Article

Modeling the Impacts of Autonomous Vehicles on Land Use Using a LUTI Model

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Abstract: Autonomous vehicles (AVs) can generate major changes in urban systems due to their ability to use road infrastructures more efficiently and shorten trip times. However, there is great uncertainty about these effects and about whether the use of these vehicles will continue to be private, in continuity with the current paradigm, or whether they will become shared (carsharing/ridesharing). In order to try to shed light on these matters, the use of a scenario-based methodology and the evaluation of the scenarios using a land use–transport interaction model (LUTI model TRANSPACE) is proposed. This model allows simulating the impacts that changes in the transport system can generate on the location of households and companies oriented to local demand and accessibility conditions. The obtained results allow us to state that, if AVs would generate a significant increase in the capacity of urban and interurban road infrastructures, the impacts on mobility and on the location of activities could be positive, with a decrease in the distances traveled, trip times, and no evidence of significant urban sprawl processes. However, if these increases in capacity are accompanied by a large augment in the demand for shared journeys by new users (young, elderly) or empty journeys, the positive effects could disappear. Thus, this scenario would imply an increase in trip times, reduced accessibilities, and longer average distances traveled, all of which could cause the unwanted effect of expelling activities from the consolidated urban center.

Keywords: autonomous vehicles; land use; LUTI model; accessibility

1. Introduction

The introduction of autonomous vehicles (AVs) in cities has generated great expectations and, at the same time, considerable concern about future mobility patterns and the potential changes they may represent to urban forms. In a context where society is more open to new forms of mobility, it is expected that AVs will favor a more efficient, safe, inclusive, and sustainable transport [1–6]. However, the future is uncertain and technological developments are advancing rapidly, so that mobility conditions linked to AVs may be different from those expected, which would have spatial effects of a different sign and magnitude that must be considered by urban and transport planners [7,8].

The immediate and most direct impacts will arise in the transport system itself. Due to the new communication systems between vehicles (V2V), road infrastructures, and traffic control centers, an increase in road capacity is expected, coupled with an improvement in congestion levels [9,10]. However, by reducing trip costs and providing inclusive mobility to non-driving people, AVs could also lead to an increase in trip generations [11–14], either by capturing demand from public transport and other active modes or by inducing demand for new trips. Soteropoulos et al. [6] pointed out that AVs could increase trip distances and reduce the market share of public transport and active modes. For Krueger et al. [15], they could provide a flexible solution compared to other modes to complete the "last mile", encouraging multimodality. Moreover, because AVs will free users from driving, a significant reduction (of around 25–75%, depending on the various

authors) in the value of trip time perceived by users is generally expected [16–18], although this reduction cannot be generalized to all cases [19].

If all these forecasts/assumptions become real, they may imply important changes in accessibility. Childress et al. [17] stated that the decrease in the value of time and the increase in the capacity of roads would lead to an improvement in accessibility in all areas and especially in rural ones, which could imply an increase of up to 20% in the total distance traveled by vehicles. Milakis et al. [20] pointed out that AVs may offer their users an increased variety of accessible activities but will have conflicting social and spatial implications. Moreover, Papa and Ferreira [21] identified critical governance decisions that could affect accessibility levels.

The expected fast development of AVs can have a disruptive impact on transport and lead to substantial changes in urban form and land use. Changes in accessibility can modify the patterns of residential location and land use distribution, which would affect the magnitude and direction of urban sprawl processes. Zakharenko [22] estimated that urban areas could expand up to 7% towards the periphery. For Litman [23], the effects will depend on transport and land use policies, with current policies implying an increase in sprawl between 10% and 30%.

The main aim of this article is to evaluate the potential effects of different scenarios, such as increases in infrastructure capacity or increases in demand caused by AVs, with special attention to their effects on the location of population and activities, using land use–transport interaction models (LUTI models). This type of evaluation on medium- to long-term effects is an area of research, which is scarce in the academic literature despite the potential use of LUTI models to support decision making [6]. We applied a LUTI model, called TRANSPACE, to simulate a series of scenarios reflecting the range of foreseeable alternatives in a specific urban system. The proposed model combines random utility theory with hedonic regression techniques and a supply–demand equilibrium transport model to estimate the location of population, economic activities, and transport patterns in the zones of an urban system. This model was applied to the urban area of Santander (Spain) as an example of the effects that autonomous driving could have in a medium-size urban system.

Following these lines, the document is organized in the next sections. The subsequent section provides a literature revision on the possible impacts that the introduction of AVs may have on the location of urban agents. Then, the model used here to carry out the simulations is presented. The case study is then introduced and the results of four scenarios that reflect alternative future situations in terms of infrastructure capacity, and individual or shared use of AVs are considered. Finally, the last section draws the main conclusions, discusses the limitations of the model and identifies future research needs.

2. Autonomous Vehicles and Location of Population and Activities

The literature on the possible impacts that AVs can have on the location choices of urban agents is still scarce, although it is growing fast. Earlier studies already showed that AVs can generate increases in accessibility and in the trip distances traveled, which would reinforce the processes of urban sprawl by making residence in peripheral and rural areas more attractive [6,17,24]. These effects would occur due to the combined action of several phenomena, but especially as a result of the reduction in trip time derived from the increase in infrastructure capacity provided by the capabilities of AVs and by the reduction in the value of trip time derived from the fact that traveling in an AV is less stressful and does not require the driver's attention.

These effects were evaluated by Meyer et al. [25], although without considering the possible medium-term changes in the location of households resulting from the introduction of AVs. The authors considered possible increases in infrastructure capacity generated by AVs (and the subsequent increase in specific location accessibility) and the rise in demand derived from new users and empty trips. Furthermore, in the latter scenario, the authors also took into account that some users could stop using public transport in favor

of individual autonomous transport and that this induced demand could be generated by accessibility improvements. All these scenarios indicated that accessibility improvements would occur mainly in peripheral urban areas and nearby rural areas which could significantly increase sprawl and make public transport competitive only in urban centers.

Subsequent research has also incorporated the possible effects on residential locations that AVs may involve, i.e., the fact that in the medium-term households may relocate given the aforementioned new accessibility conditions. In this sense, Zhang and Guhathakurta [26] used an agent-based model combined with a residential location model to study the impacts of a fleet of shared autonomous vehicles (SAVs) without considering ridesharing. The residential choice model was based on discrete choice techniques considering the socioeconomic characteristics of the households, the characteristics of the properties, the built environment, and the transport costs to work of each dwelling, including those derived from commuting time and from ownership and use of the vehicle. The simulation of the SAVs was carried out using an agent-based model in which 10,000 vehicles were generated at the beginning of the simulation, and new vehicles were added if the waiting times of any customer were longer than 15 min. The results of the modeling showed that waiting times for SAVs were significantly higher in the periphery of the study area (Atlanta Metropolitan Region, GA, USA), although the commuting costs were considerably reduced. In addition, households with older members tended to be located closer to the central business district (CBD) to achieve shorter waiting times for SAVs, while younger households generally chose to locate further away to enjoy better housing or environment. It was also found that, on average and in all types of households, commuting distances increased with the availability of SAVs.

Other studies have gone further into the estimation of more precise residential choice models to determine how the value of time may vary with the existence of AVs. This is the case of a study by Krueger et al. [27] using a stated preference (SP) survey and mixed logit discrete choice models. However, these authors did not find substantial changes in the value of trip time and, therefore, in the capacity of AVs to change residential location patterns. In a similar vein, using data collected with an SP survey, Carrese et al. [28] estimated a modal choice model that included the use of private vehicles, carsharing, or ridesharing and a binomial residential choice model between no change of location and changing residential location to the suburbs of the study area (Rome, Italy). These models combined with a transport simulation model allowed to simulate the consequences of various scenarios with different ridesharing penetration. In this way, it was detected that some households could relocate to more peripheral urban areas, which in the model resulted in an increase in congestion and trip times, as opposed to central areas where the effect was the opposite. Furthermore, these negative effects could only be avoided in the scenario where the level of ridesharing penetration was 100%.

Finally, other authors have chosen to update pre-existing LUTI models to assess scenarios with the presence of AVs, which may lead to more realistic modeling. This is the case of Emberger and Pfaffenbichler [29], who used a modification of the Metropolitan Activity Relocation Simulator (MARS) model, based on system dynamics, to quantify the impacts of AVs on transport and land use in Austria. The model was adapted to consider the fact that AVs could have an impact on the capacity of infrastructures, the location of car parks, the value of time, or the possibility that new types of users (young, elderly, and disabled) could access private or shared vehicles. In general, the scenarios proposed implied an increase in vehicle-kilometers traveled by AVs of around 30%, taking into account changes in the four factors mentioned above. Spatially, these changes mainly affected the capital (Vienna), the peripheral areas of the cities, and their nearby rural areas. Therefore, according to these simulations, an increase in the use of AVs could imply an increase in private vehicle mobility and trip distances.

A similar line of research has been developed by Basu and Ferreira [30], in this case using the LUTI model SimMobility for the evaluation of AV individual use and ridesharing mode scenarios in a study area including a planning district of Singapore with a low market

share for private vehicles. This agent-based model allows simulating urban agent choices in the short (e.g., route choice), medium (e.g., activity choice), and long (e.g., residential location choice) terms. By simulating various scenarios considering changes in the residential market, the authors detected that the presence of AVs in the district could further reduce the presence of private vehicles in the area and induce gentrification effects, i.e., the substitution of the existing population by another with a higher income level.

These studies indicate that knowledge about the impacts of AVs on urban systems is still highly uncertain. In this sense, the use of LUTI models is advisable to simulate the equilibrium between transport and land use subsystems in such a way that the effects of AVs on accessibility and network flows are endogenized in the location models. In addition, it is also interesting to consider the sites of economic activities, as these can be influenced and in turn affect the location of the population, playing an important role in urban sprawl processes.

3. Model Applied to the Simulation of Autonomous Vehicles Impacts

The simulation of scenarios was carried out using the TRANSPACE model, a tool based on previous research [31,32]. TRANSPACE is a LUTI model that combines economic base theory with discrete choice modeling to simulate changes in the location of both households and local demand-oriented businesses and services. In addition, the model is capable of estimating property prices using hedonic regression techniques to improve the results of the residential location model (Figure 1). Transport simulation is carried out by means of the Visum model (PTV AG, Karlsruhe, Germany) [33], which allows considering the three traditional steps of travel demand and its network equilibrium assignment.
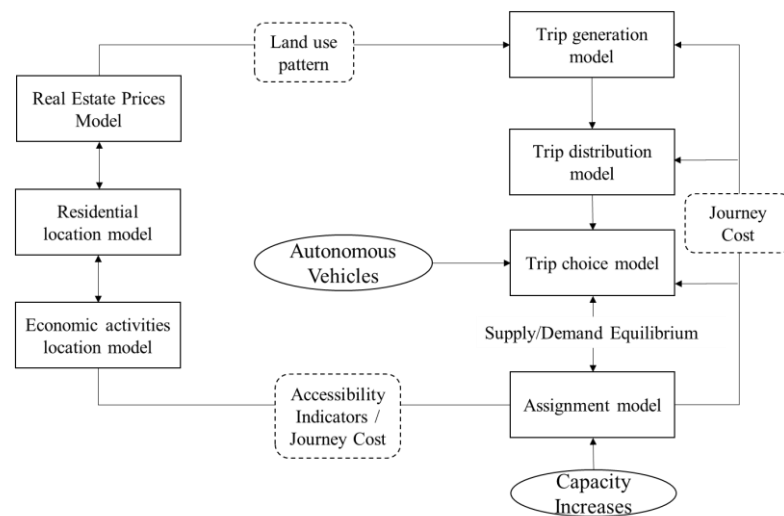

Figure 1. Structure of the land use–transport interaction (LUTI) model considering the presence of autonomous vehicles (AVs).

The relationship between land use models and the transport model is established through accessibility indicators and trip costs in the network arcs. The accessibility indicators considered are of the gravitational type [34] with two specifications, active and passive accessibility, respectively, which are

$$Acc(o) = \sum_i \left\{ \exp[\alpha_2 \cdot Cost(o, d_i)] \cdot jobs(d_i)^{\alpha_1} \right\} \tag{1}$$

$$Acc(d) = \sum_i \left\{ \exp[\beta_2 \cdot Cost(o_i, d)] \cdot res(o_i)^{\beta_1} \right\}, \tag{2}$$

where *Cost* is a measure of the trip cost between two zones, $jobs(d_i)$ are the jobs present in zone d_i as a measure of attraction and opportunities (active accessibility), and $res(o_i)$ are the

residents present in zone o_i who can access zone d (passive accessibility). Finally, α_1 and β_1 are the parameters corresponding to the attraction variables, while α_2 and β_2 are the parameters capturing the power of trip costs. All these parameters can be estimated by linearizing the expressions using logarithms and considering the production of trips in a zone as a proxy of active accessibility and the attraction of trips in each zone as that of passive accessibility. The estimated parameters can also be interpreted as accessibility's elasticity to percentual changes in the trip cost and opportunities specified in the indicators.

The model is based on the following simplifications to facilitate the modeling process:

1. The modeled area is considered closed to avoid taking into account immigration/ emigration flows. This reduces the realism of the model and simplifies it by avoiding modeling a phenomenon that is not considered fundamental to simulate the internal dynamics of the area and the impacts of AVs;
2. The model does not incorporate a sub-model of real estate supply, although it restricts the possibilities of the analyzed areas to accommodate population and activities based on their potential future growth;
3. The location of the activities considered as belonging to the basic sector is not modeled but taken as fixed and independent of accessibility to the population.

The location of the population is estimated by means of a logit-type model based on the theory of random utility in which the head of the household/main worker chooses the location that maximizes its utility. Because it is not possible for the modeler to know exactly the utilities and, therefore, the ordering of alternatives that will be made by the agents, the choice can be modeled in a probabilistic way, using an expression of the type

$$P_{res-cond}^{i}(o|d) = \frac{\exp[V^i(o|d)]}{\sum_o \exp[V^i(o|d)]},$$
(3)

where $P_{res-cond}^{i}(o|d)$ is the probability that the head of the household/main worker of type i (socioeconomic class) will choose to live in zone o given that he/she works in area d. This choice probability is modeled through the systematic utility of choosing each of the o zones conditioned to work in d $V^i(o|d)$. This systematic utility can include attributes related to the structural characteristics of dwellings in the area, environmental features, and conditions of accessibility and transport.

By means of these choice probabilities, it is possible to locate the number of workers w of type i that are located in each zone o as

$$w^i(o) = \sum_d P_{res-cond}^{i}(o|d) \cdot Emp^i(d),$$
(4)

where $Emp^i(d)$ is the total number of type i workers present in each zone d. This implies that the modeler must know, as exogenous data, how workers are disaggregated by socioeconomic class in each zone.

Finally, having estimated the number of workers in each area, it is possible to calculate the total number of residents through the following expression:

$$res(o) = k(o) \cdot \sum_i \sum_d P_{res-cond}^{i}(o|d) \cdot Emp^i(d).$$
(5)

This estimate is consistent with first simplification 1 and with economic base theory whereby an increase in employment implies an increase in population. The parameter $k(o)$ is exogenous and can be estimated for each of the o zones in a differentiated way or for the whole of the study area if more data are not available.

The location of jobs belonging to the non-base sector is also calculated using a multinomial logit model similar to (3) of the type

$$P_a(d) = \frac{\exp[V_a(d)]}{\sum_d \exp[V_a(d)]},$$ (6)

where the probability for a job belonging to the economic sector *a* to be located in *d* is given by the systematic utility of a zone *d* compared to the rest of the zones in the study area. This systematic utility can be made dependent on different advantages of each location, including its passive accessibility to the population because it applies only to non-basic sectors oriented to domestic demand. The location of jobs in an economic sector *a* in each zone is therefore given by

$$Emp_a(d) = P_a(d) \cdot EMP_a,$$ (7)

where EMP_a is the number of jobs in the economic sector *a* present in the study area. Given that the location of the population depends on the job location and that the location of activities oriented to domestic demand depends on the location of the population, the model takes into account that the solution is given by an equilibrium problem that can be treated as a fixed-point problem [31,35].

The simulation of property prices is carried out using a hedonic regression model where the prices of a property *j* located in a zone *o* depend on a series of characteristics, which may correspond to structural characteristics of dwellings, those of the environment, or conditions of accessibility and transport.

Finally, the transport model is based on a trip generation based on the data provided by location models, a gravitational trip distribution model constraint to both origins (trip production) and destinations (trip attractions), and a modal choice model that considers the possibility of choosing between an individual AV and public transport. This model is of the logit type and takes into account the total estimated trip times of each mode. The model takes the form

$$P_{SAV_{ij}} = \frac{e^{-0.043 \cdot TT_{SAV_{ij}}}}{e^{-0.043 \cdot TT_{SAV_{ij}}} + e^{-0.632 - 0.043 \cdot TT_{PT_{ij}}}} \quad \forall i, j$$ (8)

where P_{SAVij} is the probability of choosing the SAV mode between zones *ij*, TT_{SAVij} is the total trip time in SAV between zones *ij*, and TT_{PTij} is the total trip time between zones *ij* by public transport.

The transport model considers demand and infrastructure capacity at peak times, i.e., the time of the day with potentially more mobility problems. The LUTI model as a whole was originally calibrated with data from 2008. The data used to calibrate the model were obtained from four main sources: the Spanish Institute of Statistics (population and housing census and annual registers of the population), the Institute of Regional Statistics (Regional Company Directory), real estate portals and an Origin-Destination survey carried out in the study area with data from a sample of households and their trips. More information on the parameters estimated in the different models and indicators of accessibility can be found in Coppola et al. [31].

4. Case Study and Results

4.1. Case Study

The model described in the previous section was applied to the urban area of the Bay of Santander (Cantabria, Spain). This area has been defined as comprising nine municipalities—Santander, Santa Cruz de Bezana, Astillero, Camargo, Piélagos, Medio Cudeyo, Marina de Cudeyo, Villaescusa, and Ribamontán al Mar. These municipalities have a total population of 280,581 inhabitants (data for 2019). Figure 2 shows the population density of the study area, which is concentrated in the city of Santander and in the northwest-southeast corridor from Bezana to El Astillero. The population density in the

most urbanized areas, and especially in the city of Santander, is quite high with values of over 20,000 inhabitants per square kilometer. In order to facilitate the presentation of results, five large zones have been defined within the study area—the urban center of Santander (zone 1), which concentrates a high number of jobs; the highly inhabited residential neighborhoods surrounding the urban center, which have a significant population density (zone 2); the periphery of the municipality of Santander (zone 3), with a peri-urban character; the area of influence closest to the central city (zone 4), which still has high population densities and several population centers dependent on Santander such as Muriedas, Maliaño, and El Astillero; and the area furthest away (zone 5) with centers of a more rural nature (see Figure 2).
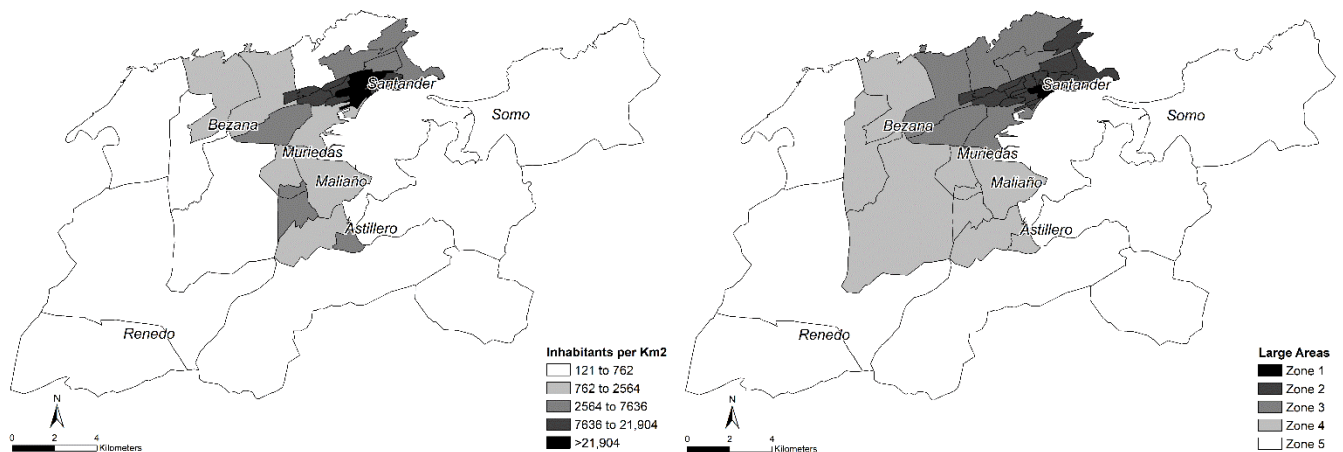

Figure 2. Population density in the study area (2019) (**left**) and division of the study area into large zones (**right**).

4.2. Scenarios and Results

Given that the implementation of AVs still presents many uncertainties, a methodology based on scenario building has been chosen to propose different situations that could arise in the future. Four large scenarios have been defined as representative of the implications of AVs to simulate their effects on the transport system, the location of population and activities, and accessibility conditions, which are as follows:

1. Increase in the capacity of interurban infrastructures. This scenario simulates the effects of the increase in capacity that could take place with a more efficient automated driving of AVs, which, as private vehicles in the initial stages, would only be available in interurban areas;
2. Increase in the capacity of interurban and urban infrastructures. In this more advanced scenario, AVs can be used privately, both in interurban areas and inside cities, given the improvements in their technological capabilities;
3. Increase in the capacity of interurban and urban infrastructure + induced demand. Unlike scenario 2, this one considers that the improvement in accessibility of specific areas can generate new trips due to the reduction in trip costs and a larger number of nearby employment opportunities;
4. Increase in urban and intra-urban infrastructure capacity + induced demand + increase in users and empty trips (SAVs). In this scenario, in addition to what has been examined in the previous ones, AVs can be sequentially shared (carsharing), which could attract new users from other modes such as public transport or on foot, and producing new empty trips.

In all four scenarios, the TRANSPACE model was used to simulate the effects of increased infrastructure capacity and the existence of SAVs on accessibility and trip times and, therefore, on the location of population and activities in the urban area studied. Simulated vehicles will be considered to be fully autonomous, i.e., level 5 according

to the Society of Automotive Engineers (SAE) On-Road Automated Vehicle Standards Committee [36] classification.

4.2.1. Scenario 1

This first scenario simulates a situation in which AVs already present a notable technological development but are not yet suitable for circulation in urban areas given their greater complexity regarding coexistence with other motorized modes and with pedestrians/cyclists, and the presence of complex intersections and other factors. Despite this, the capacity of AVs to react more quickly to other vehicle movements and their communication by means of V2V protocols may imply that their use of existing infrastructures is more efficient than at present.

The capacity changes applied to interurban roads are those calculated by Shladover et al. [10] and Friedrich [37] for motorways. These authors estimated that capacity increases with cooperative AVs can be estimated around 80% if AVs market penetration rates are close to 100%. These results are also in line with those simulated by Liu et al. [38].

The increase in capacity of interurban infrastructures implies improved trip times, especially in areas closest to motorways, with only certain areas of access to the central city experiencing a slight increase in trip times due to more congestion (Table 1 and Figure 3). These same intermediate areas, which are close to the nucleus of Santander but are not part of it (zone 4), are the ones that benefit most from the increases in active and passive accessibility (Figure 3), while the areas further away from the urban nucleus of Santander or the central areas of the city present, in some cases, reductions in their levels of accessibility to jobs and population. In terms of the distribution of the latter, the model shows how zone 4 could capture more population while zones closer to the urban nucleus (zones 2 and 3) could reduce it. This can also be seen in the increase in kilometers traveled outside the central city. On the other hand, there would be no significant change in the number of jobs. Therefore, these results point to a moderate process of population sprawl in the study area that is accompanied by improvements in mobility and accessibility.

4.2.2. Scenario 2

In this case, in addition to the changes already simulated under scenario 1, there is a 40% increase in the capacity of urban roads according to estimates made by Friedrich [37]. This may allow these areas to also benefit from improvements in trip times and reduced congestion and therefore increase their accessibility and attractiveness as places to live. The simulation carried out shows how, on this occasion, the central city does not lose population but even gains a small number of inhabitants in the residential neighborhoods (zone 2) (Figure 4) and jobs in the city center (zone 1) (Table 1). In this case, the improvement in trip times benefits both the city and its area of influence similarly. This also results in a notable increase in accessibility in almost all zones except for some of the most peripheral ones (zone 5). This scenario can therefore be considered optimistic with respect to the effects of AVs, where the increases in capacity benefit the whole area and especially the previously more congested central urban area, thus avoiding the urban sprawl effects observed in scenario 1. Furthermore, the reduction in traffic congestion also allows for a reduction in vehicle-kilometers traveled and measured trip distances, thus reducing pollutant emissions and/or energy costs derived from car mobility.
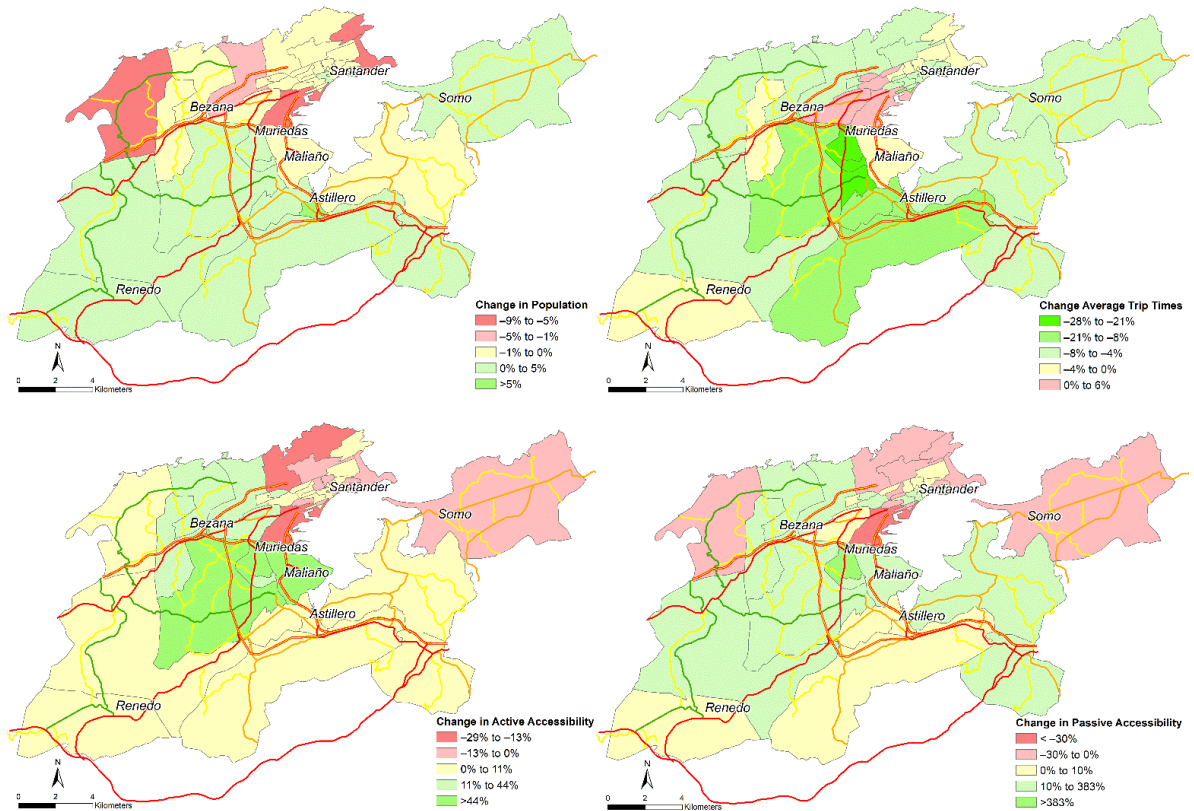
Figure 3. Changes in the distribution of the population (**top-left**), average trip times from one zone to the others (**top-right**), active accessibility (**bottom-left**), and passive accessibility (**bottom-right**); scenario 1.
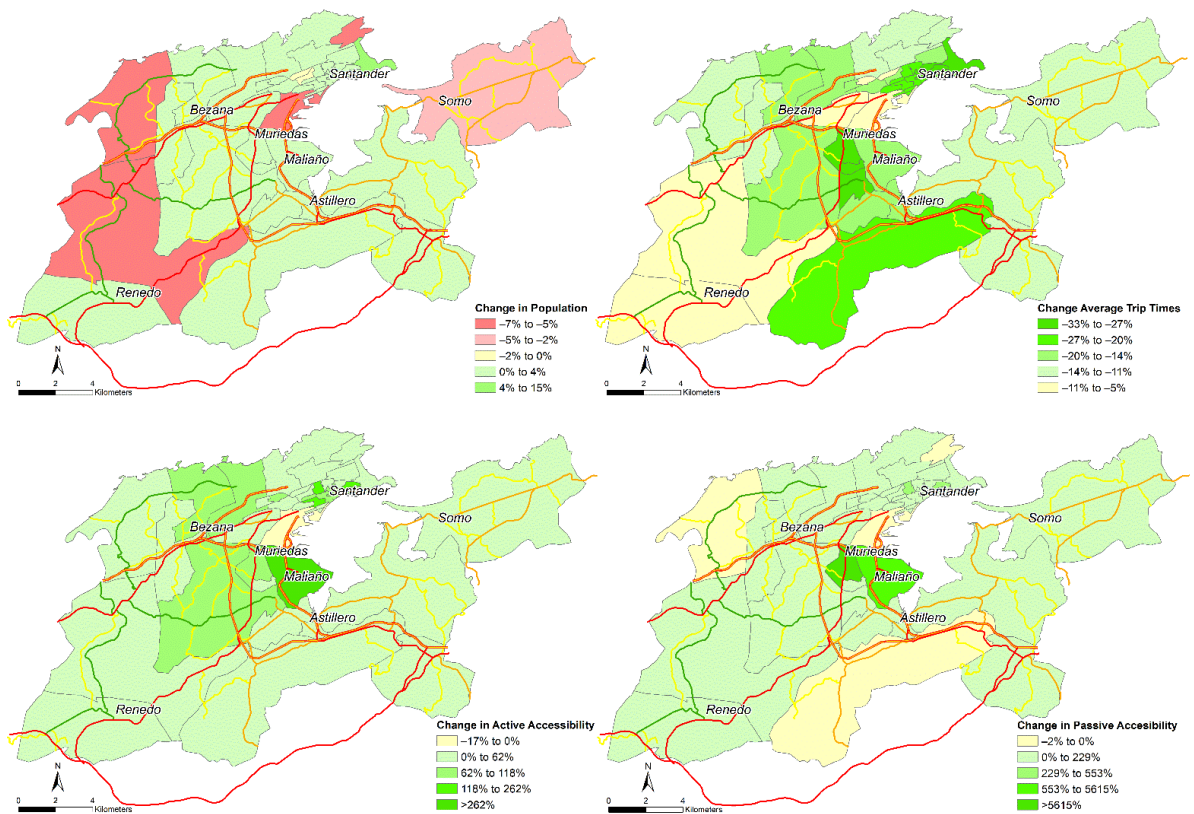

Figure 4. Changes in the distribution of the population (**top-left**), average trip times from one zone to the others (**top-right**), active accessibility (**bottom-left**), and passive accessibility (**bottom-right**); scenario 2.

4.2.3. Scenario 3

In this scenario, trip generation in the LUTI model is modified to take into account the effect of induced demand, which can be derived from the improvements in active accessibility estimated under scenario 2. The relative increase in accessibility is calculated as

$$\Delta_{ACC,i} = (A_{E2,i}/A_{BASE,i}) - 1, \tag{9}$$

where $A_{E2,i}$ is the accessibility in zone i calculated for scenario 2 and $A_{BASE,i}$ is the accessibility in zone i calculated for the base scenario.

To obtain trip production considering the induced demand, the combined elasticity of cost and estimated opportunities for the active accessibility indicator $\varepsilon = 0.385$ was applied [31]. Thus, the new trip production P'_i was calculated as

$$P'_i = P_i \cdot (1 + \varepsilon \Delta_{ACC,i}) \; \forall i \tag{10}$$

The model then balances the new estimated trip production with trip attraction and generates the total trip distribution matrix using the double-constrained gravitational model used in the TRANSPACE model.

In this case, the population of the central city grows even more than under scenario 2 due to the increase experienced by zone 2 (Figure 5 and Table 1), and jobs remain practically stable despite the additional demand induced by the improvements in accessibility. This is because, within the central city, trip times continue to show some improvement (zones 1 and 2) except in the access areas (zone 3). However, induced demand makes increases in active accessibility already scarce in this scenario with the exception of zone 1, while passive accessibility even decreases in zone 4 due to population loss. On the other hand, the number of kilometers traveled shows a strong increase due to new induced AV trips, although the average distance traveled is lower than in the base scenario. This indicates that even considering a greater trip generation, there does not seem to be a process of urban sprawl derived from the increases in capacity estimated for scenario 2, but there is an increase in the number of journeys made by AVs even though the modal split does not change because public transport users also increase in number.
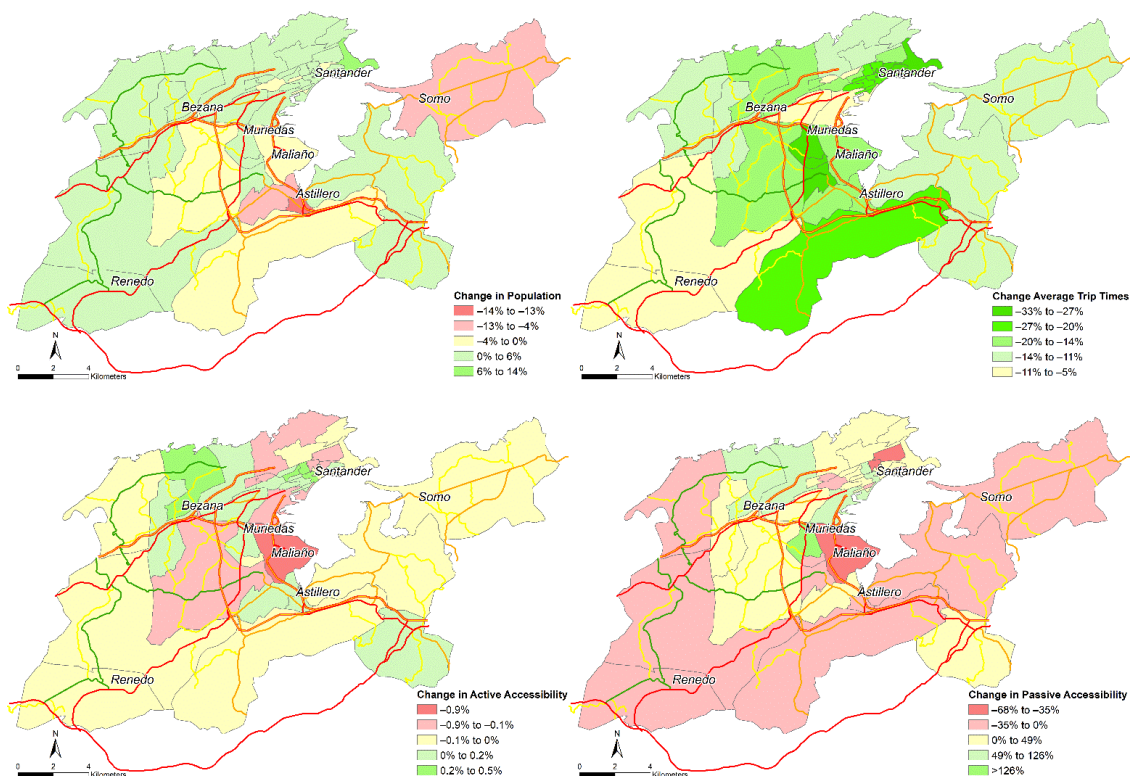

Figure 5. Changes in the distribution of the population (**top-left**), average trip times from one zone to the others (**top-right**), active accessibility (**bottom-left**), and passive accessibility (**bottom-right**); scenario 3.

4.2.4. Scenario 4

In this last scenario, in addition to increases in the capacity of urban and interurban infrastructures and induced demand, AVs can be used sequentially (carsharing) so that new users, who did not have access to private AVs, will have them available and there will also be empty trips derived from services between different users.

The methodology applied to calculate this scenario is similar to that used by Meyer et al. [25], which is based on updating the car–trip matrix by considering a fixed increase derived from the transfer of trip distances made by minors and those over 64 to car mode. However, in this case, only the increase in trips derived from active modes (walking and cycling) is considered, while the simulation of the possible transfer of users from public transport is calculated using the logit model presented in Section 3.

Based on data from a household survey carried out in 2015 in the city of Santander, the total distance traveled by minors and those over 64 years old using active modes was estimated in 19% of the total distance traveled by all car users. In this way, the updated demand between each pair of zones D'_{ij} is equal to

$$D'_{ij} = D_{ij} \cdot \gamma \ \forall i,j, \tag{11}$$

where γ is equal to 1.19 under the assumption that all trips made by these users involving active modes will be made in SAV. This assumption, although strong, means only a 19% increase in trips, which is considered realistic.

In addition, the existence of empty journeys resulting from pick-up trips between users or parking of the vehicle has also been considered. It is assumed that, on average, each person can generate one empty trip which, knowing that each individual performs an average of 2.81 trips in the study area, results in a 36% increase in total trips caused by empty ones, i.e.,

$$D''_{ij} = D'_{ij} \cdot (1 + 1/2.81) \ \forall i,j. \tag{12}$$

Both in terms of capturing trips from minors and users over 64 years old, and in terms of generating empty trips, it is assumed that their distribution will be equal to that of the demand given by the trip matrix in the previous scenario. This assumption is considered reasonable given that it affects groups that are found all over the study area and empty trips can be distributed equally among all trips made.

These hypotheses lead to the results shown in Figure 6 and Table 1. The increase in demand for transport in SAVs leads to an increase in average journey times in all areas, although especially outside the central city, and a fall in active and passive accessibility. This means that the distribution of the population is not greatly affected compared to the current situation and that in any case, the residential areas of the central city (zone 2) may grow slightly compared to a reduction in the more peripheral zones of the study area (zone 5) as was already the case in scenario 3. On the other hand, there is a slight increase in jobs outside the city, although mainly near the main communication highways (zones 3 and 4). Therefore, in this scenario, AVs would not favor urban sprawl or only to a limited extent, although the effects of increased infrastructure capacity would be neutralized in terms of increased accessibility and shorter journey times due to the higher demand for mobility, affecting the periphery more than the central city. Furthermore, the total distances and the average distance traveled by vehicles would increase considerably, which could have negative repercussions in terms of polluting emissions or energy consumption (see Figure 7).

Table 1. Comparison between indicators under the simulated scenarios and the base scenario.

| Scenario/Zone		Change in the Choice of Car Mode	Change in Average Trip Distance Covered in AV	Kilometers Covered by AV	Trip Time	Active Accessibility	Passive Accessibility	Population	Employment
Scenario 1	Z1	0.1%	−0.3%	0.9%	−4.3%	−0.4%	5.9%	0.0%	0.2%
	Z2			−1.9%	−3.2%	1.6%	1.2%	−0.7%	0.0%
	Z3			−0.7%	−0.8%	4.4%	−1.0%	−1.0%	−0.1%
	Z4			1.1%	−13.3%	30.6%	28.4%	2.1%	−0.1%
	Z5			0.3%	−5.9%	5.7%	6.6%	0.0%	0.0%
Scenario 2	Z1	0.8%	−2.9%	1.2%	−20.9%	94.6%	187.1%	0.0%	1.6%
	Z2			−1.8%	−21.1%	48.4%	43.0%	0.4%	0.0%
	Z3			−3.3%	−10.4%	37.0%	37.6%	−1.3%	−0.7%
	Z4			−1.8%	−21.1%	33.4%	29.7%	1.0%	−0.8%
	Z5			−2.1%	−13.2%	6.6%	7.2%	−1.9%	−0.2%
Scenario 3	Z1	0.0%	−1.4%	40.7%	−4.1%	17.4%	43.9%	0.0%	0.2%
	Z2			24.9%	−3.8%	0.7%	1.7%	0.8%	0.0%
	Z3			25.0%	4.6%	−1.2%	11.6%	0.0%	−0.1%
	Z4			55.7%	0.3%	0.7%	−2.0%	−2.3%	−0.1%
	Z5			1.9%	1.2%	0.9%	0.7%	0.9%	0.0%
Scenario 4	Z1	2.1%/0.0% [1]	5.0%	137.7%	30.6%	−58.3%	−71.1%	0.0%	−0.8%
	Z2			111.1%	37.2%	−41.9%	−31.8%	0.7%	−0.3%
	Z3			107.2%	48.3%	−73.0%	−77.8%	0.0%	0.6%
	Z4			170.9%	41.2%	−28.2%	−34.4%	0.1%	0.7%
	Z5			69.3%	49.9%	−24.6%	−27.6%	−2.7%	0.1%

[1] Without considering empty trips.
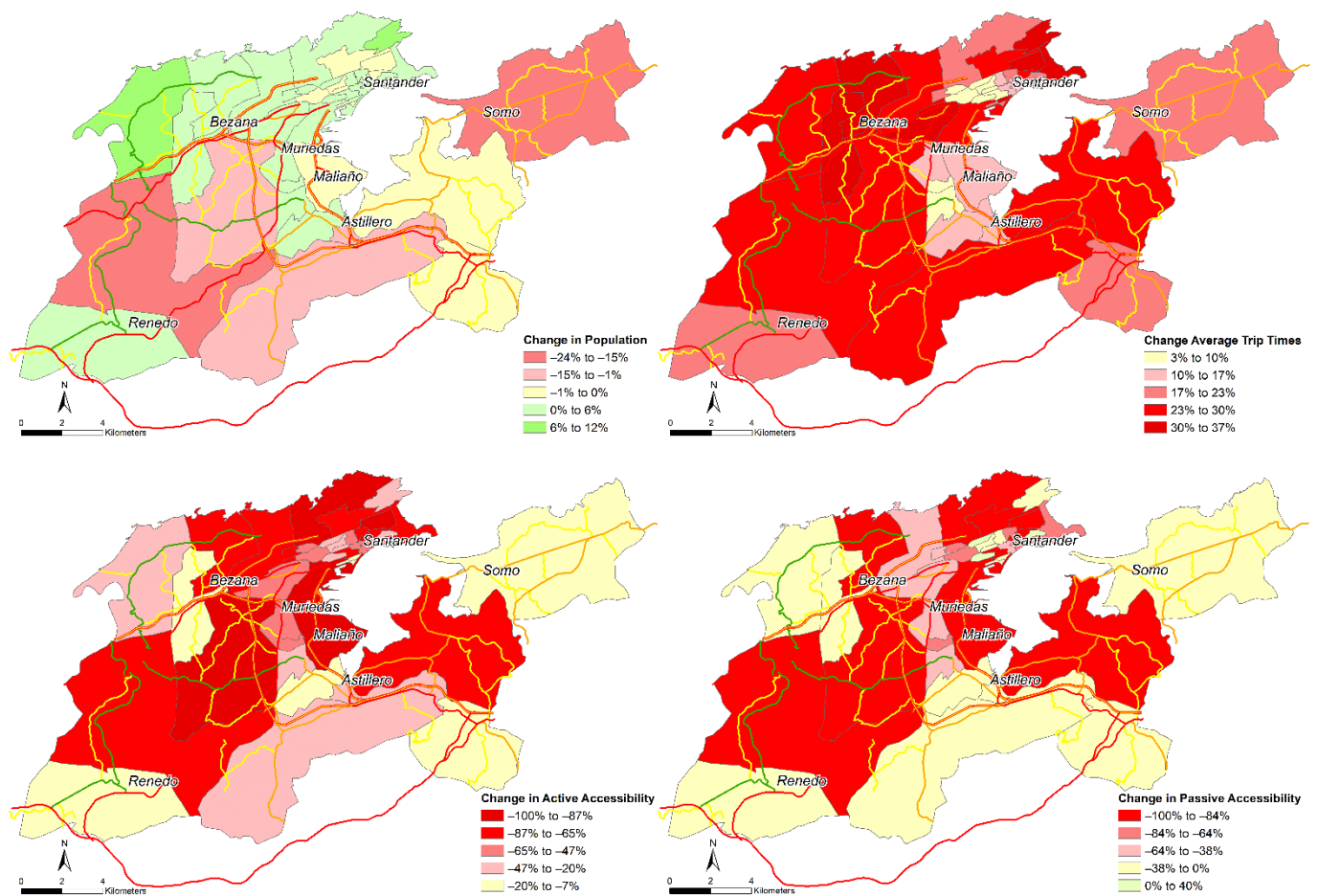
Figure 6. Changes in the distribution of the population (**top-left**), average trip times from one zone to the others (**top-right**), active accessibility (**bottom-left**), and passive accessibility (**bottom-right**); scenario 4.
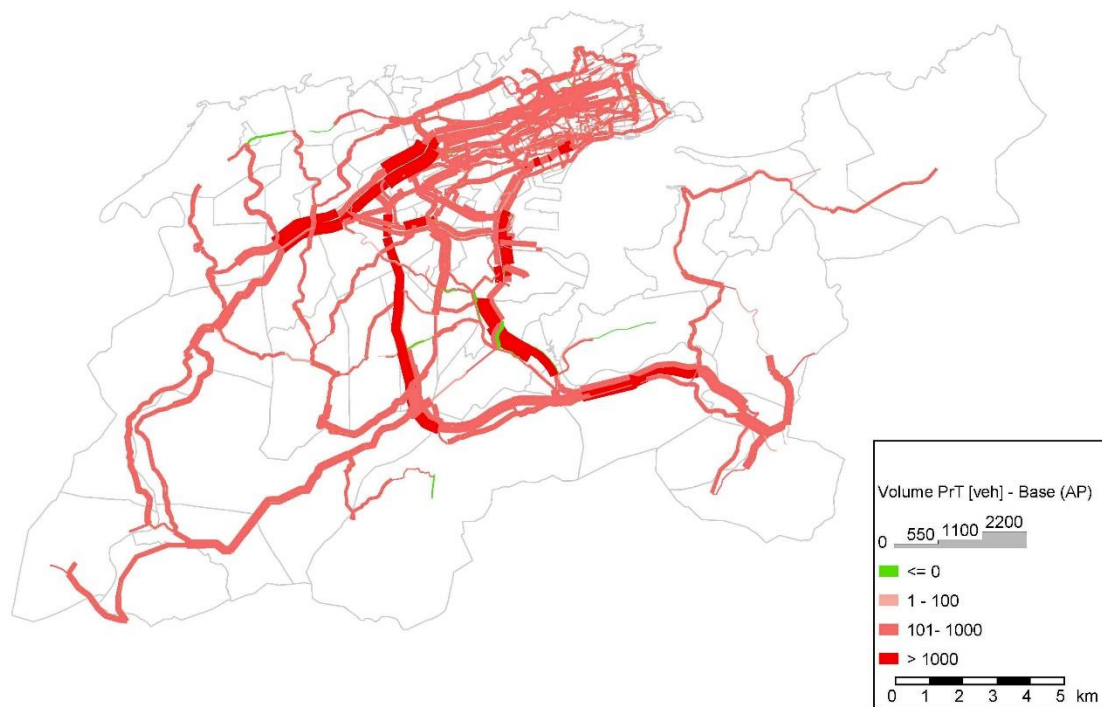
Figure 7. Difference between the volume of vehicles assigned in scenario 4 and the base scenario.

5. Conclusions

The potential spatial repercussions of autonomous vehicles are still unknown, although they may be very significant and lead to a profound reorganization of cities as we know them. To study these implications is complex given the important interrelations between transport systems and land uses and due to all the uncertainties that the technological and organizational development of AVs still present. In this research, a scenario building technique and a LUTI model were used to try to shed light on these possible effects, and in this way, help adjust policy interventions within the framework of planning practice. As the applicability of the results depends on urban configuration characteristics, the results of this study will be particularly relevant for countries and regions with comparable urban structures, such as medium-sized European cities. In addition, the results obtained show that AVs could have a significant impact depending on the urban context in which they are implemented. Considering that AVs will generate an increase in the capacity of interurban infrastructures, augmented accessibility is expected, especially in municipalities located in the surroundings of urban areas and near highways, favoring a moderate sprawl of the population, which confirms previous findings [25]. If AVs allow an increase in the capacity of existing infrastructures, both interurban and urban, the effects on population and activity location could be limited, and notable gains in trip times and accessibility would be obtained which could benefit central cities more than peri-urban or rural areas. In addition, the reduced congestion could also mean a decrease in vehicle kilometers traveled, although public transport could see its share reduced in the modal split.

However, if these increases in infrastructure capacity, shorter trip times, and greater accessibility result in a higher trip generation, either by private AV or by SAVs, some of these benefits could be lost. The higher number of trips could significantly increase total vehicle-kilometers traveled and average trip distances, which could have important negative externalities in terms of greater pollution and/or greater energy consumption, as pointed out by other authors [6,17,26,29,39]. In the last simulated scenario, both accessibility to population and jobs and trip times could be significantly degraded in urban areas, which could imply moderate sprawl effects, especially on jobs. However, mobility could be hampered even more in the most peripheral areas, a phenomenon that was also detected

by Carrese et al. [28] in Rome. This implies that if vehicles were autonomous, and even if they were shared sequentially, their possible negative effects on mobility and accessibility could be felt, especially by the share loss of other transport modes between segments of users who previously had no access to or used cars to a lesser extent, and by the effect of empty journeys between different services.

To consider different scenarios that reflect the range of foreseeable alternatives gives decision makers the opportunity to anticipate by formulating policies and actions that minimize or mitigate negative effects caused by AVs and at the same time promote their potential benefits. Measures could include policies aimed at promoting active modes and public transport, which could be enhanced given the possibilities offered by automation, by restricting the use of AVs in certain urban areas or establishing appropriate pricing for their use [40]. Dynamic road pricing to reduce kilometers traveled could easily be implemented in AVs thanks to in-vehicle navigation and communication systems [39]. The automation of public transport could be particularly useful in counteracting the sprawl effect of AVs, while also making it possible to reduce their associated environmental impacts [6,29,41].

It should be noted that the simulations carried out have not taken into account the fact that AVs could be shared on the same trip (ridesharing), which could reduce some of the most negative effects detected. The promotion of autonomous mobility through ridesharing could therefore be another of the policies which would ensure a future of sustainable mobility compatible with the presence of AVs, and it will be examined in subsequent studies.

Author Contributions: Conceptualization, R.C., S.N., and J.L.M.; methodology, R.C. and E.G.-G.; validation, R.C., S.N., and J.L.M.; formal analysis, R.C. and E.G.-G.; investigation, R.C., S.N., and E.G.-G.; resources, S.N. and J.L.M.; data curation, R.C. and J.L.M.; writing—original draft preparation, R.C. and E.G.-G.; writing—review and editing, S.N. and J.L.M.; visualization, R.C. and E.G.-G.; supervision, S.N.; project administration, S.N. and J.L.M.; funding acquisition, S.N. and J.L.M. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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