require a designated parking spot. Instead, the user of the vehicle allows it to continuously drive on the streets, waiting to pick up the next passenger or just the end of the activities by the owner (Bischoff et al., 2019). Lastly, if the AV's passenger does not anticipate using the vehicle in the near future, it could be sent back home to serve other household members (Bischoff et al., 2019; Litman, 2020a). Nevertheless, this continuous circulation or added trips could contribute to substantial additional traffic on the streets. With more cars on the road, even if they are empty, there is a possibility of worsening traffic congestion in the area and significant surplus of electricity/fuel consumption, as well as air pollution by brakes and tires due to an increase in vehicle mileage (and of the additional engine activities in case of an internal combustion engine). Therefore, while the transformation of parking spaces and the introduction of AVs offer various benefits, careful consideration is necessary to address the potential challenges associated with increased empty vehicle travel and its impact on environmental effects.

The objective of this research is to provide empirical evidence regarding the environmental and traffic implications of new parking strategies enabled by vehicle automation. The study specifically focuses on a hypothetical scenario where AVs are privately owned electric vehicles (EVs) and utilized in a similar manner to conventional private cars. This dual assumption is grounded in the projection of an evolving mobility landscape where the integration of AV and EV technologies represents a path towards achieving greater energy efficiency, reduced emissions, and enhanced traffic management. The convergence of AV and electric transport technologies not only mirrors the anticipated trajectory within the automotive industry but also aligns with broader environmental and sustainability objectives. Additionally, while the future modalities of vehicle ownership remain uncertain, considering AVs as predominantly privately owned in our model allows us to explore a scenario deeply relevant to current patterns of vehicle usage and ownership. The methodology employs a multinomial logit model (MNL) estimated from stated preference (SP) data to analyse four parking options—cruising, garage parking on the outskirts of a city, sending the AV home, and on-street parking. Connected to an activity-based demand model (ABM) and a micro-traffic simulation of Santander, Spain, this approach allows for comprehensive insights into the shifting urban mobility landscape. This approach aids in understanding the implications of such a transition on urban parking dynamics, traffic congestion, and energy consumption under a specific yet plausible future scenario.

Our research advances the discourse on the future of urban mobility by concentrating on the integration of AV-EVs within the framework of private ownership. Specifically, the following contributions could be highlighted:

- Exploration of private ownership models: By maintaining a focus on privately owned AVs, our study delves into a critical aspect of future mobility scenarios often overlooked in existing research. We provide a nuanced analysis of how the persistence of private vehicle ownership patterns could shape the adoption and utilization of AVs, offering insights into the complex interplay between technological advances and societal norms.
- In the investigation of parking choices, a focus is placed on utilizing SP data rather than relying solely on simple monetary optimization, as it is anticipated that the choices regarding parking might not be entirely economical. Four potential parking strategies identified as plausible in literature are examined, emphasizing the nuanced decision-making process individuals undergo when selecting parking options.
- The consequences of these parking choices are uncovered using an agent-based modelling approach, which incorporates the behavioural aspect of choice. The repercussions of these decisions, in terms of energy consumption and potential empty kilometres travelled, are reported. This methodological approach allows for a detailed exploration of how individual preferences and behaviors can significantly impact broader urban mobility and sustainability outcomes.

The study adopts a structured three-step methodology to explore the future impact of AV parking strategies on urban environments. Initially, a survey gathers insights into individuals' preferences among four distinct parking options: on-street parking nearby, dedicated parking at the outskirts of the city, cruising, and sending AVs back home. The responses from this survey inform the second stage, where a demand model of city of Santander, inclusive of a MNL, is developed to depict the parking decisions. This model quantitatively translates the surveyed preferences into predictable parking behaviors. Finally, these behaviors are input into a microsimulation model. This simulation not only reflects the anticipated parking behaviour within the population of Santander but also enables an evaluation of the consequent environmental and traffic impacts. The outcome of this research is expected to assist transport modelers in simulating and assessing the impact of future scenarios involving AVs, while also providing urban planners with initial insights for conceptualizing future cities.

The paper is structured as follows: it begins with a review of relevant literature, followed by the methodological section which explains the data collection process and the modelling and simulation approach employed to analyse the collected data. Next, the results and discussion of the simulation study are presented, leading to a concluding section that summarizes the main findings of the research and its possible future directions.

2. Literature review

The uptake of AVs will bring a period of significant transformation within the urban mobility ecosystem, fraught with uncertainties concerning their deployment timelines, methodologies, and particularly their environmental impacts (Garus et al., 2023). The path to integrating AVs into our cities requires a nuanced approach to planning, given the unpredictability of their effects on travel patterns, infrastructure needs, and the overarching aim of achieving sustainable urban transport. Scholarly discourse offers a broad spectrum of views on these topics, highlighting the complexity of navigating the potential outcomes of AV integration (Berrada and Leurent, 2017; Fagnant and Kockelman, 2015; Garus et al., 2022; Golbabaei et al., 2021; Kopelias et al., 2020; Litman, 2020a; Maheshwari and Axhausen, 2021; Othman, 2022; Silva et al., 2022). This body of work underscores the necessity for strategic public policies that carefully balance the anticipated benefits and inherent risks of AVs.

As we anticipate the evolution of AV technology, a notable concern is the likelihood of their initial appeal to wealthier individuals due to high costs and initial functionality limitations, potentially fostering a trend towards private ownership (Litman, 2020a). This scenario presents a challenge for urban planning and policymaking, which must aim to harness the benefits of AV technology to enhance mobility while avoiding an escalation in socio-economic disparities. The transition towards AVs, therefore, necessitates adaptable and forward-looking policy frameworks. These frameworks must prioritize environmental sustainability and address the potential for private AV ownership, which could have significant implications for urban congestion and pollution levels (Garus et al., 2023; Silva et al., 2022). Informed by ongoing research and developments in the field, policies must strategically navigate the complexities of AV adoption to ensure it contributes positively to the goal of sustainable urban transportation (Golbabaei et al., 2021; Maheshwari and Axhausen, 2021; Silva et al., 2022).

2.1. AVs impact on the environment

The exploration of the environmental impacts of AVs and SAVs unveils a complex landscape of potential benefits and challenges. Numerous researchers have highlighted the multifaceted nature of these impacts, spanning air, land, water, noise, and light pollution. Notably, a review study by Silva et al. (2022) suggests that while AVs could positively affect noise and light pollution through vehicle electrification, reduced congestion, and the ability to drive without lights, the implications for land, water, and air pollution are more complex and significantly dependent on the deployment strategies of these vehicles.

A particularly complex aspect of this environmental puzzle relates to emissions. On the positive side, AVs offer the potential of more efficient driving for singular vehicle or even for numerous ones through the use of platooning—where vehicles travel in close formation, reducing air drag and thus energy consumption—along with the advantages of electrification and optimized routing that could lead to lower overall emissions (Kopelias et al., 2020; Makridis et al., 2020). However, these benefits are not guaranteed and are influenced by various factors. The shift towards AVs could induce behavioural changes, such as increased willingness to engage in longer commutes due to the reduced burden of driving, potentially leading to more vehicle kilometres travelled (VKT) and, paradoxically, an increase in emissions if not managed carefully (Garus et al., 2023, 2022; Silva et al., 2022). Moreover, the environmental benefits of electrification hinge on the energy mix powering the electrical grid; a grid that relies heavily on fossil fuels may diminish the positive impact of moving to EVs. The comprehensive studies presented in numerous review articles (Garus et al., 2022; Golbabaei et al., 2021; Kopelias et al., 2020; Maheshwari and Axhausen, 2021) have employed diverse methodologies, including system dynamics, energy optimization models, and traffic simulations, to estimate the environmental effects of AVs, including their potential to alter electricity demand patterns and CO_2 emissions.

The research into CO_2 emissions reveals a complex picture, with outcomes dependent on fleet size, pricing, and the energy mix of a simulated system. For instance, Gawron et al. (2019) estimated that a fleet of SAVs in Austin, Texas, could lead to a reduction in CO_2 emissions of up to 60 % compared to combustion-engine vehicles, with the possibility of even greater reductions if the energy mix becomes more renewable. However, the extent of emissions reduction varies significantly across different studies, with factors such as SAV pricing, fleet size, and charging strategies playing crucial roles (Liu et al., 2019; Lokhandwala and Cai, 2018; Martinez and Viegas, 2017; Miao et al., 2019).

Furthermore, the potential for AVs to contribute to environmental sustainability is tempered by the need for a comprehensive understanding of their indirect effects on emissions. The phenomenon known as the rebound effect, where reductions in per-mile costs lead to increased total driving distances, has yet to be fully assessed in the context of AVs and SAVs, as these vehicles are not fully available. Nevertheless, simulations studies that focus on these changes show that the environmental promise of SAVs may be complicated by such behavioural adjustments (Coulombel et al., 2019; Garus et al., 2023; Oh et al., 2020; Vyas et al., 2019). This underscores a growing imperative for detailed impact assessments of both AV and SAV deployment on key environmental externalities like energy consumption, CO_2 emissions, and air quality, particularly in light of the urban areas' focus on environmental sustainability.

The discourse on land use further illuminates the dual potential of AVs to either promote densification or facilitate sprawl, with the outcome likely to be shaped by local transport and land-use policies, as well as the nature of AV mobility solutions adopted. Studies focusing on the topis (Bagloee et al., 2016; Faisal et al., 2019; Smolnicki and Sołtys, 2016) suggest that improved accessibility and lower transport costs could drive ex-urbanization, leading to sprawl in green areas around metropolitan regions, with implications for land and water resources. Conversely, at the urban level, the adoption of commuting AVs and SAVs could dramatically reduce parking demand, freeing up space for more sustainable and people-focused urban designs (Heinrichs, 2016; Zhang et al., 2019). This nuanced view of AVs' environmental impacts underscores the critical need for integrated planning and policy-making that prioritizes sustainability in the era of autonomous mobility.

2.2. Modelling parking behaviour of AVs

As mentioned earlier, researchers have already made initial attempts to predict the future of parking. These predictions suggest that the availability of self-parking AVs could significantly reduce the need for parking spaces (Bischoff et al., 2019; Duarte and Ratti, 2018; Fagnant and Kockelman, 2015; Litman, 2020a; Zhang et al., 2019). In this section, we briefly present the key sources that discuss future urban parking scenarios.

Firstly, there was a set of studies that aimed to qualitatively envision the parking revolution brought about by the ability of vehicles to park themselves. It was predicted that in densely populated areas and at final destinations, parking will predominantly occur in collective garages located in less desirable locations outside city centres (Bischoff et al., 2019; Heinrichs, 2016). These collective garages are expected to be more space-efficient compared to current parking areas since the vehicles of the future will require less room for door opening and user access (Nourinejad et al., 2018). Levin et al. and Lai et al. have recently conducted studies focusing on designing such collective parking facilities, with a focus on efficient vehicle repositioning and parking spot sharing (Lai et al., 2021; Levin et al., 2020). On the other hand, AVs could choose not to park at all and instead continuously roam the streets, awaiting signals from their passengers to end cruising (Bischoff et al., 2019; Millard-Ball, 2019). This approach, however, could lead to increased VKT, congestion, as well as higher energy consumption and pollution. Another parking strategy identified in the literature involves vehicle sharing among household members. It assumes that after dropping off a passenger at a particular location, an AV would return home to serve other members of the household (Vyas et al., 2019).

In addition to contemplating future parking possibilities, several studies have attempted to model the impacts of changing parking strategies. Bischoff et al. and Vyas et al. incorporated alternative parking scenarios into their ABMS, where the choice of parking option was determined based on maximum utility, considering the cost of parking (Bischoff et al., 2019; Vyas et al., 2019). Likewise, other authors of future parking simulation studies employed a comparable methodology (Millard-Ball, 2019; Zhang et al., 2019). Furthermore, modelling studies have investigated the changes in daily activity timings resulting from the fact that AVs can drop off users directly at their activity locations without the need for additional time spent on access and egress or searching for parking spots (Liu, 2018; Zhang et al., 2019). Moreover, Bahrami et al. examined the traffic impact of cruising vehicles, where the decision to either park or cruise depended on the total costs associated with each strategy (Bahrami et al., 2021). Lastly, Wang et al. developed a parking management model for AVs, allowing vehicles to park in multiple locations and optimizing pricing policies based on the location of parking areas (Wang et al., 2021).

However, the cost-minimization approach employed in these modelling studies completely disregards personal parking preferences. Users may prefer to make their vehicles available to other household members or choose to keep them parked nearby due to environmental concerns or other factors. To explore whether such factors can indeed influence parking strategy preferences, the authors of this paper conducted a SP study. SP studies are recognized as suitable tools for developing parking demand models and supporting policy decisions (dell'Olio et al., 2019; Dell'Olio et al., 2015). Based on the identified preferences from the SP study, a microsimulation of parking behaviour was created to unravel the environmental impact of these new parking strategies. This approach allowed for a deeper understanding of the potential consequences and benefits associated with different parking choices in the era of AVs. To the best of our knowledge, no other similar attempts to model parking preferences in the era of AVs have been documented in the existing literature.

3. Methodology

In the methodology section, an integrated approach is utilized, initially focusing on the collection of data to ascertain the implications of privately owned AV adoption on urban parking dynamics and environmental impact. Data collection is commenced through a survey, aimed at capturing individuals' parking preferences in the context of AVs, establishing the foundation for modelling realistic parking choices.

Following this, the process of population synthesis is depicted, where socioeconomic and demographic attributes are incorporated to construct a representative model of urban mobility patterns. The behaviour of this synthesized population is then explored through the use of the SimMobility agent-based model (Adnan et al., 2015), enabling the simulation of daily activities and mobility patterns that reflect a diverse range of individual preferences and behaviors within the AV context.

The transition to modelling preferences is subsequently outlined, where SP data forms the basis of a MNL. This model serves to analyse the choice behaviour among various parking strategies, providing a quantitative foundation for understanding parking preferences.

The section culminates with the simulation of chosen parking strategies within an urban traffic model, employing the Aimsun microscopic simulation to capture the nuanced interactions between AVs and the urban environment. This sequence of steps is designed to provide a comprehensive understanding of potential shifts in urban mobility due to the integration of privately owned AVs.

The chapter is structured to methodically present each stage of the methodology, ensuring clarity and a systematic progression through the techniques and models employed in the analysis. This organization aims to offer readers a clear insight into the research process and the foundational elements that contribute to the holistic understanding of the anticipated changes in urban mobility patterns. The overall modelling methodology is presented on Fig. 1.

3.1. Data collection

As level 4 or level 5 AVs, which enable unsupervised parking, are not yet available on the market, a SP experiment was used to obtain information about future parking preferences. This section discusses the design of the SP experiment. Following three parts of the questionnaire was used [11]:

1. Questions regarding the mobility habits and preferences of respondents
2. Socioeconomic and sociodemographic questions, to gain insight into characteristics of the respondent, such as gender, age, employment, highest obtained education level, income level, household size.
3. Six choice sets to gain insights into the preferred parking alternatives of individuals. The respondents were first presented with the textual description of each of the parking concepts, and then with a series of six choice sets between four parking alternatives. An example has been showed on Fig. 2. The four possible parking alternatives included are:
   a. Parking in a dedicated area. In this parking strategy the vehicle drops off its user and parks in a dedicated garage area on the outskirts of the city or central business district, where land demand and efficiency are not of the highest importance.
   b. Parking nearby in a city centre. In this parking strategy the vehicle drops off its user and starts looking for an available parking spot nearby, relocating if there is a limit on the permitted duration of parking. Such parking was expected to be more costly in comparison to the other considered alternatives, as per assumed higher land demand and utilisation in the area.
   c. Sending the vehicle back home. In this parking strategy the vehicle drops off its user and returns home, to serve other household members or wait for the principal user's request.
   d. Cruising. Finally, in this parking strategy the vehicle drops off its user and start driving in nearby locations until called again.

The SP experiment was designed using a qualitative approach based on variables obtained from a series of focus groups (Duboz et al., 2022). During focus groups conducted in Q2 and Q3 of 2020, respondents were asked about the variables affecting the parking choice in the era of AVs. The decision variables identified during the focus groups included: total parking cost, environmental impact and waiting time for the AV to arrive. Therefore, the respondent was confronted with the choice of the most suitable strategy based on parking costs, fuel costs (used as an environmental proxy) and waiting time for the AV to arrive.

To maximise information obtained from each choice set, the SP experiment was created as a Bayesian efficient design using the Ngene software (ChoiceMetrics, 2012; Ibeas et al., 2014; Rose and Bliemer, 2009). An efficient design requires to run a pilot of the survey to obtain more accurate and precise prior parameters calibrating a MNL. The priors were obtained through estimations using data collected in the pilot phase with 35 respondents. Despite the small sample, all relevant priors resulted statistically significant and of the expected range and sign. The efficient design resulted in 12 scenarios, divided into two blocks of 6 choice sets presented to the respondent. The main survey had a sample size of 160 respondents, each participating in six choice sets, resulting in a total of 960 choices. This number is significantly larger than the estimated requirement of 113 completed questionnaires needed to achieve statistical significance (S-optimum) (Rose and Bliemer, 2009).

The attributes levels were chosen using the estimated costs of driving the AV provided by Litman (Litman, 2020b). The parking costs used in the survey accurately reflect Santander's parking rates, ranging from 1.5 to 2 EUR per hour, with the highest costs associated with a full working day and lower costs for shorter durations and other purposes. These costs were reflected in the survey to capture the variation in parking preferences for different trip purposes. In the parking choice model, the costs were adjusted based on the trip duration, incorporating the influence of trip purpose into the decision-making process. This approach allowed us to effectively capture the heterogeneity in parking preferences without overwhelming respondents with additional decision variables.

For all the parking options a zero-minute wait time was included to reflect scenarios where users can pre-order the vehicle to arrive at a specific time or location, ensuring immediate availability upon request. Additionally, to account for potential delays such as unforeseen events on the road or the vehicle serving another household member, we incorporated 5-minute and 10-minute wait times for the sending AV home option and parking in a dedicated area on the outskirts of the city, in which the vehicle is further away from the user. Given that the simulated environment is relatively small and uncongested, a 10-minute wait time was deemed sufficient to reflect these possibilities.

Moreover, the attributes levels were designed to reflect the assumed functioning of the parking strategies and expected parking policies:

- There is a possible delay in arrival of AV, due to late request or unforeseen events, if the vehicle is further away (parked in a dedicated spot or sent home). Hence the user could be required to wait for the vehicle. If the vehicle is nearby the waiting time is marginal and not applicable to the given scenario.
- Fee for parking in the dedicated parking area on the outskirts of the city is lower than that in the central areas nearby.
- Cruising should not be the cheapest option, as it's expected that there will be dedicated parking policies to reduce the empty kilometres travelled. Nevertheless, to reduce the complexity of the survey, the cost increase is reflected in the raise of fuel price.

The final used attribute levels are presented in the following Table 1:

[1] A copy of the one of the survey could be accessed under the following link.

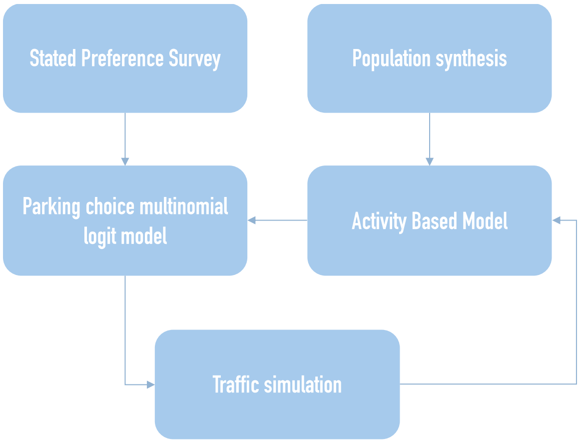

Fig. 1. Components of the modelling methodology.

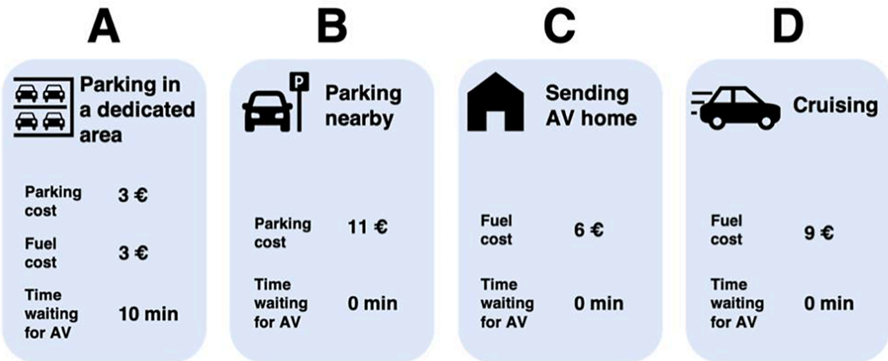

Fig. 2. Example of choice sets presented to the respondent.

Due to budgetary constraints, the initial recruitment for the SP survey relied on voluntary online responses, which potentially introduced a selection bias. Nevertheless, the sample obtained via internet survey distribution has a decent distribution in terms of socio-demographic characteristics (Fig. 3) (Population structure and ageing, n.d.). Given the overall focus of the survey on the active population group, the young and senior individuals are underrepresented. To mitigate this and ensure the findings were representative of the Santander population, we employed post-stratification weighting. This method involved adjusting the survey data to match demographic distributions known from the city's census data, such as age, gender, and income levels. By applying these weights to the online survey responses, we corrected for the non-randomness of our sample, allowing the results to reflect the parking choice behaviour more accurately across the entire population of Santander.

3.2. Population synthesis and demand estimation

Population synthesis was obtained using a deep generative modelling approach from machine learning based on a Variational Autoencoder (VAE) proposed by Borysov et al, which allows to generate a population with a higher number of socioeconomic modelled attributes (Borysov et al., 2018). The synthesised population attributes were gender, age, employment status, education level, occupation, income, public transport subscription, driving license, zonal assignment and household assignment. Parameters for the vehicle ownership model were estimated with MNL and mobility survey data. The choice set of the model was {0,1,2,3} (corresponding to the number of cars in the household). The estimated parameters for choice characteristics included: household size, age

Table 1
SP experiment attributes and their levels.

	Parking in a dedicated area (A)	Parking nearby (B)	Sending AV home ©	Cruising (D)
Parking costs	0€ | 3€ | 6€	7€ | 11€ | 15€	0 €	0 €
Fuel costs	1€ | 3€ | 5€	0 €	6€ | 8€ | 10€	5€ | 9€ | 13€
Waiting time	0 min | 5 min | 10 min	0 min	0 min | 5 min | 10 min	0 min

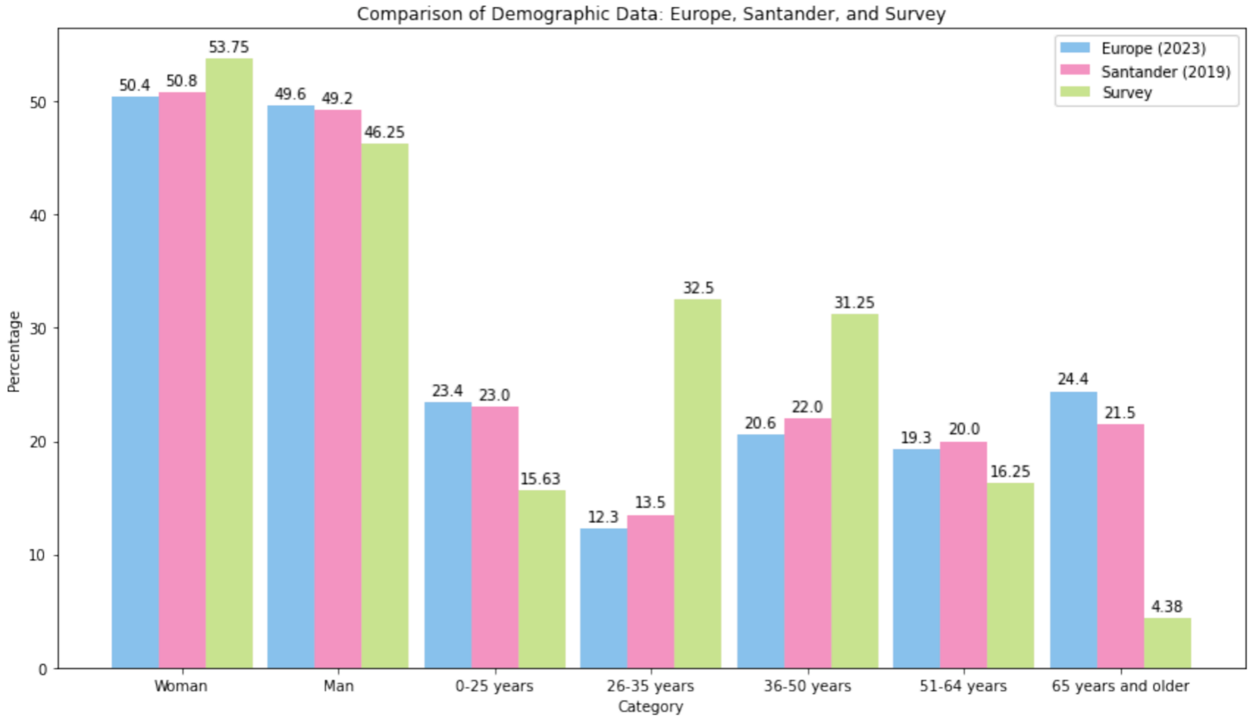

Fig. 3. Sociodemographic characteristics of the sample.

and gender of the head of household, and household income.

The demand for transport activities was employed in SimMobility – an open-source activity-based simulation platform (Adnan et al., 2015). We used a fraction of SimMobility – a Pre-day simulator which is used to obtain the daily activity schedules of the entire synthetic population generated. The Pre-day ABM is a chain of hierarchical discrete choice models (MNL and nested logit models) divided into three levels: the day-pattern level, the tour level, and the intermediate stop level. The day pattern level consists of MNL

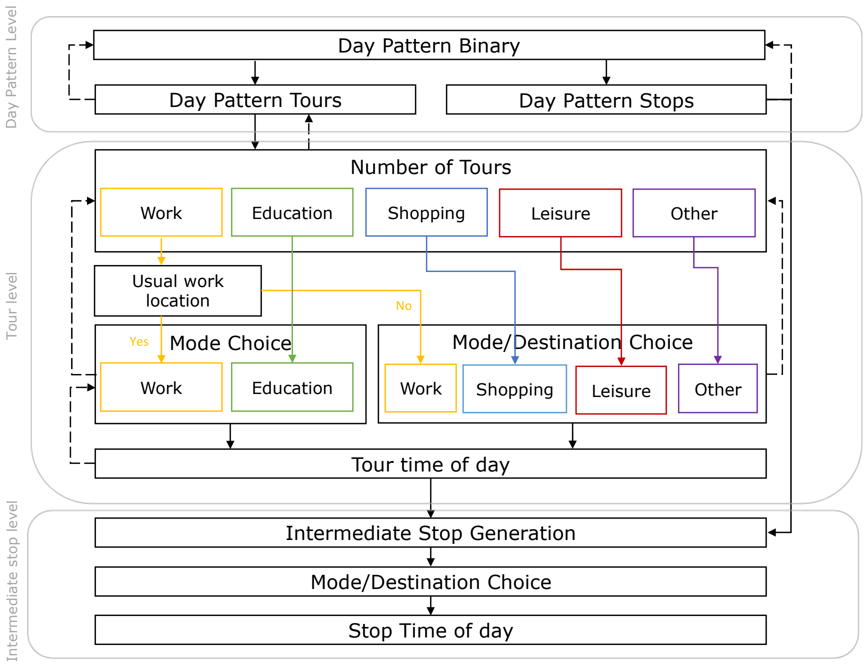

Fig. 4. Components of the Pre-day activity-based model in SimMobility.

models that predict the occurrence of tours and availability of intermediate stops for considered purposes (work, education, shopping, leisure, and others). The day pattern level generates a list of tours and availability of intermediate stops for everyone in the synthetic population. The tour level of the Pre-day model consists of further discrete choice models that predict the destination, mode, and time of day (arrival time and departure time) for each previously predicted primary activity of each tour. Finally, the models at the intermediate stop level predict the destination, travel mode and timing of the stops for the secondary activities. A simulation of the ABM yields activity schedules for everyone in the synthetic population, including the timing (arrival time and departure time) of each activity at a resolution of 30 min, at the destination zonal level and according to the travel mode for each tour (Oh et al., 2020). To fully represent the demand of a given population the parameters describing the behaviour of this population at every level of the model are needed.

The calibration of the demand estimation was made by changing the alternative specific constants to better represent the real traffic data in form of trip counts between the zones as well as results obtained from travel diaries.

Moreover, the usage of ABM allows to acknowledge the potential for induced demand with the introduction of AVs. The demand is induced by individuals who previously did not have the possibility to use the household vehicle due to lack of a driving license but have the availability of a driverless vehicle. However, to maintain a manageable and focused study, the assumption was made that vehicle ownership rates and models would remain constant. This approach emphasizes the importance of establishing regulations for AV parking before these vehicles become common. While the future ownership model of AVs remains a debated topic, with numerous experts and stakeholders suggesting that AVs could be privately owned, it is essential to analyse this scenario. The detailed scheme of the Pre-day SimMobility model is given in Fig. 4 hereunder.

3.3. Parking choice modelling

In our study, we employed a MNL with panel data to analyse parking choices, considering four alternatives: nearby on-street parking, sending the vehicle home, dedicated parking garage, and cruising. The MNL model was estimated using the SP survey data, utilizing the Pandas Biogeme software (Bierlaire, 2020). The SP data collection process is described in more detail in the next section of the paper.

According to random utility theory, individuals evaluate each available option based on the perceived utility, aiming to maximize their overall utility (Ortúzar and Willumsen, 2011). The utility (U) is composed of a deterministic component, which includes explanatory variables and alternative attributes, and a stochastic component represented by an error term (ε) accounting for unobserved factors (Ortúzar and Willumsen, 2011). The utility of alternative i can be expressed as (Ortúzar and Willumsen, 2011):

$$U_{in} = \beta X_{in} + \varepsilon_{in} \tag{1}$$

Where β is the vector of parameters to be estimated.

In our model, we assumed a MNL specification, where the random residuals follow a Gumbel distribution and are independent and identically distributed (Ortúzar and Willumsen, 2011). The estimation process was carried out using the Pandas Biogeme software, employing an iterative procedure that excluded variables found to be statistically insignificant in the decision-making process. The utility functions considered in the model incorporated socioeconomic characteristics, alternative attributes (such as waiting time, parking cost, and fuel cost), and alternative-specific constants (ASC). The model parameters were estimated by using the results of the stated SP survey. The SP survey was organised to make sure that the parking choice reflects the behaviour of European population and in turn secures a realistic modelling framework given the lack of any type of data on the subject.

To estimate the model parameters, the log-likelihood function is utilized, which for the MNL can be generally expressed as:

$$LL(\beta) = \sum_{n=1}^{N} \sum_{i=1}^{M} y_{in} \bullet \log\left(\frac{e^{\beta X_{in}}}{\sum_{j=1}^{M} e^{\beta X_{in}}}\right)$$

where y_{in} is a binary indicator that equals 1 if individual n chooses alternative i and 0 otherwise, N is the total number of individuals, and M is the number of alternatives.

Following the estimation of the parking choice model and the overall demand for AV trips using the ABM model, we implemented an additional Python plug-in to calculate the utility of each parking choice for the four available options. This plug-in leveraged the estimated model parameters to compute the utilities. Based on the distribution of utility values, the Monte Carlo simulation assigned the final parking choice for each AV trip.

3.4. Traffic simulation

The pre-day simulation generated activity schedules for individuals, which were processed and assigned a parking strategy using a Python script. The script organized trip-chains into origin–destination (OD) matrices, used as demand input for the traffic simulator Aimsun Next (Casas et al., n.d.). In setting up our microsimulation model for Santander, we utilized standard behavioural parameters, incorporating Aimsun’s Cooperative Adaptive Cruise Control module package designed to represent AV behaviour simulation. This setup adjusted car following, lane changing, and gap acceptance models to represent nuanced operational characteristics of AVs within urban traffic networks (Makridis et al., 2020). The decision to use this package and adjustments is based on the expected practical limitations of AV technology, including the absence of widespread vehicle platooning between different manufacturers’ vehicles.

Moreover, the simulation's EV dynamics was ensured by aligning with Aimsun's Battery Consumption Model, which, along with the pollutant emission model, played a crucial role in estimating the environmental impacts of AV-EV integration (He et al., 2020). The microscopic traffic simulation capabilities of Aimsun facilitated a comprehensive analysis, providing valuable inputs for assessing the environmental rebound effect associated with the adoption of AVs and EVs. Through this methodological approach, our model simulates the behaviour of electric AVs on the road and enables a detailed evaluation of their potential effects on traffic flow, energy consumption, and urban mobility.

In the Aimsun simulation, the parking strategies were implemented as follows:

1. On-street parking: This strategy involved the vehicle arriving at a designated centroid and departing when the passenger moved on to another leg of their trip. The vehicle would park on the street near the centroid during this time.
2. Sending the vehicle home: To simulate this strategy, two additional trips were generated in the OD matrices. After dropping off the passenger at their destination, a trip was added from the destination to the vehicle's home. Then, an empty trip was added from home to the destination, timed to pick up the passenger at their desired pickup time.
3. Dedicated parking: Similar to sending the vehicle home, two additional trips were added in the OD matrices. However, instead of returning home, the vehicle was sent to the closest centroid where dedicated parking was available for either the origin or destination. The vehicle would then proceed to pick up or drop off the passenger at the desired location.
4. Cruising: This strategy involved adding random trips between centroids until the passenger specified their desired pickup time. The vehicle would continue cruising between centroids until the designated time for passenger pickup.

These parking strategies were incorporated into the Aimsun simulation to simulate different parking behaviors and their impact on the overall transportation system.

3.5. Case study

Santander, Spain (population 172,957) (Instituto Nacional de Estadistica, 2022), was selected as a case study to represent a small-sized European city with minimal congestion. The municipality and transport agency of Santander provided detailed information on travel choices, enabling the estimation of user preferences. The case study utilized a transport diary survey conducted in 2013 with a sample size of 1,384 individuals. This survey, along with total population counts per transport zone, was used to synthesize the population of Santander using deep generative modelling techniques. As per the vehicle ownership model we assumed that the ownership distribution would be like todays, however all vehicles would be AVs. We obtained the ownership rates using an MNL estimated based on survey data.

The transport diary survey data provided the necessary parameters for demand estimation in SimMobility, a modelling tool used to simulate transportation systems. The estimated model was calibrated and validated using the travel diary dataset, ensuring its reliability and accuracy.

The traffic in Aimsun is simulated using microscopic traffic simulation with static path assignment combined with dynamic path reassignment for 30 % of all vehicles. The supply model, apart from simulating AV trips, also includes the public transportation simulation of the up-to-date bus schedule.

The supply side of the model – Aimsun microsimulation was set up to include the Santander's network copy. The supply model of Santander was developed and calibrated by the SUM Lab of University of Cantabria and is often used for the development of local transport policies along with the regional authorities. The used network included behavioural parameters for AV trips encoded as per the recommendations given by Aimsun. The network of Santander is not considered to observe heavy traffic flows. An overview of the simulation network is given in Fig. 5.

Fig. 5. Network of Santander, Spain.

4. Results and discussion

In this study, we investigated parking choices following the automation of vehicles and estimated a discrete choice model to analyse the preferences of individuals across four parking options: cruising, parking in a dedicated garage on the outskirts of a city, sending the vehicle home, and utilizing the typical on-street parking available currently. The model was estimated in an iterative manner using the Pandas Biogeme (Bierlaire, 2020) library for Python, which allowed us to efficiently handle the dataset and accurately estimate the model parameters.

Within the iterative model estimation process, we incorporated a wide range of socioeconomic variables, including age, gender, income, household size, education level, employment status, and the number of travels per day. These variables were integrated into our analytical framework to assess their influence on parking choice behaviour, thereby capturing the relationship between individual socioeconomic profiles and their parking preferences. This approach enabled us to delineate the socioeconomic factors that significantly influence parking decisions. The best model fit, as evidenced by the results presented in Table 2, highlights the critical role these variables play in shaping parking behaviour, thereby underscoring the importance of considering a diverse set of socioeconomic characteristics in understanding and modelling parking choice dynamics.

In refining our model, we examined the potential to separate fuel costs from other parking-related expenses to assess their individual impacts on parking choice behaviour. However, the exploration revealed that incorporating fuel costs as a separate variable alongside parking fees led to multicollinearity issues, complicating the model's estimation process. Consequently, to ensure the robustness and reliability of our analysis, we opted to aggregate fuel costs into the total cost measure for each parking alternative. This decision was supported by subsequent model testing, which indicated that a singular total cost variable provided a clearer, more effective representation of cost influences on parking choices, enhancing the model's overall explanatory power. The superior performance of this approach is evidenced in the final model specification, where the total cost variable effectively captures the comprehensive cost considerations of respondents, as presented in Table 2. This streamlined model not only addressed the multicollinearity concern but also yielded more coherent and interpretable insights into the determinants of parking behaviour.

Regarding the attributes of the alternatives (waiting time and costs), both alternative-specific coefficients and generic coefficients were considered. Ultimately, the alternative-specific coefficients were selected based on their enhanced ability to reflect the distinct impacts of each parking option on choice behaviour, as evidenced by the detailed findings in Table 2. This choice allowed us to more accurately capture the varying influences of cost and waiting time across the different parking alternatives.

The estimation process yielded insightful results, shedding light on the factors influencing individuals' decisions. We found that individuals aged 25 and below exhibit a strong preference for cruising ($\beta = 2.050$, $p < 0.001$) and sending the vehicle home ($\beta = 1.000$,

Table 2
Multinomial Logit Model Results for Parking Choices after Vehicle Automation.

Variable	Value	Std error	p-value	t-value
Age below 25 cruising	2.05	0.471	0.000***	4.348
Age below 25 sending AV home	1	0.303	0.001***	3.301
Age 51–65 cruising	−0.177	0.035	0.000***	−5.057
Age 51–65 dedicated area	0.806	0.292	0.006***	2.760
Age 51–65 on street parking	0.39	0.0298	0.000***	13.086
Area rural	−0.662	0.256	0.010**	−2.586
Cost cruising	−0.497	0.0586	0.000***	−8.483
Cost dedicated area	−0.239	0.0394	0.000***	−6.071
Cost_sending AV home	−0.341	0.0577	0.000***	−5.908
Cost on street parking	−0.327	0.0376	0.000***	−8.694
Education PhD cruising	0.569	0.253	0.025*	2.248
Education Master degree dedicated area	1.21	0.268	0.000***	4.513
Employed cruising	1.09	0.358	0.002**	3.046
Household size five cruising	−0.625	0.2937	0.034*	−2.13
Household size five sending AV home	1.22	0.26	0.000***	4.692
Household size four dedicated area	1.05	0.23	0.000***	4.565
Household size four sending AV home	0.898	0.279	0.001***	3.220
Household size single dedicated area	0.755	0.257	0.003**	2.937
Household size single sending AV home	0.768	0.293	0.009**	2.619
Income low garage	−1.41	0.281	0.000***	−5.014
Wait time garage	−0.0837	0.0279	0.003**	−3.003
Wait time sending AV home	−0.0521	0.025	0.038*	−2.084
Woman sending AV home	0.538	0.176	0.002**	3.056
ASC cruising	−0.177	0.035	0.000***	−5.057
ASC dedicated area	0.806	0.292	0.006**	2.760
ASC on street parking	0.39	0.198	0.050*	1.970
Log-Likelihood	−1330.843			
Null Log-Likelihood	−951.624			
McFadden's R-squared	0.265			
Number of observations	960			

$p < 0.01$). Conversely, if an individual lives in a rural area they are less likely to send their vehicle back home ($\beta = -0.662$, $p < 0.01$). Evidently parking cost plays a vital role in decision-making, with higher costs associated with reduced probabilities of choosing each option. Nevertheless, the cost impact is higher for cruising ($\beta = -0.497$, $p < 0.001$) than for home parking ($\beta = -0.341$, $p < 0.001$) and garage parking ($\beta = -0.239$, $p < 0.001$). This finding could be caused by our habitual acceptance for parking fees in dedicated garages. Notably, individuals with a low income exhibit a strong aversion to garage parking ($\beta = -1.410$, $p < 0.001$). The wait time for a vehicle to arrive to pick us up also influences decisions, with longer wait times decreasing the likelihood of garage parking ($\beta = -0.0837$, $p < 0.01$) and home wait times affecting the sending the vehicle back home ($\beta = -0.0521$, $p < 0.05$). However, the wait time is more likely to be accepted if the vehicle is sent back home and could be used by other household members. Furthermore, certain household characteristics impact preferences, such as a stronger inclination towards home parking among individuals with larger household sizes ($\beta = 1.220$, $p < 0.001$). The findings are further presented in Table 2 hereunder.

The results from the MNL model provided valuable insights into the parking choices of the population in Santander. The findings in Table 2 align with previous research on AV parking behaviour. Bischoff et al. demonstrated that the adoption of AVs could significantly reduce the need for urban parking spaces and lower parking search times, supporting the preference for sending AV home identified in this study (Bischoff et al., 2019). Similarly studies highlighted the impact of vehicle automation on parking patterns, indicating a shift towards more efficient parking strategies, which aligns with the high usage of parking on the outskirts observed (Garus et al., 2022). Additionally, previous research confirmed that AVs' ability to relocate for household use influences parking choices and VKT, consistent with the findings of this study (Zhang et al., 2018).

In interpreting the survey results, we observed a strong preference for sending the AV home with approximately 53 % of individuals favouring this option. While this could initially be attributed to the convenience and the potential for vehicle sharing among household members, it's important to consider other factors that may influence this choice. Notably, the lower parking cost (only fuel costs) associated with this option, along with the greater familiarity and feelings of security provided by using one's own garage or dedicated parking space, likely contribute to its appeal. These factors together may make sending the AV home a particularly attractive option, underscoring the multifaceted nature of parking preferences in the context of AV technology.

On the other hand, parking in a dedicated garage was also a popular choice, with around 36% of individuals opting for it. The availability of secure and designated parking spaces likely contributed to its popularity. Moreover, individuals who live further away from the areas in which the parking is located also opted for this option as more environmental and convenient. Furthermore, our analysis identified a minimal preference for the cruising option. Further insights from qualitative survey responses enriched our understanding, revealing that individuals with lower trust in AV technology, those less inclined towards innovation, and participants expressing environmental concerns were notably less likely to select cruising. These findings underscore the significant influence of personal technology acceptance, innovativeness, and environmental consciousness on the decision-making process regarding AV parking options.

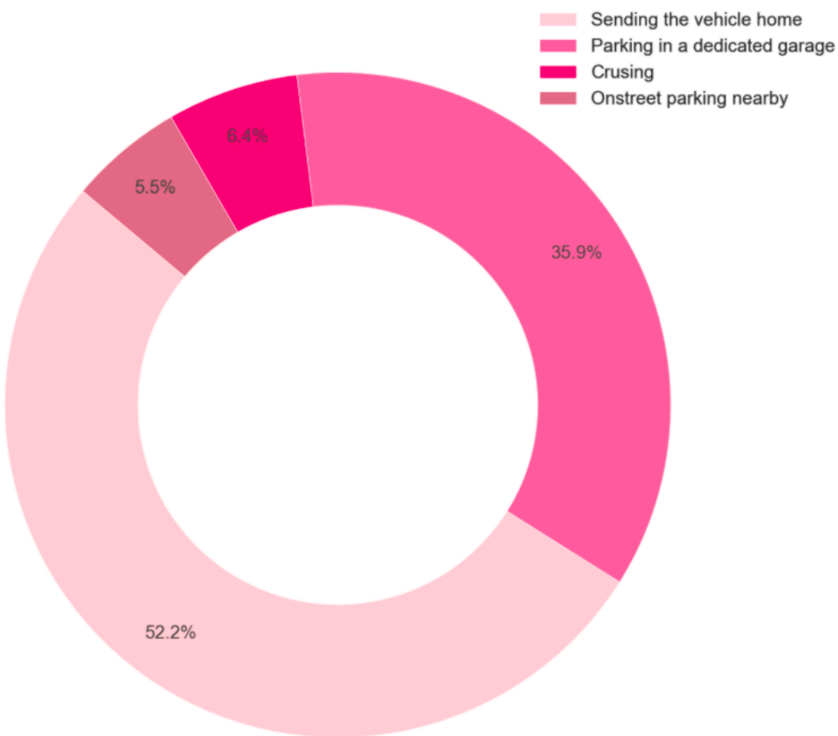

Fig. 6. Parking choices of the population of Santander.

While the on-street parking option near the destination was selected by only 5.5% of respondents, indicating it as the least preferred, this outcome could be influenced by the choices and attribute levels presented in the SP survey. In the survey design, parking nearby was intentionally presented with higher costs compared to cruising, reflecting the anticipation of a future decrease in available on-street parking spaces due to urban space repurposing trends identified in the literature (Duarte and Ratti, 2018; Garus et al., 2022; Millard-Ball, 2019). This strategic choice aligns with projections that urban areas may see a reduction in on-street parking availability, leading to an increase in parking fees. As such, while direct generalizations from our survey findings should be made cautiously, the scenario of declining on-street parking spaces is widely accepted. This anticipated change opens discussions on alternative uses of urban space formerly dedicated to parking, such as the creation of green spaces, pedestrian zones, or dedicated cycling lanes, suggesting a shift towards more sustainable and liveable city landscapes. The results of parking choice preferences are graphically represented on Fig. 6 hereunder.

The following Fig. 7 presents an analysis of trip purposes across different parking choices, highlighting notable differences in usage patterns. For cruising, the primary trip purpose is for work, accounting for 40% of the choices. This is followed by other purposes (28%), leisure (15%), shopping (11%), and education (7%). In contrast, parking on the outskirts shows a more diverse distribution of trip purposes, with leisure trips dominating at 32%, followed by work (29%), other purposes (21%), shopping (9%), and education (8%). This indicates a significant reliance on peripheral parking for leisure activities. Sending AV home option is predominantly used for work-related trips, constituting 41 % of the choices, mirroring the high work-related usage seen in cruising. This option is also utilized for other purposes (25%), leisure (15%), shopping (11%), and education (8%). Notably, the on-street parking option is heavily skewed towards other purposes, making up 44% of the choices, which is the highest among all parking choices for this category. Leisure trips account for 22%, shopping 17%, work 15%, and education a mere 2%. Although cruising has the highest percentage of work trips among its users, the total number of work trips using cruising is relatively low (5%) when compared to the overall total number of work trips. These findings suggest that different parking choices cater to distinct trip purposes with sending AV home heavily oriented towards work-related trips, whereas sending the vehicle to park on the outskirts more commonly used for leisure. This analysis underscores the importance of tailoring parking strategies to accommodate the specific needs of different trip purposes and optimizing the efficiency and accessibility of parking options in urban areas.

During the one-day simulation of AV behaviour in Santander, we focused on analysing the energy consumption of the vehicles, with particular attention to the impact of empty travels. The data from the simulation provided valuable insights into how AVs' parking choices affect their electricity consumption. The results of the comparative analysis of business as usual in which all vehicles were electrified and chose to park nearby showed that automation and introduction of new parking alternatives resulted in a 105% increase

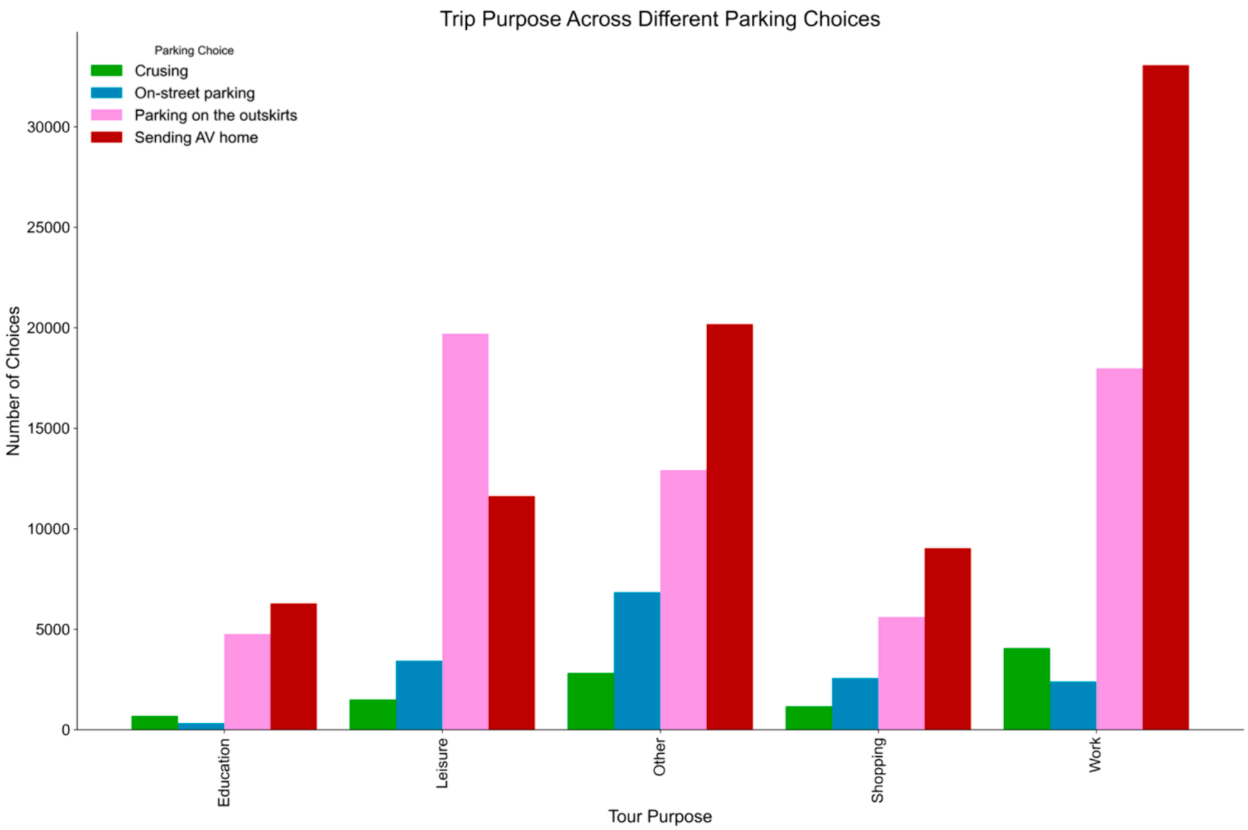

Fig. 7. Trip purpose across different parking choices.

in energy consumption because of the empty VKT.

The one-day simulation of AV behaviour in Santander provided valuable insights into the energy consumption of the vehicles based on different parking choices. One concerning finding was that approximately 55% of the total energy consumed by AVs was attributed to empty travels. Empty travels occur when AVs are moving without passengers, leading to a significant waste of resources and posing environmental concerns. Addressing this issue is crucial for promoting sustainable transportation and minimizing the environmental impact of AVs. The results are presented on Fig. 8 hereunder.

Among the various parking modes analysed, sending the vehicle home emerged as the most popular choice among the population of Santander. Consequently, this parking mode also accounted for the highest energy consumption. Notably, the energy consumption difference between full and empty AVs in this mode was relatively small. This can be attributed to the fact that the distance travelled by the AVs to return home and back to pick up the passenger was approximately equal to the distance travelled with passengers, and the roadways in Santander are not heavily congested. While sending the vehicle home is favoured by users, optimizing energy consumption in this mode remains essential for the sustainable integration of AVs into urban transportation systems. For instance, this mode could be promoted if the distance between the origin and home is shorter than the distance between the closest dedicated parking location or if a family decided to lower their vehicle ownership rate in favour of sharing one AV.

Another prominent parking option was parking in a dedicated garage, chosen by more than 35% of individuals. However, this mode exhibited less efficiency in terms of energy consumption from empty trips compared to sending the vehicle back home. The location of dedicated garages on the outskirts of the city may contribute to increased empty travel distances, leading to higher energy consumption. Additionally, streets nearby the garages may experience higher congestion, further impacting energy efficiency. Addressing these challenges is crucial to encourage the adoption of energy-efficient parking choices and promote sustainable AV usage. For instance, these garages could be located in convenient areas next to major roads and not too far away from central locations such as current park and ride facilities. The locations used in the simulation are presented on Fig. 9 hereunder.

Among the new parking strategies, cruising was the least desired choice, with only 6.4% of individuals opting for this option. Despite its limited popularity, cruising accounted for a considerable percentage (16%) of the overall energy consumption. As per the energy consumed by empty AVs, cruising accounted for 25%. To mitigate this issue, and the other externalities linked to cruising (such as contribution to additional congestion and pollution) effective measures must be taken to discourage cruising within cities. Implementing policies such as imposing high fees for cruising in central areas could effectively reduce unnecessary energy consumption and incentivize more sustainable parking behaviors.

In conclusion, the simulation results shed light on the energy consumption patterns of AVs based on parking choices in Santander. Understanding these trends is vital for designing policies and urban planning strategies that promote energy efficiency and sustainability in future AV-dominated transportation systems.

5. Conclusions and future research

In the conducted study, an extensive exploration of parking choices following the uptake of auotmated vehicles (AVs) was undertaken. Utilizing SimMobility for agent-based modelling to simulate daily activities and mobility patterns, and Aimsun for microscopic traffic simulation, preferences across four parking options were examined: cruising, parking in a dedicated garage, sending the vehicle home, and utilizing on-street parking. The personal preferences for the analysed population of Santander were represented using an additional MNL model. This comprehensive approach allowed for the integration of a wide range of socioeconomic variables,

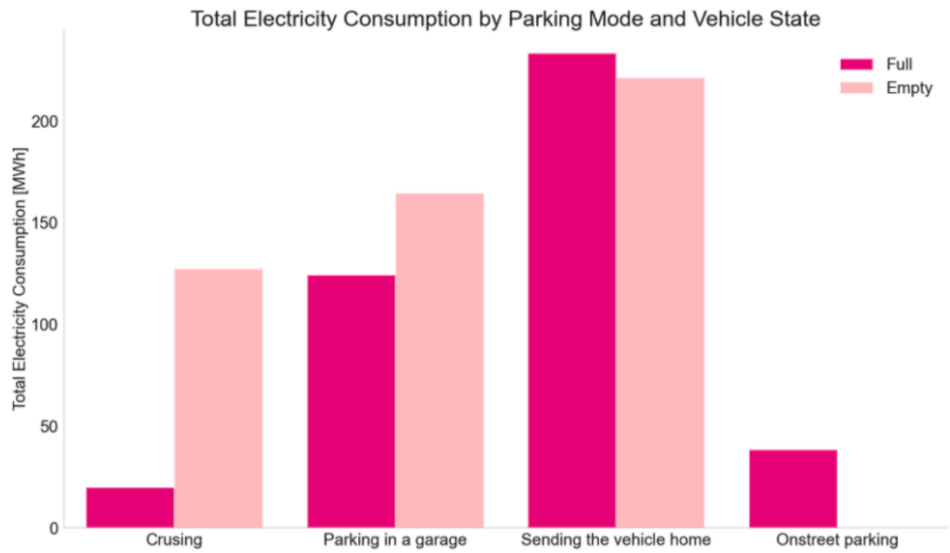

Fig. 8. Energy consumption resulting from travel with various parking choice.

Fig. 9. The location of the dedicated parking garages.

facilitating a nuanced analysis of how these factors influence parking decisions in an era of automated mobility.

This study's investigation into privately owned AV parking choices has showed distinct preferences among Santander's population, underpinned by quantitative analysis. The MNL model, employing socioeconomic variables, revealed that approximately 53% of respondents favour sending AVs home, a choice significantly influenced by the convenience of vehicle sharing and reduced parking costs. This finding, supported by a strong preference coefficient (β = 1.000, $p < 0.01$), underscores a potential shift toward more efficient use of vehicles and possible reduction in vehicle ownership in the future.

Conversely, cruising emerged as the least preferred new parking option, with only 6.4% of individuals selecting it. Based on analysing the general responses to the SP survey this was largely due to environmental concerns and a lower trust in AV technology. This preference was quantitatively supported by a negative coefficient for cruising costs (β = -0.497, $p < 0.001$), indicating cost as a deterrent and potential mean for policy makers to discourage individuals from allowing their vehicles to cruise.

The study further delved into the energy implications of AV parking choices, revealing that the adoption of new parking strategies could lead to a 105% increase in energy consumption due to empty travels. Notably, sending AVs home accounted for the highest energy consumption among the options, a critical insight for urban planning and policymaking aimed at sustainable AV integration. This analysis revealed varying levels of efficiency, underpinning the sustainability implications of each choice. Sending AVs home emerged as the most energy-intensive option, not solely because it was the most frequently chosen option by participants, but also due to the inherent inefficiency of vehicles traveling empty to and from the same location. This preference led to a doubling of energy usage for such trips, marking it as a significant concern for sustainable urban mobility. For parking in dedicated areas, the inefficiency in energy consumption was found to be even higher, not merely because of the possibility of longer distances travelled to the parking locations but also due to the congestion encountered when entering and exiting these facilities. This congestion can significantly increase the time spent and energy consumed by AVs in transit, exacerbating the environmental impact of this parking strategy. Moreover, cruising, despite being chosen by a 6% of respondents, accounted for an outsized 16% of the total energy consumption. This imbalance underscores the inefficiency of cruising as a parking strategy, where AVs continuously operate without passengers, awaiting their next use. The high energy consumption associated with cruising, relative to its low preference, points to a need for policy measures aimed at discouraging this behaviour to conserve energy and reduce emissions. Such policy measures should appear preferably before the vehicles are fully available and its passengers used to this convenient parking option.

These insights into the energy efficiency of various AV parking strategies underline the necessity for comprehensive urban mobility solutions. Addressing the inefficiencies identified, particularly the environmental cost of garage parking due to congestion and the disproportionate energy use of cruising, requires innovative approaches in urban planning and policy development. Optimizing the placement of dedicated parking areas to minimize travel distances and designing entry and exit strategies to reduce congestion could significantly enhance the sustainability of AV integration into urban transport systems.

This study, while offering novel insights into the implications of privately owned AVs integration on urban mobility, acknowledges several limitations. The assumption that all AVs are privately owned electric vehicles may not encompass the full spectrum of future transportation scenarios, including variations in ownership and vehicle technology and its usage. For instance, automation could enable relocating an AV to another pickup location to serve another household member after completing a drop-off. This alternative could impact vehicle travel patterns introducing a flexible dynamic in household mobility. However, previous studies have analysed this option and its implications (Bahk and Hyland, 2024; Correia and van Arem, 2016; Khayati et al., 2021; Zhang et al., 2018). Integrating such an option could influence the environmental benefits, future research could explore this scenario to provide a comprehensive understanding of its sustainability. Another significant aspect enabled by AV technology is the potential for more flexible carpooling within households, often referred to as ridepooling. Future activity-based models (ABMs) should incorporate this capability, reflecting that any independent travellers, including those without a driver's license, can travel autonomously, being easily picked up and dropped off by AVs. While the development of such ABMs is beyond the scope of this paper, it is important to acknowledge their potential impact. Ridepooling could substantially reduce VKT, a key performance metric in this study, and decrease the number of vehicles required per household. By optimizing the use of AVs, ridepooling could enhance the efficiency and sustainability of urban transportation systems. Future research should explore the integration of ridepooling in ABMs to fully understand and leverage its benefits for reducing VKT and vehicle ownership.

Additionally, the reliance on SP data and agent-based modelling, while robust, may not capture all nuances of human behaviour and technological adaptation. Nevertheless, it is a step forward in research on privately owned AVs, a topic often overlooked in literature, due to optimistic assumption of full implementation of sharing economy when it comes to these vehicles.

Moreover, identifying the singular pricing strategy applied to various parking alternatives in our survey as a limitation highlights a critical area for future research. Investigating the sensitivity of respondents' choices to monetary values and different pricing strategies emerges as a pivotal future research direction. This would entail exploring how varying levels of financial penalization for choices like cruising could promote more environmentally friendly parking habits. Furthermore, the consideration of Urban Vehicle Access Regulations as a policy mechanism warrants further exploration to ascertain its efficacy in guiding private AV usage towards alleviating congestion and minimizing energy consumption. Analysing these policies' potential to penalize less sustainable behaviors, and encourage the adoption of more eco-friendly parking strategies represents a critical avenue for enhancing urban mobility solutions. The future research approach would aim to uncover effective strategies for managing the transition towards AV usage, with an emphasis on promoting environmental sustainability and reducing potential further urban traffic inefficiencies.

The results from both the discrete choice model and the one-day simulation provide valuable insights into the parking choices and energy consumption patterns of AVs in Santander. Understanding these trends is vital for designing effective policies and urban planning strategies that promote energy efficiency and sustainability in future AV-dominated transportation systems with respect to the easy yet energy intensive choices that AVs may induce. As AV technology continues to evolve, optimizing parking choices and energy consumption will therefore play a crucial role in creating more sustainable and efficient urban mobility solutions.

CRediT authorship contribution statement

Ada Garus: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Andrés Rodríguez:** Writing – review & editing, Writing – original draft, Software, Conceptualization. **Andromachi Mourtzouchou:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Luigi dell'Olio:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Borja Alonso Oreña:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Biagio Ciuffo:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Data availability

The authors do not have permission to share data.

Author statement

We confirm that the manuscript has been read and approved by all named authors. This work was partly realised with the Collaboration of the European Commission Joint Research Centre and the University of Cantabria under the Collaborative Doctoral Partnership Agreement N035297. The opinions expressed in this article are those of authors only and should not be considered as representative of the European Commission's official position.

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