Modelling sprawl in a medium-sized urban area considering the future arrival of autonomous vehicles

The corrections made in this section will be reviewed and approved by a journal production editor.

Rubén Cordera, Soledad Nogués, Esther González-González and José LJosé Luis Moura[Comment: ORCID Esther González-González: 0000-0002-5252-3247ORCID José Luis Moura: 0000-0001-5645-8289]

University of Cantabria, Spain

Rubén Cordera, Geography, University of Cantabria, Avda de Los Castros 44, Santander 39006, Spain. Email: ruben.corderar@unican.es

Rubén Cordera, Department of Geography, Urban and Regional Planning, University of Cantabria, Avda de Los Castros 44, Santander 39005, Spain. Email: ruben.cordera@unican.es

Data Availability Statement included at the end of the article

Abstract

Cities may undergo important changes in the coming years driven by various economic, social, and technological innovations, such as those related to autonomous mobility. Among other effects, autonomous vehicles may affect morpho-functional patterns of urban development and, especially, may reinforce or reduce dispersed development patterns, which have been relevant in many cities, particularly in the last decades. In order to offer an assessment of these possible effects, we propose a new urban sprawl index to measure the degree of dispersion/concentration of settlements in the medium-sized urban area of a Spanish city (Santander, Cantabria). Further, we explain the distribution of this index by means of a regression model, showing that variables such as average household income, trip time to the main urban centre, or the percentage of people using cars to commute to work are relevant factors that correlate positively with urban sprawl. Finally, we apply the proposed model to different scenarios to examine how the development of autonomous mobility could affect the characteristics of the analysed settlements. The results obtained suggest that, in scenarios with higher car usage and longer trip times to the urban centre because of the larger number of circulating vehicles, the form of urban settlements, especially those at an intermediate distance from the urban core, could experience an increase in sprawl. Therefore, Autonomous Vehicles could promote, under certain conditions, an urban form with more sustainability problems.

Keywords:

Urban sprawl, sprawl index, autonomous mobility, sustainability

Funding Information

Funding Source : Spanish Ministry of Science and Innovation (MICINN) / ERDF (EU) in the framework of the State Plan for Scientific and Technical Research and Innovation 2017-2020Spanish

Ministry of Science and Innovation (MICINN) / ERDF (EU) in the framework of the National Plans for Scientific and Technical Research and Innovation 2017-2020 and 2021-2023

Funder DOI :

Award Number : PID2019-110355RB-I00
PID2022-140649OB-I00

Award Recipient :

Introduction

Major changes with the potential to have a profound impact on the sustainability of cities are expected in the coming years (Butler et al., 2020). One of the main changes stems from autonomous driving technology. Autonomous Vehicles (AVs) are expected to have clear effects on urban form and land use, and their inadequately planned introduction could conflict with the achievement of urban sustainable development goals (González-González et al., 2019; Milakis, 2019; Stead and Vaddadi, 2019). In addition, these vehicles could pose significant competition to traditional public and active modes of transport (Ashkrof et al., 2019). On the other hand, there could be positive impacts, such as a reduced demand for parking space and space dedicated to vehicular traffic in inner-city areas, which could provide opportunities to repurpose land for new uses (Fayyaz et al., 2022).

Among the negative impacts of AVs, the potential growth of urban sprawl is a crucial issue raising experts' concern (Nogués et al., 2020), as this type of development has clear adverse effects on the sustainability of cities (EEA, 2016; Gielen et al., 2018). In suburban areas, autonomous driving could reduce the value of drivers' trip time, improve accessibility, and thus cause an increase in urban sprawl (Gutierrez, 2021; Homem de Almeida Correia et al., 2019; Steck et al., 2018).

To avoid unintended consequences and guide the development of this autonomous technology from a sustainable point of view, it is necessary to gain more knowledge on urban sprawl effects generated by the implementation of AVs and to identify key guidelines and policies that allow public institutions to provide early and informed responses.

In this regard, this study proposes a methodology to measure the degree of sprawl of different settlements, based on diverse variables, the level of dispersion, land use, and typology of buildings. Finally, the evaluation of different scenarios is proposed to assess how the characteristics of settlements could evolve if AVs were to generate a greater dependence on motorised mobility and cause changes in trip times.

To evaluate the proposed methodology, we select a European medium-sized city. Medium-sized urban areas, which have encountered the problems of large cities later in their development, have also been seriously affected by the dispersion of urban activities albeit in very different ways (Olazabal and Bellet, 2019; Oueslati et al., 2015). However, even though they are predominant, for example, in Europe (Giffinger et al., 2007) and in the USA (Saeed et al., 2020), and key to achieving more cohesive and sustainable territories, they have been less studied both in sprawl studies (Abreu e Silva and Correia, 2023) and regarding the implementation of AVs (Zhang et al., 2024). As the benefits of the different AV implementation options depend on the urban and socio-economic characteristics of the various city typologies (Fraedrich et al., 2019; Makahleh et al., 2024; Richter et al., 2022; Zhang et al., 2024), the present study aims to help policymakers, especially in neglected medium-sized cities, better steer AV deployment.

Q1 The paper is structured in five sections. The second s~~S~~ection ~~2~~ reviews the literature on urban sprawl and the methods used to measure it. The third s~~S~~ection ~~3~~ explains the methodology proposed in this study. ~~Section 4~~The fourth section presents the main results obtained and carries out a scenario analysis. Finally, the last s~~S~~ection ~~5~~ contains the discussion and summarises the main conclusions of the study.

Literature review

The urban sprawl problem

Urban sprawl has been defined as a specific form of urban growth on the periphery of cities or metropolitan areas characterised by low-density, dispersed, and extensive developments through residential and economic activities and a high dependence on automobiles (Ewing et al., 2002; Ewing and Hamidi, 2017; Hasse and Lathrop 2003; Jaeger et al., 2010; López and Hynes, 2003; Squires, 2002).

In general, high levels of urban sprawl are associated with negative social, economic, and environmental effects from a sustainability perspective (Angel et al., 2005; Carruthers and Ulfarsson, 2003; EEA, 2016; Ewing, 1994; Johnson, 2001; OECD, 2018). Many of the impacts attributed to urban sprawl have been related to transport, in particular air pollution, which most authors consider to be its most important negative effect (EEA, 2016). Cars have been recognised as clear contributors to sustainability problems in urban areas. Strategies to reduce their impact have therefore focused on reducing travel demand and encouraging a modal shift towards modes of transport alternative to private cars (Stone et al., 2007; Wilson and Chakraborty, 2013).

Urban growth has always been strongly related to transport and the development of technological innovations in this field. Hence the interest in exploring the potential consequences of AVs. This type of vehicles, equipped to sense its environment and capable of driving without human intervention (Arora et al., 2013; Stead and Vaddadi, 2019), presents a technological development taking place at a very fast pace. Many real-world tests have been conducted over the past recent years (Almlöf, 2024; Shladover, 2018), but the technology has not yet been fully implemented. We are currently at a level between three and four according to SAE (2021), and full automation (SAE level 5) is expected to be implemented between 2030 and 2050 (Hörl et al., 2016; Milakis et al., 2017).

The fact that the innovations are in the process of being introduced to the market, and the lack of certainty about how the vehicles will be used, makes it difficult to determine the precise impact on urban sprawl. This impact may depend on several factors and vary according to the types of AVs, that is, autonomous public transport, autonomous car sharing, or private autonomous cars, the latter being the types of vehicles considered in this study. It is possible that the advent of AVs will lead to an increase in accessibility and travel distances that will reinforce urban sprawl processes and generate a decline in public transport and non-motorised modes (Childress et al., 2015; Emberger and Pfaffenbichler, 2020; Kim et al., 2015; Meyer et al., 2017; Soteropoulos et al., 2019). Specifically, a decrease in trip times could occur, fostered by the expected increases in infrastructure capacity with AVs, as well as the reduction in the value of trip time because of the lack of driver's attention needed by AVs. However, prioritising car sharing and opting for a more efficient automated public transport system could lead to a population rise in urban areas (Dupuis et al., 2015; Soteropoulos et al., 2019).

New accessibility conditions could generate changes in population and activity location patterns, and thus increase dispersion. These changes differ according to the socio-economic and occupational characteristics of households, the characteristics of real estate, the built environment, and the transport-to-work costs of each dwelling. Thus, considering a hypothetical long-term all-AV future, Kim et al. (2020) indicated that a considerable proportion of the population, particularly young and low-income residents, were more likely to image and prefer a change in residential location. For Llorca et al. (2022), the migration of workers from city centres to the outskirts, due to a decrease in the value of time, would be compensated by the increased attractiveness of dwellings in core cities in the absence of parking problems for autonomous vehicles. Guan et al. (2021) concluded that if citizens had an AV, 42.3% of Chinese respondents and 29.8% of US respondents would consider to move, suggesting that the advent of autonomous vehicles may lead to a new round of urban sprawl, which may be even larger in the case of China.

There is therefore previous evidence that AVs may reinforce urban sprawl, especially among certain socio-economic groups (youth and low-income) and perhaps to a greater extent in some countries than in others. This study aims to quantify whether this dispersion could occur in a medium-sized urban area by locating the settlements where it might be most pronounced through the estimation and application of a sprawl index.

Existing methods to measure sprawl

Sprawl is a complex phenomenon resulting from the confluence of multiple processes related to morphological, functional, socio-economic, and connectivity/mobility dimensions, as previously mentioned. This multidimensional character makes it difficult to analyse and evaluate, requiring the use of interdisciplinary approaches.

Among sprawl assessment methods two main families can be identified: those focused on the assessment of a single dimension of sprawl and those focused on the holistic assessment of the phenomenon. The latter also uses individual measures of various dimensions to later integrate them, usually through the creation of composite indicators.

As regards measures based on a single dimension or variable, population density was the first and most used one in sprawl studies (Galster et al., 2001; López and Hynes, 2003), due to its ease of measurement and its good representation of the phenomenon (Hamidi et al., 2015).

Among multidimensional methods, the work of Galster et al. (2001), considered eight dimensions of land use to measure dispersion: density, continuity, concentration, clustering, centrality, mixed uses, and proximity. After an extensive literature review, the authors presented a specific indicator for each of these dimensions, indicating the unit of analysis, method or tool of application, and its interpretation. Six of these measures, excluding continuity and diversity of use to focus only on residential uses, were subsequently used to assess sprawl in 13 large areas in the United States. As the last step of the assessment, they proposed an aggregation of dimensions by linearly adding the Z-scores of all indicators to obtain a composite sprawl value or indicator.

Later on, Ewing et al. (2002) developed a global compactness/sprawl index in which a more complex aggregation method than the linear sum of components was applied, representing a clear advance in integrated assessment. This study, which was applied to 83 metropolitan areas in the US, considered the use of 21 variables corresponding to 4 dimensions, that is, density, mixed uses, centrality, and connectivity. Aggregation was conducted using Principal Component Analysis. In addition, a final verification step, consisting of the comparison of the results obtained with variables related to transport, was included under the assumption that the most dispersed areas are directly dependent on private transport. This study was later revised by Hamidi et al. (2015) extending the analysis to 221 territories, substituting some variables and adding new ones related to employment density or walkability.

Randall and Baetz (2015) focused on a smaller, neighbourhood scale. In this case, the authors proposed the GIS-based Land Use Diversity Index method, based on the weighted sum aggregation of 34 variables corresponding to four dimensions – diversity of land uses, diversity of building typologies, provision of goods and services, and proximity to services. This approach is also novel and makes the method easier for professional planners to understand. This is because it focuses on obtaining an absolute measure of sprawl, where the ideal theoretical situation is modelled, and each variable is defined according to the value considered most sustainable, as a basis for comparison with the result obtained from a real situation.

In a similar vein, Gálvez et al. (2018)Ruiz et al. (2018) proposed a composite indicator to measure sprawl at an infra-municipal scale. Dimension and variable definition were achieved through an expert consultation process, after which 6 commonly used variables were obtained: population density, net residential density, building coverage ratio, types of land use, percentage of residential use, and average year of construction of the building. The creation of the composite indicator was also a novelty in this study.

As shown, both types of measures have advantages and disadvantages. On the one hand, unidimensional measures facilitate the availability of data, the simplicity of application, and the interpretation of results, but they do not correctly represent sprawl complexity. On the other hand, multidimensional ones analyse sprawl more comprehensively, allow classifying and comparing different territories, and facilitate their interpretation but may hide certain processes or patterns due to trade-offs between variables (Frenkel and Ashkenazi, 2008; Gielen et al., 2018; Luan and Fuller, 2022). The choice of a specific assessment method will therefore depend on the aim of the study. What does seem to be repeated in all studies is the use of the same basic dimensions of analysis, consisting of density, land uses, and building, with some variations in the indicators used, the selection of which is conditioned by the availability of data and the scale of analysis.

Study area and methodology proposed

Study area

The area selected to study urban sprawl corresponds to the zone of influence of the city of Santander, a European area of 281,540 inhabitants (INE, 2021), comprising nine municipalities. Santander is a medium-sized city, capital of the region of Cantabria (Spain), with 172,221 inhabitants (INE, 2021). The city has a clear zone of influence with several nuclei with a strong residential component and home-work pendular movements linked to Santander. These municipalities are Santa Cruz de Bezana, Camargo, El Astillero, and Piélagos in the western part of the Bay of Santander, and Villaescusa, Medio Cudeyo, Marina de Cudeyo, and Ribamontán al Mar in the eastern part of the Bay of Santander. The eastern municipalities also have links with the capital, but they have a stronger rural character and smaller populations (Figure 1).

Figure 1.

Study area. Red lines show the limits of the municipality of Santander and the eight surrounding municipalities.

The choice of the study area was determined by the dynamics of transformation of this territory that in recent decades have been closely related to the spread of residential settlements. This area has shown, especially since the 2000s, an important residential growth outside the city of Santander (the central city had 185,231 inhabitants in 2001, so it has lost 7% of its population). A large part of this population has moved to nearby municipalities where there has been an increase in housing supply, generally with a more dispersed urban form than in the main city. The most common modes of transport in the city of Santander in 2015 were by foot (48% of trips), by private motorised vehicle (car/motorbike/taxi, 42%), and by urban bus (9%). In the municipalities of the zone of influence, the importance of private motorised vehicles was even greater, with an average weight in the modal share of journeys to work of 63%, reaching values close to 70% in some municipalities (INE, 2011). Therefore, Santander and its zone of influence can be an effective scope for identifying and assessing policies to improve the quality of urban space based on more sustainable forms of mobility that could be applicable to many regions. In this paper, we use 'settlement', as defined in the Spanish *nomenclator* of each municipality's population register, as the unit of analysis to measure sprawl. This statistical source delimits permanently inhabited (or exceptionally uninhabited) nuclei, which are clearly differentiated morphologically and have a toponymy that identifies them. In total, the study area has 63 settlements of this type. They were graphically delimited considering the National Topographic Base at a scale of 1:100,000 (BTN100), which is available from the Spanish National Geographic Institute (*Núcleos de Población* layer) (IGN, 2015). The settlement boundaries of this layer were manually updated using the most recent orthophotography available (2020) to take into account the latest real estate developments.

It should be borne in mind that some of the settlements in the study area were originally rural. Nowadays, all of them, due to their proximity to the urban area of Santander and the increase in mobility, show a certain relationship with urban development and a significant degree of transformation. The rural nuclei of Cantabria have traditionally been characterised by a morphology based on single-family dwellings, so they somewhat resemble some characteristics of urban sprawl. This may cause the index to indicate a higher degree of sprawl for this kind of settlements, a fact that should be considered when interpreting the results.

The FUT sprawl index proposed

In order to measure the degree of sprawl of the units of analysis, we propose the FUT (Form, Use, Typology) index combining 10 indicators (Table 1). The proposed indicators, according to the results obtained by previous studies, cover three characteristics considered as clearly relevant to define the degree of sprawl: urban form, land uses present, and typology of the buildings.

Table 1.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Indicators forming part of the proposed FUT sprawl index.

Urban characteristic	Variable	Indicator	Formula	Expected effect on the FUT index
Form	Density	Gross population density	$GD_i = \frac{P_i}{A_i}$	(−)
		Net population density	$ND_i = \frac{P_i}{RA_i}$	(−)
		Gross dwelling density	$GDD_i = \frac{D_i}{A_i}$	(−)
		Net dwelling density	$NDD_i = \frac{D_i}{RA_i}$	(−)
	Irregularity	Shape indicator	$SHP_i = L_i/2\sqrt{\pi A_i}$	(+)
Use	Type of land use	Presence of at least 40% of residential land in non-collective housing	$\begin{cases} RNCA_i = \frac{1, \text{if}\left(RNC_i\right.}{A_i}\Bigg) >= 0.4 \\ RNCA_i = 0, \text{otherwise} \end{cases}$ $\begin{cases} RNCA_i = 1, \ if \ \left(\frac{RNC_i}{A_i}\right) >= 0.4 \\ RNCA_i = 0, \ \text{otherwise} \end{cases}$	(+)
		% Of residential land	$R_i = \frac{(RA_i)}{A_i} * 100$ $R_i = \left(\frac{RA_i}{A_i}\right) * 100$	(+)
	Land use diversity	Entropy of land uses	$LUE_i = -\frac{\sum(LU_{ij} \ln LU_{ij})}{\ln J}$	(−)
Typology	Construction	Average year of construction	$\overline{Y}_i = \sum y_{ik}/n$	(+)
	Height	Height of buildings	$\overline{H}_i = \sum h_{ik}/n$	(−)

P_i: Population of settlement *i*

D_i: Dwellings in settlement *i*

A_i: Area of settlement *i* (m^2)

RA_i: Residential use area of settlement *i* (m^2)

L_i: Length of the settlement's perimeter *i* (m)

RNC: Area of residential use in non-collective housing in settlement *i* (m^2)

LU_{ij}: Proportion of land use area of type *j* in settlement *i*

y_{ik}: Year of construction of building *k* of settlement i

ih_{ik}: Height of building *k* of settlement *i* (m).

To describe urban form, indicators of both population density and housing density were considered. Furthermore, gross density, considering the total land area of the settlement, was differentiated from net density, which only considered the area of actual residential use. A higher population and housing density, gross or net, can be assumed to be typically linked to a lower degree of sprawl. The urban form also incorporates an indicator of irregularity, such that settlements with a larger perimeter, with respect to the circumference, will present a higher index of irregularity and therefore a greater tendency to be areas with a typical sprawl pattern, characterised by more irregular shapes and perimeters with lines and right angles.

The land use indicators consider the presence of residential uses, in relation to total available land, and the diversity of existing uses. In this way, a lower entropy in land uses (greater homogeneity of uses) and a larger presence of residential use will imply an area with a higher FUT index, typically characterised by residential monofunctional areas.

Finally, in relation to the typology of the buildings, an indicator related to the average year of construction of the buildings in each area was included. We assumed that an older age of the buildings would be associated with areas of a lower degree of sprawl, since this type of urban form has developed mainly in recent decades (from the 1990s onwards in the case of Spain). On the other hand, building height was also considered, as taller buildings can be associated with higher urban concentrations. This indicator has been estimated using data on the number of floors per building obtained from the Spanish property cadastre and considering an average height of 3 m per floor.

The population of each unit of analysis was estimated from the population reported in the municipal population register for the year 2021 at census section level (INE, 2021), the minimum disaggregation unit in Spanish official statistics. Subsequently, the population of each census section was further disaggregated based on dwelling location, which was obtained from the Spanish land registry in the study area. This made it possible to count the dwellings and inhabitants of each settlement more accurately. Information on the year of completion of construction of the properties, used to calculate the average year of construction, was also obtained from the land registry.

We used a GIS information layer on land uses and land cover in the region (Servicio de Cartografía y SIG del Q2 Gobierno de Cantabria, 2022)~~(Servicio de Cartografía y SIG del Gobierno de Cantabria, 2022)~~ to obtain information on land uses in each settlement. This information layer combines LiDAR data sources, aerial image analysis, and real estate data to characterise the land uses and land cover present in Cantabria using the 2017–2020 period as a reference. The information on land uses included in this layer was aggregated to consider only seven types of use: j = 1 agricultural/cattle industry/forestry; j = 2 commercial; j = 3 public facilities; j = 4 extractive/industrial; j = 5 infrastructure; j = 6 residential; and j = 7 other. The information on the square metres occupied by each use in each settlement allowed the calculation of the land use entropy indicator. Residential land use was divided into two sub-types: residential with collective housing and residential with non-collective housing. The non-collective housing type of residential use is characterised by having segregated access to each dwelling, unlike collective housing, which has common access for all of them. This sub-division allowed estimating which settlements have at least 40% of their total surface area devoted to non-collective housing, a clear indicator of an increased sprawled urban form.

The 10 indicators were aggregated using Principal Component Analysis (PCA) (Table 2), to calculate the uncorrelated components that explain the common variability present in the proposed indicators. Other aggregation methods such as Factor Analysis were tested, although PCA was the one that presented the most clearly interpretable components and had the highest explanatory capacity of the total variance of the indicators.

Table 2.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Q3 **Principal Component Analysis of sprawl indicators.**

Indicator	PC1	PC2	PC3	PC4
GD	**0.96**	0.08	0.07	−0.11
ND	**0.97**	−0.06	0.02	0.05
GDD	**0.96**	0.05	0.13	−0.12
NDD	**0.97**	−0.10	0.13	0.02
SHP	−0.11	0.07	0.20	**0.91**
RNCA	−0.12	**0.96**	−0.01	0.07
R	0.09	**0.77**	0.54	−0.05
LUE	**0.68**	−0.13	−0.04	0.50
$\overline{Y}$	0.08	0.14	**0.94**	0.21
$\overline{H}$	**0.95**	−0.05	−0.07	−0.02
Interpretation	Density, typology, and diversity	Type of land use	Typology	Irregularity
Sum of squared loadings	5.13	1.59	1.26	1.16
Proportion of variance	0.51	0.16	0.13	0.12
Cumulative variance	0.51	0.67	0.80	0.92

The PCA detected the existence of four components with eigenvalues larger than one. In total, they explained 92% of the variance of the original indicators, so that almost all the information they contained was included in these four components. The first component (PC1) was interpreted as corresponding to density, building typology and urban diversity, as it had high loadings (above 0.6) on population and housing densities (gross and net), on the entropy indicator (LUE) and on average building height ($\overline{H}$). PC2 focused instead on the type of land use and, more specifically, on whether this type of land use was residential, with high loads on the RNCA (at least 40% residential land in non-collective housing) and R (percentage of residential land) indicators. PC3 also had a notable loading in R (0.54), although the indicator that explained this component was the average age of the buildings, so it was interpreted as a component that considers the typology of the construction. Finally, PC4 had only one high factor in SHP, the irregularity of the shape of the units of analysis. The components therefore captured the main characteristics considered to be associated with sprawl: urban form (PC1 and PC4), land use (PC1 and PC2), and building typology (PC1 and PC3).

As a last step, the sprawl index was obtained by combining the four extracted factors. In the case of PC1, its influence on sprawl was considered to be negative (the higher the density, average building height or diversity of uses, the lower the sprawl), while the other components had a positive influence. Each factor was weighted by the relative importance of the proportion of variance it explained. Thus PC1, density, building typology, and diversity of uses, had the highest weight (0.51), while PC2, land use type, PC3, and PC4 had 0.16, 0.13, and 0.12 weightings, respectively.

Selection of indicators

In order to carry out a correlation analysis of the factors that influence sprawl, 13 independent variables were selected (Table 3). These variables can be related to different components correlated with sprawl such as population and number of dwellings, type and available land, socio-economic factors (income and education level), accessibility, mobility, and spatial location considered.

Table 3.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Independent variables considered.

Indicator	Type	Description	Data source	Expected effect on the FUT sprawl index
LNPOP	Volume	Natural logarithm of population size	INE (2021)	-
LNDWE	Volume	Natural logarithm of number of dwellings	Spanish Land Registry	-
SLOPE	Terrain	Dummy = 1 slope >= 10%	Digital Slope Model (2012)	+
ALAND	Land	Available land for development (m^2)	Urban Development Information System of Cantabria SIUCAN (2021)	+
PCI	Socio-economic	Average household income (€)	INE (2019)	+
HEDU	Socio-economic	Number of highly educated people	INE (2011)	+
TCBD	Accessibility	Trip time to the urban centre of Santander considering congestion (min)	Calculated using GIS	+
DCOST	Accessibility	Distance to the coast (m)	Calculated using GIS	-
ACCESS	Accessibility	Accessibility type cumulative opportunities to population (5 min trip time)	Calculated using GIS	-
CAROWN	Mobility	Number of cars	Vehicle fleet DGT (2021)	+
CARUSE	Mobility	Car use for commuting to work (%)	INE (2011)	+
LOCATION1	Location	Dummy = 1 if the settlement belongs to the municipalities closest to Santander (Bezana, Camargo, or El Astillero)	Calculated using GIS	+
LOCATION2	Location	Dummy = 1 if the settlement belongs to the municipalities furthest from Santander (Piélagos, Villaescusa, Medio Cudeyo, Marina de Cudeyo, or Ribamontán al Mar)	Calculated using GIS	+

First, the natural logarithm of the population and dwellings present in each settlement were considered, both of which should be negatively associated with sprawl. We used the natural logarithm of these variables to account for the fact that this negative relationship may reach a saturation point.

In terms of terrain and land, some authors have argued that areas with higher slopes may present more sprawl, as they are more conducive to dispersed settlement in single-family dwellings (Frenkel and Ashkenazi, 2008). A larger amount of land suitable for building, according to each municipality's urban planning (SIUCAN, 2021), may also be positively associated with sprawl, as settlements with more available land to build on may be more likely to promote low-density building.

In terms of socio-economic factors, both a higher level of household income (Oueslati et al., 2015) and a higher level of education can be associated with larger single-family dwellings and available land, so they were considered to have a clear positive effect in explaining the level of sprawl of a settlement. This data was obtained from INE (2011, 2019).

Accessibility and mobility levels have also been considered as potentially relevant factors to explain sprawl levels (Abreu e Silva and Correia, 2023). Thus, a longer trip time to the main urban centre (Santander) should be associated with higher sprawl, while a shorter distance to the coast could be associated with a greater sprawl, since single-family dwellings could be preferred near coastal areas with better landscape quality. A greater accessibility to opportunities, in this case measured using a proxy variable of the amount of population reachable within 5 min, should be negatively associated with urban sprawl, as these types of low-density developments tend to imply fewer opportunities nearby. In addition, private car ownership or use (DGT, 2021; INE, 2011) should also be positively related to urban sprawl (Rubiera Morollón et al., 2016) since the lower population density of these areas usually implies a lower supply of available public transport and a greater reliance on private motorised vehicles for both mandatory and non-mandatory trips.

Finally, two location dummy variables were added, so that municipalities further away from Santander in a first ring (Santa Cruz de Bezana, Camargo, and El Astillero) or especially in a second ring (Piélagos, Villaescusa, Medio Cudeyo, Marina de Cudeyo, or Ribamontán al Mar) would present a higher level of sprawl.

In order to consider different factors that can affect the sprawl index, we defined a multiple linear regression model, well adapted to the continuous nature of this dependent variable. This aggregated model does not attempt to explain sprawl, since sprawl depends primarily on decisions made by planners, developers, households, and companies. Instead, it aims to point out certain factors with which sprawl is correlated and whose modification could be associated with the expansion of this type of urban form in the future.

Results

Sprawl index and model estimated

Q4 The FUT sprawl index of all settlements in the study area was estimated based on the methodology described ~~in section 3.2~~before. The index was obtained from the combination of the four components extracted by the PCA and was normalised with values between 0 and one to facilitate its interpretation.[1]

The distribution of the normalised index in the settlements of the study area revealed six settlements whose index was below the mean (0.73) minus one standard deviation (0.18). These settlements correspond to the most populated urban settlements in the area considered, that is, El Astillero, Santander, Maliaño, Cueto, and Peñacastillo. On the opposite side were three nuclei whose sprawl index was higher than the mean plus one standard deviation, presenting the highest degree of dispersion in the area (Table 4).

Table 4.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

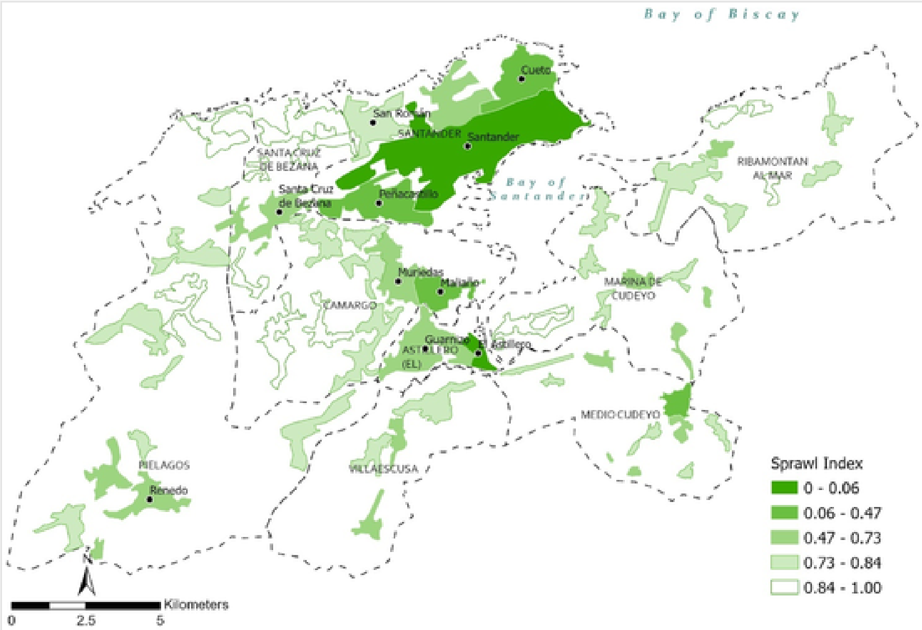
Settlements with the highest and lowest normalised sprawl indexes.

Settlement	Lower normalised FUT index	Settlement	Higher normalised FUT index
El Astillero	0.00	Maoño	0.90
Santander	0.06	Liencres	0.90

Maliaño	0.36	Camargo	0.91
Cueto	0.39	Arce	0.97
Solares	0.46	Langre	1.00

The spatial distribution of the FUT (Figure 2) shows that the most compact settlements are located on the western part of the bay, close to the city of Santander, while at an intermediate, more peripheral distance, the detected dispersion was generally higher.

Figure 2.



Distribution of the FUT sprawl index across settlements.

The regression model estimated to obtain factors correlated with sprawl (Table 5) finally presented six variables, since the presence of multicollinearity was detected among some of the 13 available indicators. Using Variance Inflation Factors (VIFs), it was observed that there were high values (above 7) for the following variables: LNPOP, LNDWE, ALAND, HEDU, CAROWN, LOCATION1, and LOCATION2. Therefore, a model of the sprawl index could be estimated with a smaller number of factors, although still covering all the types considered in Table 3: population size (LNPOP), terrain (SLOPE), socio-economic (PCI), accessibility (TCBD), mobility (CARUSE), and location (LOCATION2). The only aspect which was left out of the model was available land for development (ALAND), as it was clearly a non-significant factor. The model was estimated using R software and, more specifically, the 'stats' package and the 'car' package to calculate VIFs. Eventually, the specified model presented the following functional form:

$$FUT_i = \alpha + \beta_1 LNPOP + \beta_2 SLOPE + \beta_3 PCI + \beta_4 TCBD + \beta_5 CARUSE + \beta_6 LOCATION2 + \varepsilon_i \quad (1)$$

Table 5.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Regression model of the estimated sprawl index.

Symbol	Variable	Parameter	*t* Test	*p*-Value	*p*-Value based on robust SE	VIF
α	(Intercept)	−2.11	−2.47	0.016	0.011	-
β_1	LNPOP	−0.17	−4.01	0.000	0.001	1.39
β_2	SLOPE	−0.25	−2.08	0.042	0.020	1.18
β_3	PCI	0.00	3.94	0.000	0.000	1.26
β_4	TCBD	0.02	2.94	0.005	0.000	1.04
β_5	CARUSE	1.03	1.34	0.185	0.075	1.20
β_6	LOCATION2	0.41	2.60	0.012	0.010	1.83
R_2	0.53					
R_2 Adj	0.48					
F	10.43 (0.000)					
AIC	84.63					

Elasticities have also been calculated, using the package 'marginaleffects' to get a clearer picture of the influence of each variable on the dependent variable, the FUT index (Table 6). The estimated model presented an acceptable goodness of fit to the data ($R^2 = 0.53$, adjusted $R^2 = 0.48$). Increasing population and a higher average slope were both negatively related to sprawl. According to the elasticities, a 1% increase in the natural logarithm of population can mean a 2.8% reduction in the FUT index. Conversely, the negative effect of the slopes was opposite to what was expected, which may be due to the fact that some nuclei with a low level of dispersion, such as Santander or El Astillero, have significant average slopes.

Table 6.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Elasticities of the estimated model.

Symbol	Variable	Elasticity
β_1	LNPOP	−2.77
β_2	SLOPE	−0.70
β_3	PCI	6.72
β_4	TCBD	1.13
β_5	CARUSE	2.01
β_6	LOCATION2*	2.85

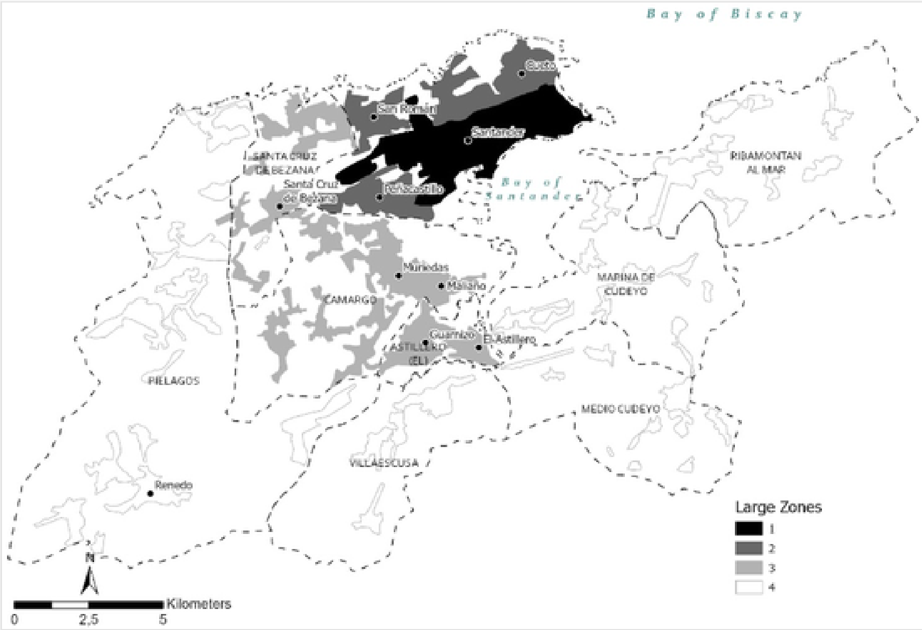
*Arc Elasticity.

Among the variables that generated a positive and significant effect on sprawl was the average income per household, given that a 1% increase in average income can cause a 6%–7% increase in the dispersion obtained. Distance from the urban centre of Santander, in terms of trip time for work purposes, and location in the most peripheral municipalities of the area also showed a clear positive correlation with dispersion. Finally, car use, although not clearly significant ($p < 0.1$), showed that a 1% increase in car use for commuting to work was associated with a 2% increase in the sprawl index. This lower significance of the CARUSE variable was closer to a p-value of 0.05 whenever standard errors were robust to heteroscedasticity (Table 5).

Scenarios considering AVs

To examine how the future implementation of AVs could affect urban sprawl, a series of estimates were made using the FUT index and the model formulated in the previous sections. These estimates were based on the construction of three scenarios, which were defined also considering the simulated results obtained in a previous study using a Land Use – Transport Interaction Model (Cordera et al., 2021). For the construction of the scenarios, we divided the study area into four main zones (Figure 3): the settlement of Santander as the centre of the urban area (Zone 1), the settlements close to Santander and within its municipality (Zone 2), the three municipalities closest to Santander (Zone 3, coinciding with dummy variable = 1 LOCATION1), and the five municipalities furthest from Santander but located within its area of influence (Zone 4, coinciding with the dummy variable = 1 LOCATION2).

Figure 3.



Main zones of the study area.

The following scenarios were constructed. The full description of changes in the variables, based on the simulated result of the previous research, can be found in Table 7:

- Scenario 1. Increase in the capacity of urban and interurban transport infrastructures: in this scenario there is an increase in the capacity of interurban and urban infrastructures resulting from AVs and their ability to reduce distances between vehicles (platooning). This scenario may have implications for reduced trip times due to reduced congestion and a slight increase in car use.

- Scenario 2. Increased capacity of urban and inter-urban transport infrastructure with induced demand: increased infrastructure capacity may make car travel more attractive and thus generate additional trips. These trips may even eliminate the reductions in trip times achieved by capacity increases resulting from a more efficient use of space by AVs.

- Scenario 3. Increased capacity of urban and interurban transport infrastructure with induced demand and increased ridership and empty trips: in addition to increased infrastructure capacity, and possible increases in the number of trips, new trips may also occur because AVs can generate empty trips and attract new users (young people, people without the ability to drive or without driving license).

Table 7.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

Proposed scenarios for the simulation of urban sprawl variation.

Zone	Scenario 1	Scenario 2	Scenario 3
Zone 1	• No change in trip times	• No change in trip times	• No change in trip times
	• 1% increase in car use	• 2% increase in car use	• 3% increase in car use
Zone 2	• 10% reduction in trip time by car	• 5% increase in trip time by car	• 40% increase in trip time by car
	• 1% increase in car use	• 2% increase in car use	• 3% increase in car use
Zone 3	• 10% reduction in trip time by car	• 5% increase in trip time by car	• 40% increase in trip time by car
	• 1% increase in car use	• 2% increase in car use	• 3% increase in car use
Zone 4	• 10% reduction in trip time by car	• 5% increase in trip time by car	• 40% increase in trip time by car
	• 1% increase in car use	• 2% increase in car use	• 3% increase in car use

The results from the model were obtained by introducing the new values of the variables, according to the proposed scenarios and zone of location of the different settlements. In addition, 100 random simulations were extracted for each settlement and in each of the scenarios from the normal distribution of the model error term. These calculations (Table 8) suggest that in scenario 1, with a reduction in car trip times due to the increased capacity of the infrastructure adapted for AVs, there could be a significant reduction in urban sprawl. This phenomenon would also occur regardless of a slight increase in car use, and the result can be interpreted according to the type of aggregate model used, in line with Alonso's (1964) monocentric model of urban economy. Thus, the reduction in trip times would imply a concentration of the study area and, therefore, the possibility of a certain densification of population and activities in the settlements due to their closer proximity to the main centre of employment and opportunities.

Table 8.

The table layout displayed in this section is not how it will appear in the final version. The representation below is solely purposed for providing corrections to the table. To view the actual presentation of the table, please click on the PDF located at the top of the page.

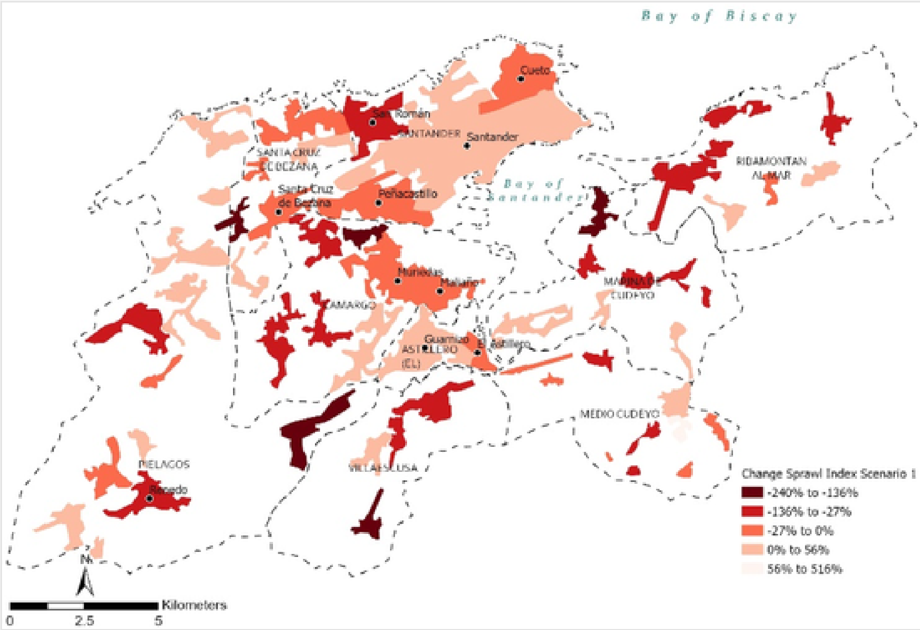
Indicators of changes in the sprawl index between the base case scenario and the proposed ones.

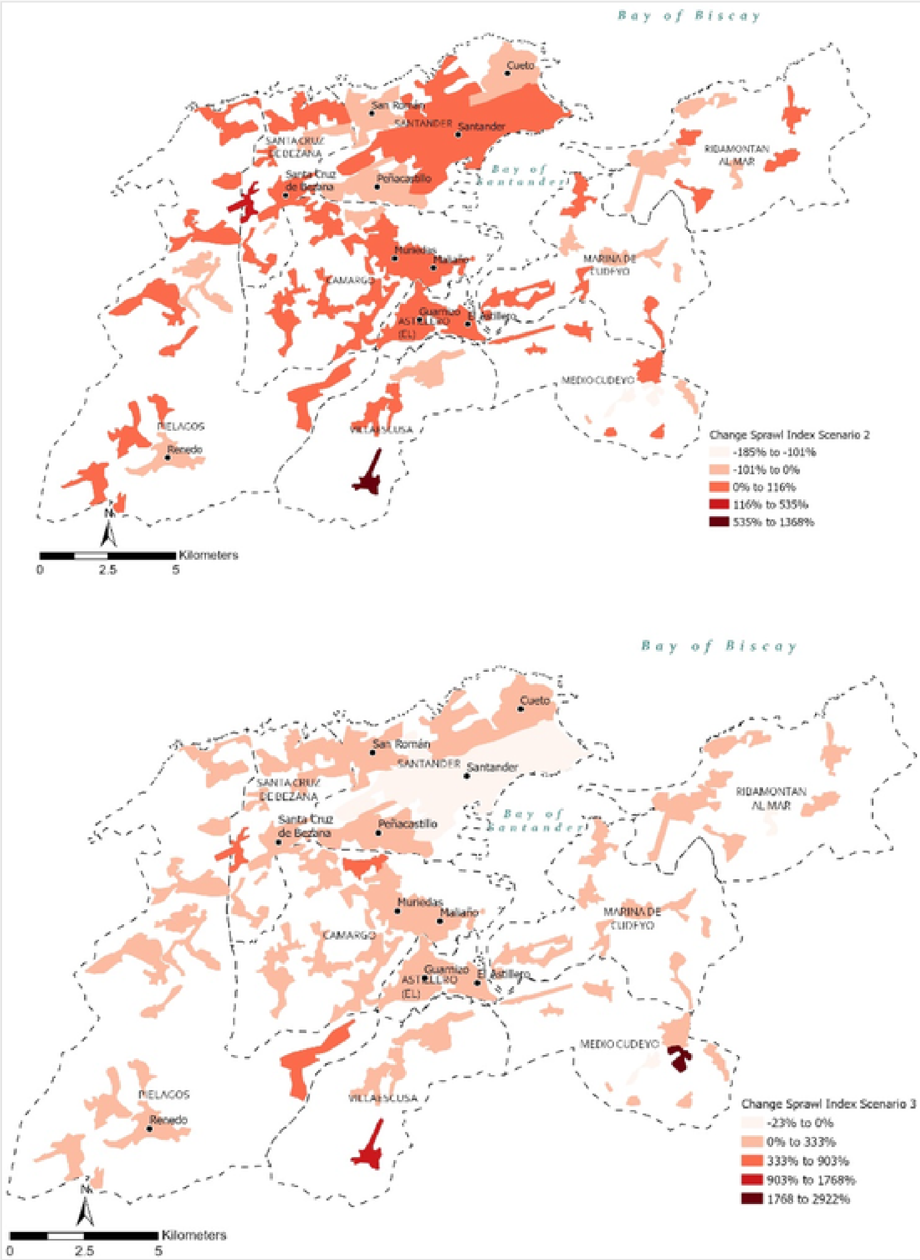
Indicator	Base	Scenario 1	Scenario 2	Scenario 3
Mean Model FUT Index	−0.01	−0.03	0.03	0.18

Std Dev FUT Index	0.63	0.63	0.63	0.65
Average % Change FUT Index Scenario/Base	0%	−17.5%	37.1%	188.0%

In scenario 2, and especially in scenario 3, the significant increase in trip times and car use, which could result from new AV trips and even empty trips, can generate a considerable increase in both urban sprawl and differences in dispersion of the index between the different centres (Std Dev. rises from 0.63 to 0.65 in Scenario 3). The spatial pattern of the proposed scenarios (Figure 4) shows that there are similarities among all of them, given the characteristics of the aggregated regression model used. In scenario 1, the settlements with a stronger reduction in the FUT index are nuclei at an intermediate distance from Santander, in the municipalities of Camargo, Piélagos, or Marina de Cudeyo. Settlements that already have a lower dispersion do not show relevant changes and may even slightly increase their dispersion, as is the case of Santander.

Figure 4.





Changes in the FUT sprawl index in the three estimated scenarios.

In scenarios 2 and 3, the spatial pattern of settlements experiencing the largest increases in dispersion was similar. The most concentrated settlements, such as Santander and settlements relatively close by, did not show large changes, while some settlements at an intermediate distance from the main urban centre showed the largest increases in dispersion. These scenarios could indicate that, if the presence of AVs in the market were to imply a greater use of vehicles in daily commuting and/or longer trip times, there could be a higher urban sprawl in some settlements. This could be due to the higher reliance on private cars for commuting. With longer trip times to the main urban centre, there would be more demand for floorspace in peripheral dwellings to balance the preference for living in more remote locations with that of households preferring to live in more central and denser settlements, as proposed by classical urban economic theory.

Discussion and conclusions

The North American model of a sprawled city has spread to Europe in recent decades (Arribas-Bel et al., 2011; Christiansen and Loftsgarden, 2011). The recent evolution of new developments in cities in Southern European countries, such as Spain, shows that although they have traditionally been much more compact and have a dense historic core, large and middle-sized cities tend to sprawl (Muñoz, 2003; Olazabal and Bellet, 2019; Rubiera Morollón et al., 2016) and there is a risk that this process will expand rapidly (European Commission, 2006).

This type of urban spatial expansion represents a major challenge for urban and transport planning to achieve sustainable urban development. Hence the concern and interest in the impact that the various innovations expected in the economic, social, and technological fields may have on the future development of cities. Among them, AVs are presented as one of the most disruptive, with ramifications in several areas, including possible impacts on urban morphology (González-González et al., 2019; Stead and Vaddadi, 2019). Thus, AVs can either encourage greater urban concentration or further incentivise the dispersion of population and economic activities, which is linked to several negative dynamics that make it difficult to achieve more sustainable development. In this research, a sprawl index, a model of sprawl, and a series of scenarios have been proposed to assess the impact of AVs on the morphology of urban areas organised by medium-sized cities.

The proposed sprawl index was calculated using various indicators combined with PCA in the urban area of Santander (Spain). The index showed how several settlements such as the city of Santander, and others nearby in the west area of Santander Bay, presented a high degree of concentration, while other more peripheral ones were clearly more dispersed. These more dispersed settlements had, in general, lower populations and housing densities, a lower entropy in land uses, and more non-collective residential uses built more recently. Some of these settlements belong to traditional rural settlements, but in general they have been altered in recent times by new dwellings intended to cover demand for second homes, tourist housing, and from the population originating in more populated settlements.

To considerer the variations in the index, a regression model was specified, which allowed estimating which variables, such as higher household income, longer trip time to the centre, higher use of private motorised vehicles to commute to work, or lower population and lower average slopes, had a positive correlation on the dispersion of settlements. These results are similar to those obtained by Frenkel and Ashkenazi (2008) for Israel, where also income, population size, and higher car dependency for mobility were relevant factors correlated with sprawl. However, these authors found that areas with higher slopes had a higher level of sprawl, while in our study the effect was the opposite. Our result was however similar to that obtained by Rubiera Morollón et al. (2016) and Olazabal and Bellet (2019), for the case of all Spanish urban areas, where slopes also had a negative relationship with sprawl. On the other hand, Frenkel and Ashkenazi (2008) also found that a greater amount of land available for building was positively correlated with sprawl, while in the present study this variable was clearly not significant, so it cannot be assumed that municipalities planning to grow are also those with a higher sprawl. Therefore, according to these variables, sprawl is likely to increase in the future if the income level of households increases. In addition, reliance on motor vehicles for daily mobility shows an association with sprawl, as does the larger extent of urban areas.

From the point of view of the impact that AVs could have on the future dispersion/concentration of settlements, the estimated model was used to test the results of three scenarios. The results obtained indicate that an increase in car use, with longer trip times due to higher car use by new groups of people who previously did not have access to this mode of transport and empty trips, could lead to an increase in urban sprawl in many settlements. This would be particularly true for some towns located at an intermediate distance from the main urban centre. Only if AVs really generate a reduction in car trip times with a moderate increase in modal split, could their implementation be linked to a higher concentration of settlements, resulting from a general concentration of the whole urban area. A phenomenon also supported by the fact that, as corroborated by previous research (Rubiera Morollón et al., 2016), a higher degree of monocentricity is associated with a reduced sprawl.

These results suggest that the development of AVs could encourage sprawl in urban areas unless the number of vehicles on the roads can be reduced to a level that does not further increase the current congestion and car dependency situations, which are particularly noticeable in suburban areas. This could be achieved through the development of shared AVs (SAVs) which, according to some estimates, could reduce the number of vehicles on the road by up to 90% (Fagnant and Kockelman, 2014; Martinez and Viegas, 2017; Soteropoulos et al., 2019).

All of these findings, in addition to informing the form of expansion typical of medium-sized cities in our geographical context, can help decision-makers determine public policies to ensure the implementation of AVs in line with sustainable growth. Future research could extend the findings of this study in a number of ways. Firstly, this methodology could be applied to other study areas, including large urban areas, to determine whether the explanatory factors for urban sprawl and the possible consequences of the presence of AVs on urban form are similar to those found in this study. Secondly, the methodology used could be refined to include temporal data in order to strengthen the results obtained.

Acknowledgements

This research has been developed within the projects 'InnovAtive Urban and Transport planning tOols for the implementation of New mObility systeMs based On aUtonomouS driving' – AUTONOMOUS (2020–2023) (PID2019-110355RB-I00) and 'Planning and design recommendations to guide new Autonomous Vehicles in Cities' – AV-Cities (2023-2026) (PID2022-140649OB-I00) funded by the Spanish Ministry of Science and Innovation (MICINN)/ERDF (EU) under the National Plans for Scientific and Technical Research and Innovation 2017-2020 and 2021-2023 respectively..

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: ~~This work was supported by the Spanish Ministry of Science and Innovation (MICINN)/ERDF (EU) in the framework of the State Plan for Scientific and Technical Research and Innovation 2017–2020 (PID2019-110355RB-I00).~~This work is based on the research projects: 'InnovAtive Urban and Transport planning tOols for the implementation of New mObility systeMs based On aUtonomouS driving' – AUTONOMOUS (2020-2023) (PID2019-110355RB-I00) and 'Planning and design recommendations to guide new Autonomous Vehicles in Cities' – AV-Cities (2023-2026) (PID2022-140649OB-I00) funded by the Spanish Ministry of Science and Innovation (MICINN)/ERDF (EU) under the National Plans for Scientific and Technical Research and Innovation 2017-2020 and 2021-2023 respectively.

ORCID iDs

Ruben Cordera https://orcid.org/0000-0001-8272-6662

Soledad Nogues https://orcid.org/0000-0002-1040-6886

Esther González-González https://orcid.org/0000-0002-5252-3247

José Luis Moura https://orcid.org/0000-0001-5645-8289

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.*

Biography

Q7 ■■■

References

The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

Abreu e Silva J and Correia M (2023) The main drivers of urban sprawl in Portuguese medium cities between 2001 and 2011. *Land Use Policy* 132: 106803. doi: 10.1016/j.landusepol.2023.106803

Almlöf E (2024) Beyond the hype: a critical look at the motivations driving automated driving systems research. *Transportation Research Interdisciplinary Perspectives* 24: 101075. doi: 10.1016/j.trip.2024.101075

Alonso W (1964) *Location and Land Use: Toward a General Theory of Land Rent*. Cambridge: Harvard University Press.

Angel S, Sheppard S, Civco DL, et al. (2005) *The Dynamics of Global Urban Expansión*. Washington, DC: World Bank, Transport and Urban Development Department.

Arora M, Kochar P and Gandhi T (2013) Autonomous driven car. *International Journal of Advances in Engineering Sciences* 3(3): 36–39.

Arribas-Bel D, Nijkamp P and Scholten H (2011) Multidimensional urban sprawl in Europe: a self-organizing map approach. *Computers, Environment and Urban Systems* 35(4): 263–275. doi: 10.1016/j.compenvurbsys.2010.10.002

Ashkrof P, Homem de Almeida Correia G, Cats O, et al. (2019) Impact of automated vehicles on travel mode preference for different trip purposes and distances. *Transportation Research Record* 2673(5): 607–616. doi: 10.1177/0361198119841032

Butler L, Yigitcanlar T and Paz A (2020) Smart urban mobility innovations: a comprehensive review and evaluation. *IEEE Access* 8: 196034–196049. doi: 10.1109/ACCESS.2020.3034596

Carruthers J and Ulfarsson G (2003) Urban sprawl and the cost of public services. *Environment and Planning B: Planning and Design* 30(4): 503–522. doi: 10.1068/b12847

Childress S, Nichols B, Charlton B, et al. (2015) Using an activity-based model to explore the potential impacts of automated vehicles. *Transportation Research Record* 2493: 99–106.

Christiansen P and Loftsgarden T (2011) Drivers behind urban sprawl in Europe. TØI report, 1136. ~~TØI report, 1136.~~https://www.toi.no/getfile.php?mmfileid=17329

Cordera R, Nogues S, Gonzalez-Gonzalez E, et al. (2021) Modeling the impacts of autonomous vehicles on land use using a LUTI model. *Sustainability* 13(4). doi: 10.3390/su13041608

DGT (2021) Parque de Vehículos a nivel municipal (Vehicle fleet at municipal level). https://sedeapl.dgt.go
Q5 b.es/WEB_IEST_CONSULTA/

Dupuis N, Cooper Martin C and Rainwater B (2015) *City of the future: technology & mobility*. Washigton: ~~Washigton~~National League of Cities.

EEA (European Environment Agency) (2016) *Urban Sprawl in Europe. Joint EEA-FOEN Report*. Luxembourg: Publication Office of the European Union.

Emberger G and Pfaffenbichler P (2020) A quantitative analysis of potential impacts of automated vehicles in Austria using a dynamic integrated land use and transport interaction model. *Transport Policy* 98: 57–67. doi: 10.1016/j.tranpol.2020.06.014

European Commission (2006) *Environmental Aspects of Urban Spread in Europe*. Brussels: Joint Research Centre.

Ewing R (1994) Characteristics, causes, and effects of sprawl: a literature review. *Environmental and Urban Issues* 21(2): 1–15.

Ewing R and Hamidi S (2017) *Costs of Sprawl*. New York: Taylor & Francis.

Ewing R, Pendall R and Chen D (2002) *Measuring Sprawl and its Impact: The Character and Consequences of Metropolitan Expansion*. Washington DC: Smart Growth America.

Fagnant DJ and Kockelman KM (2014) The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies* 40: 1–13. doi: 10.1016/j.trc.2013.12.001

Fayyaz M, González-González E and Nogués S (2022) Autonomous mobility: a potential opportunity to reclaim public spaces for people. *Sustainability* 14(3): 1568. doi: 10.3390/su14031568

Fraedrich E, Heinrichs D, Bahamonde-Birke FJ, et al. (2019) Autonomous driving, the built environment and policy implications. *Transportation Research Part A: Policy and Practice* 122: 162–172. doi: 10.1016/j.tra.2018.02.018

Frenkel A and Ashkenazi M (2008) The integrated sprawl index: measuring the urban landscape in Israel. *The Annals of Regional Science* 42(1): 99–121. doi: 10.1007/s00168-007-0137-3

Galster G, Hanson R, Ratcliffe MR, et al. (2001) Wrestling Sprawl to the ground: defining and measuring and elusive concept. *Housing Policy Debate* 12(4): 681–717. doi: 10.1080/10511482.2001.9521426

Gálvez D, Diaz P, Braçe O, et al. (2018) Developing an Index to Measure Sub-municipal Level Urban Sprawl. *Social Indicators Research* 140(3): 929–952. doi: 10.1007/s11205-017-1801-3

Gielen E, Riutort-Mayol G, Palencia-Jiménez JS, et al. (2018) An urban sprawl index based on multivariate and Bayesian factor analysis with application at the municipality level in Valencia. *Enviromental Planning B: Urban Analytics and City Science* 45(5): 888–914. doi: 10.1177/2399808317690148

Giffinger R, Fertner C, Kramar H, et al. (2007) *Smart Cities. Ranking of European Medium-Sized Cities. Final Report*. Vienna UT: Centre of Regional Science. Available at: https://www.smart-cities.eu/download/smart_cities_final_report.pdf.

González-González E, Nogués S and Stead D (2019) Automated vehicles and the city of tomorrow: a backcasting approach. *Cities* 94: 153–160. doi: 10.1016/j.cities.2019.05.034

Guan J, Zhang S, D'Ambrosio LA, et al. (2021) Potential impacts of autonomous vehicles on urban sprawl: a comparison of Chinese and US car-oriented adults. *Sustainability* 13: 7632. doi: 10.3390/su13147632

Gutierrez CI (2021) A new wave of urban sprawl: influence of autonomous vehicles on the policy toolkit and property tax revenue of local governments. *Journal of Urban Technology* 28(3–4): 155–174. doi: 10.1080/10630732.2021.1959784

Hamidi S, Ewing R, Preuss I, et al. (2015) Measuring sprawl and its impacts: an update. *Journal of Planning Education and Research* 35(1): 35–50. doi: 10.1177/0739456X14565247

Hasse JE and Lathrop RG (2003) Land resource impact indicators of urban sprawl. *Applied Geography* 23(2–3): 159–175. doi: 10.1016/j.apgeog.2003.08.002

Homem De Almeida Correia G, Looff E, Van Cranenburgh S, et al. (2019) On the impact of vehicle automation on the value of travel time while performing work and leisure activities in a car: theoretical insights and results from a stated preference survey. *Transportation Research Part A: Policy and Practice* 119: 359–382. doi: 10.1016/j.tra.2018.11.016

Hörl S, Ciari F and Axhausen KW (2016) Recent perspectives on the impact of autonomous vehicles. *Arbeitsberichte Verkehrs-und Raumplanung* 1216.

IGN (2015) *Base topográfica nacional a escala 1:100.000 (BTN100)*. Spain: National Topographic Base at a scale of 1:100.000. Instituto Geográfico Nacional.

Q6 INE (2011) *Censo de Población y Vivienda (Census of Population and Housing)*. Spain: Instituto Nacional de Estadistica.

INE (2019) *Atlas de distribución de renta de los hogares (Atlas of household income distribution)*. Spain: Instituto Nacional de Estadística.

INE (2021) *Padrón Municipal de Habitantes (Municipal Register of Inhabitants)*. Spain: Instituto Nacional de Estadistica.

Jaeger JA, Bertiller R, Schwick C, et al. (2010) Suitability criteria for measures of urban sprawl. *Ecological Indicators* 10(2): 397–406. doi: 10.1016/j.ecolind.2009.07.007

Johnson MP (2001) Environmental impacts of urban sprawl: a survey of the literature and proposed research agenda. *Environment & Planning A* 33(4): 717–735. doi: 10.1068/a3327

Kim KH, Yook DH, Ko YS, et al. (2015) *An Analysis of Expected Effects of the Autonomous Vehicles on Transport and Land Use in Korea*. New York, NY, USA: New York University.

Kim SH, Mokhtarian PL and Circella G (2020) Will autonomous vehicles change residential location and vehicle ownership? Glimpses from Georgia. *Transportation Research Part D: Transport and Environment* 82: 102291. doi: 10.1016/j.trd.2020.102291

Llorca C, Moreno A, Ammar G, et al. (2022) Impact of autonomous vehicles on household relocation: an agent-based simulation. *Cities* 126: 103692. doi: 10.1016/j.cities.2022.103692

López R and Hynes HP (2003) Sprawl in the 1990s: measurement, distribution, and trends. *Urban Affairs Review* 38(3): 325–355. doi: 10.1177/1078087402238805

Luan H and Fuller D (2022) Urban form in Canada at a small-area level: quantifying “compactness” and “sprawl” with bayesian multivariate spatial factor analysis. *Environment and Planning B: Urban Analytics and City Science* 49(4): 1300–1313. doi: 10.1177/23998083211062901

Makahleh HY, Sakamoto Ferranti EJ and Dissanayake D (2024) Assessing the role of Autonomous vehicles in urban areas: a systematic review of literature. *Future Transportation* 4: 321–348. doi: 10.3390/futuretransp4020017

Martinez LM and Viegas JM (2017) Assessing the impacts of deploying a shared self-driving urban mobility system: an agent-based model applied to the city of Lisbon, Portugal. *International Journal of Transportation Science and Technology* 6: 13–27. doi: 10.1016/j.ijtst.2017.05.005

Meyer J, Becker H, Bósch PM, et al. (2017) Autonomous vehicles: the next jump in accessibilities? *Research in Transportation Economics* 62: 80–91.

Milakis D (2019) Long-term implications of automated vehicles: an introduction. *Transport Reviews* 39(1): 1–8. doi: 10.1080/01441647.2019.1545286

Milakis D, van Arem B and van Wee B (2017) Policy and society related implications of automated driving: a review of literature and directions for future research. *Journal of Intelligent Transportation Systems* 21(4): 324–348. doi: 10.1080/15472450.2017.1291351

Muñoz F (2003) Lock living: urban sprawl in Mediterranean cities. *Cities* 20(6): 381–385. doi: 10.1016/j.cities.2003.08.003

Nogués S, González-González E and Cordera R (2020) New urban planning challenges under emerging autonomous mobility: evaluating backcasting scenarios and policies through an expert survey. *Land Use Policy* 95: 104652. doi: 10.1016/j.landusepol.2020.104652

OECD (2018) *Rethinking Urban Sprawl: Moving towards Sustainable Cities*. Paris: OECD Publishing.

Olazabal E and Bellet C (2019) De la ciudad compacta a la ciudad extensa. Procesos de urbanización recientes en áreas urbanas españolas articuladas por ciudades medias. *Anales de Geografía de la Universidad Complutense* 39(1): 149–175. doi: 10.5209/AGUC.64681

Oueslati W, Alvanides S and Garrod G (2015) Determinants of urban sprawl in European cities. *Urban Studies* 52(9): 1594–1614. doi: 10.1177/0042098015577773

Randall TA and Baetz BW (2015) A GIS-based land-use diversity index model to measure the degree of suburban sprawl. *Area* 47(4): 36–375. doi: 10.1111/area.12182

Richter MA, Hagenmaier M, Bandte O, et al. (2022) Smart cities, urban mobility and autonomous vehicles: how different cities needs different sustainable investment strategies. *Technological Forecasting and Social Change* 184: 121857. doi: 10.1016/j.techfore.2022.121857

Rubiera Morollón F, González Marroquin VM and Pérez Rivero JL (2016) Urban sprawl in Spain: differences among cities and causes. *European Planning Studies* 24(1): 207–226.

SAE-International (2021) Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles. ~~*Consejería de Obras Públicas, Ordenación del Territorio y Urbanismo*. Santander: Dirección General de Urbanismo y Ordenación del Territorio~~Society of Automotive Engineers. Available at: ~~https://www.sae.org/standards/content/j3016_202104/ServiciodeCartografíaySIGdelGobiernodeCantabria~~https://www.sae.org/standards/content/j3016_202104/.

Saeed TU, Burris MW, Labi S, et al. (2020) An empirical discourse on forecasting the use of autonomous vehicles using consumers' preferences. *Technological Forecasting and Social Change* 158: 120130. doi: 10.1016/j.techfore.2020.120130

Servicio de Cartografía y SIG del Gobierno de Cantabria (2022) Cartografía de Usos y Cobertura del Suelo de Cantabria (Cartography of Land Uses and Land Cover in Cantabria). Santander: Consejería de Obras Públicas, Ordenación del Territorio y Urbanismo. Dirección General de Urbanismo y Ordenación del Territorio.

Shladover SE (2018) Connected and automated vehicle systems: introduction and overview. *Journal of Intelligent Transportation Systems* 22(3): 190–200. doi: 10.1080/15472450.2017.1336053

SIUCAN (2021) Sistema de Información Urbanística de Cantabria (Urban Development Information System of Cantabria). https://www.territoriodecantabria.es/urbanismo/siucan

Soteropoulos A, Berger M and Ciari F (2019) Lmpacts of automated vehicles on travel behaviour and land use: an international review of modelling studies. *Transport Reviews* 39(1): 29–49. doi: 10.1080/01441647.2018.1523253

Squires GD (2002) *Urban Sprawl: Causes, Consequences and Policy Responses*. Washington, DC: Urban Institute Press.

Stead D and Vaddadi B (2019) Automated vehicles and how they may affect urban form: a review of recent scenario studies. *Cities* 92: 125–133. doi: 10.1016/j.cities.2019.03.020

Steck F, Kolarova V, Bahamonde-Birke F, et al. (2018) How autonomous driving may affect the value of travel time savings for commuting. *Transportation Research Record* 2672(46): 11–20. doi: 10.1177/0361198118757980

Stone Jr B, Mednick AC, Holloway T, et al. (2007) Is compact growth good for air quality? *Journal of the American Planning Association* 73(4): 404–418. doi: 10.1080/01944360708978521

Wilson B and Chakraborty A (2013) The environmental impacts of sprawl: emergent themes from the past decade of planning research. *Sustainability* 5(8): 3302–3327. doi: 10.3390/su5083302

Zhang Z, Liu J, Pena Bastidas J, et al. (2024) Charging infrastructure assessment for shared autonomous electric vehicles in 374 small and medium-sized urban areas: an agent-based simulation approach. *Transport Policy* 155: 58–78. doi: 10.1016/j.tranpol.2024.06.017

Notes

Text Footnotes

[1] Normalisation was carried out using the formula: $X_{normalized} = X - X_{\min}/X_{\max} - X_{\min}$.

Queries and Answers

Q1

Query: As per style section heads area unnumbered, Kindly check and update.

Answer: The references to the numered sections have been corrected.

Q2

Query: Please check and list the unlisted references "Ruiz et al (2018) and del Gobierno de Cantabria (2022)".

Answer: The reference Ruiz et al. (2018) has been corrected to Gálvez et al. (2018) and added in the references section.

The reference Servicio de Cartografía y SIG del Gobierno de Cantabria (2022) has been corrected.

Q3

Query: Bold values present in "Table 2", Kindly update.

Answer:

This footnote could be added to Table 2:

Bold values indicate loadings above 0.6

Q4

Query: As per style section heads are unnumbered, Kindly check and update.

Answer: The reference to the section has been corrected.

Q5

Query: Please provide full details for references "Christiansen and Loftsgarden (2011) and DGT (2021)".

Answer: I have included the link to the report in Christiansen and Loftsgarden (2011).

The reference DGT (2021) is a link to the statistic source.

Q6

Query: Please provide Location for references "Ewing and Hamidi (2017), IGN (2015), INE (2011), INE (2019) and INE (2021)".

Answer: The locations of the references have been added.

Q7

Query: Please provide author biography for all authors for this article.

Answer: See attached file.