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Exploring paradigm shift impacts in urban mobility: Autonomous Vehicles and Smart Cities

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Abstract

Urban mobility is a dynamic system that has had a (slow) natural evolution. Scientists and engineers are currently developing new mobility technologies. A progressive paradigm shift will change everything from the fuel type to the way of driving vehicles. Vehicles will progressively become autonomous and will communicate and cooperate with each other. In the long run, profound changes are expected in mobility as a service. Furthermore, urban areas will have a higher level of development, and cities will likely turn into Smart Cities in which the vehicles will interact with the urban infrastructure. The main objective of this paper is to explore the macroscopic effects of mobility interaction in a radial-circular urban road system for current and future cities (Smart Cities). In the literature, there is documentation of the direct effects of autonomous vehicles, but some indirect effects will cause undesirable impacts such as an increase in demand and more congestion, which change the demand behavior and the urban structure. Finally, this paper exhibits the results of direct and indirect effects calculated through analytical tools (Continuous Approximation Method). In fact, our research shows that if demand increases by about 50%, the current scenario could have the same total cost as the future scenario with autonomous vehicles. Moreover, if the city radius increases by about 33% and the subjective value of time decreases about 20%, the benefits of the autonomous cars will be compensated. Therefore, the paper proves that autonomous vehicles could encourage the urban sprawl in the long run. Finally, Administrations should define transport strategies and policies to control these externalities, because autonomous driving could deteriorate mobility even worse than it is now.

Keywords: urban road network; autonomous car; continuous approximation

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1. Introduction

In the 1960s, the renowned English engineer Colin Buchanan had already pointed out that traffic congestion was one of the most significant problems in cities nowadays (Buchanan, 1963). Administrations have traditionally applied several strategies to control it. Recently, the implementation and the effects of new technologies are being discussed, particularly the autonomous vehicles. Autonomous vehicles will come to our cities in the coming years. Some experts estimate that it will be during the next decade, while others are not so optimistic. One thing is for sure; there would be a transition period in which two types of vehicles will coexist, manual (MVs) and autonomous vehicles (AVs) with different levels of automatization (NHTSA, 2016).

Urban mobility has had a slow, natural evolution. The next challenge to face is a technological jump; it brings together a change of paradigm in urban mobility, which makes it necessary to evaluate it and get used to it, at the same time our cities and infrastructures do. The primary objective of the research is to assess AV implementation and their possible macroscopic impacts on decongestion and efficiency of an urban network and potential benefits for society. The research has two stages. The first one is a conceptual revision of AV implementation effects, while in the second stage a mathematical model is developed to assess the impact of those effects. For this, the Continuous Approximation Method (CA) allows for modeling a continuous and two-dimensional space through a circular-radial network to explore and compare results between a base scenario with only MVs and a future scenario (Smart Cities) with AVs provided with total automatization.

The next section shows a conceptual and systematic analysis of AVs. The following section explains the mathematical model developed. In the fourth section, the model allows assessing the two urban scenarios mentioned. Finally, the last section discusses the main conclusions of the paper.

2. AV direct and indirect effects

AVs (and vehicles communicated among them, V2V) will generate positive changes in transportation and mobility (e.g. Childress et al., 2015; Kockelman, 2017; Kohli and Willumsen, 2016), but it also will produce non-desirable effects. Bahamonde-Birke et al. (2016) gather the AV impacts in effects of the first and second-order.

2.1. Direct effects

AV direct effects (or first-order) directly impact on one attribute of the transportation system. Five items contain the direct impacts that researchers have widely discussed in the literature:

- The automatization of the driving process (AVs) will reduce the generalized travel costs.
- The operation of taxis and public transportation will be more efficient and flexible than MVs.
- AVs will allow increasing the urban road capacity due to platoon formations in urban roads.
- Reduction of pollution.
- Improvement of road safety.

2.2. Indirect effects

AV indirect effects, called as second-order or systemic in Bahamonde-Birke et al. (2016), will lead to changes in demand behavior, demand volume, new requirements in infrastructure in the long run, and in some cases, undesirable effects will be caused (Smith, 2012):

- AVs will reduce the value of travel time (VTTS) due to the reduction of the driving disutility.
- New users (minors, the elderly, disabled people, and induced demand) could use AVs (Smith, 2012).
- AVs will produce an increment of induced demand due to the reduction in congestion, the value of time and travel times will cause an increase in the trip generation (induced demand).
- AVs will increase vehicle-kilometer traveled (VKT) due to trips without users and others (Smith, 2012).

- The reduction of costs, congestion levels and the value of travel time will generate longer trips than at this time. These effects will produce changes on the trip generation, attraction, and distribution matrix.
- The changes in trip distribution will cause changes in the urban structure and the activity system in the long run due to more disperse cities (urban sprawl), changes in place of residence and employment (Smith, 2012).

3. Analytical model to analyze AV effects

3.1. Continuous Approximation Method (CA)

The methodological focus of this work is in a two-dimensional and continuous analysis; therefore, it was appropriate to use the CA Method. If we have no accurate information, CA will be valid (Newell, 1973). CA resolves a problem based on local costs which have a density structure (Daganzo, 2005). CA has several applications in transportation and logistics. For instance, Pilachowski (2009) optimizes the bus bunching process. Medina-Tapia et al. (2013) simultaneously optimize the location of bus stops and the headways (operation). Pulido et al. (2015) locates warehouses and designs distribution strategies for a freight system with time windows.

3.2. Proposed model

The following table describes the parameters used to assess two mobility scenarios: the current case with only MVs (the driver without passengers), and the future case with only AVs with Level 5 of automation.

Nomenclature

$d_c(r)$	distance function between circular roads at the radius r km [km/street]
$d_r(r,\theta)$	distance function between radial roads at a city point (r,θ) [km/street]
$\Phi(\theta)$	angle function between radial roads at a city point with angle θ [radian/street]
T	duration of period [h]
μ	value of travel time [$/h]
v_f	car speed to access main roads of the city [km/h]
v_c	free-flow car speed on main road [km/h]
v_p	cruising speed looking for a parking spot [km/h]
v_a	average walking speed for accessing to the destination point from parking site [km/h]
a and b	parameters of BPR volume-delay function [dimensionless]
c	congestion parameter that represents the effect of cars looking for a parking spot [dimensionless]
k_V	capacity road per lane [veh/lane·h]
τ_V	average time spent by a vehicle when crosses a crossroad [h/street]
λ_P	mean density of vacant parking space [parking/km]
d_p	distance before arriving at the destination where the drivers begin to look for a parking spot [km]
d_s	distance (width) of influence between the main road and the destination point [km]
φ^t	car cost per distance unit [$/km]
φ^p	parking fee [$/veh·h]

A circular city with radius R km and circular-radial road system is assumed. The demand density function $P(r_f,\theta_f,r_t,\theta_t)$ in polar coordinates represents the density of car trips from an area $dr_f\, r_f\, d\theta_f$ about the origin (r_f,θ_f) to an area $dr_t\, r_t\, d\theta_t$ at a destination (r_t,θ_t) (Vaughan, 1986). In Equation 1, Δ represents the total trips in the city.

$$\Delta = \int_0^{2\pi}\int_0^{R}\int_0^{2\pi}\int_0^{R} P\left(r_f,\theta_f,r_t,\theta_t\right)\, r_t\, dr_t\, d\theta_t\, r_f\, dr_f\, d\theta_f \tag{1}$$

Car users choose the shortest route (minimum distance) between two points. Therefore, there are three private mobility patterns: radial-circular, circular-radial, and radial-radial trips (Medina-Tapia and Robusté, 2018).

3.3. User costs

The model only includes private transportation costs. The total cost of car users (C_C^u) is the addition of three sub-costs: accessibility cost to main roads (C_F), regular car trip cost (C_V), and cost for arriving at the destination (C_A).

3.3.1. Accessibility cost to main roads

In this section, we have calculated the cost expended when users drive from the origin (household or place of residence) to the nearest main road. The demand function ($[veh/km^2 \cdot h]$) represents the vehicle density that accesses to the main road on circular ($f_F^c(r,\theta)$) and radial road corridors ($f_F^r(r,\theta)$) (Medina-Tapia and Robusté, 2018).

Average cost ($[\$/veh]$) for accessing to circular ($c_F^c(r)$) and radial road ($c_F^r(r,\theta)$) (Eq. 2) depends on the distance between the origin and the main street ($d_c(r)/4$ or $d_r(r,\theta)/4$), and the generalized cost per kilometer (Ψ^F). This generalized cost has two components: travel cost at a speed v_f, and monetary cost of operation (φ^t).

$$c_F^k(r)=\begin{cases}\dfrac{d_c(r)\cdot\Psi^F}{4}=\dfrac{d_c(r)}{4}\cdot\left(\dfrac{\mu}{v_f}+\varphi^t\right) & k=c:circular\\ \dfrac{r\cdot\Phi(\theta)\cdot\Psi^F}{4}=\dfrac{d_r(r,\theta)}{4}\cdot\left(\dfrac{\mu}{v_f}+\varphi^t\right) & k=r:radial\end{cases} \tag{2}$$

AVs should impact on local cost function in two aspects:

- Reduction of generalized cost (Ψ^F): the speed (v_f) should increase, and the operation cost (φ^t) should decrease.
- Reduction of the value of travel time (μ): the AVs will allow that users do other activities during the trip.

Finally, the total cost of accessibility (C_F in [\$]) is the integration of local cost function (demand density, period, and the average cost of accessibility) on the urban area (Eq. 3).

$$C_F=\int_0^{2\pi}\int_0^{R}\frac{1}{4}\cdot\left(f_F^c(r,\theta)\cdot T\cdot d_c(r)+f_F^r(r,\theta)\cdot T\cdot r\cdot\Phi(\theta)\right)\cdot\Psi^F\, r\,dr\,d\theta \tag{3}$$

3.3.2. Regular trip cost

Vehicle flow density function ($[veh/km \cdot h]$) at a point has different formulations for circular ($f_V^c(r,\theta)$) and radial road corridors ($f_V^r(r,\theta)$) (Medina-Tapia and Robusté, 2018).

Local generalized travel costs ($[\$/km \cdot veh]$) has three components (Eq. 4). Firstly, we model the travel cost through a BPR function (Bureau of Public Roads). The free-flow travel cost per kilometer (μ/v_c, $[\$/km]$) is multiplied by the congestion factor. This factor depends on the car flow: regular travel flow ($F_V^c(r,\theta)=f_V^c(r,\theta)\cdot d_c(r)$ or $F_V^r(r,\theta)=f_V^r(r,\theta)\cdot d_r(r,\theta)$), and cruising flow for parking ($F_P^c(r,\theta)$ or $F_P^r(r,\theta)$). The car flow also depends on the road capacity ($K_V^c(r,\theta)$ or $K_V^r(r,\theta)$). Secondly, the function contains a component for crossing regulated crossroads, and it is defined as a ratio between time spent by crossing a road intersection and road density ($1/d_c(r)$ or $1/d_r(r,\theta)$). Finally, the function contains a monetary component of operation travel cost (φ^t).

$$c_V^k(r)=\begin{cases}\dfrac{\mu}{v_c}\cdot\left(1+a\cdot\left(\dfrac{F_V^c(r,\theta)+c\cdot F_P^c(r,\theta)}{K_V^c(r,\theta)}\right)^b\right)+\dfrac{\mu\cdot\tau_V}{r\cdot\Phi(\theta)}+\varphi^t & k=c:circular\\ \dfrac{\mu}{v_c}\cdot\left(1+a\cdot\left(\dfrac{F_V^r(r,\theta)+c\cdot F_P^r(r,\theta)}{K_V^r(r,\theta)}\right)^b\right)+\dfrac{\mu\cdot\tau_V}{d_c(r)}+\varphi^t & k=r:radial\end{cases} \tag{4}$$

AVs should impact on local generalized travel cost function in seven aspects:

- Reduction of the value of travel time (μ).
- Speed increase due to an efficient driving (v_c).
- Increment of vehicles that are looking for a parking spot ($F_P^c(r,\theta), F_P^r(r,\theta)$) due to "ghost trips" (empty cars) to the origin point.
- Reduction of congestion impacts due to AVs will have perfect information of the parking location ($c = 1$).
- Road capacity increase due to platoons, less headway, and others ($K_V^c(r,\theta)$ and $K_V^r(r,\theta)$).
- Reduction of time for crossing intersections (τ_V) due to platoons, traffic lights coordination, less reaction time, communication V2I, and others (Smart City).
- Reduction of car operational cost due to efficient driving (φ^t).

About demand functions of users that look for a parking spot, there are two types of functions (Medina-Tapia and Robusté, 2018). AVs will not have to look for a parking space before the destination ($d_p = 0$) because the vehicles will directly arrive at the destination and, after that, they will go to a parking spot without users (Medina-Tapia and Robusté, 2018). In the modeling, we have assumed that drivers neither can stop and wait for a parking site, nor they can come back upstream (Arnott and Rowse, 1999).

Finally, the total travel cost in the urban system (C_V in [\$]) is the double integral of local cost function on circular city area which includes the demand density, duration of the period, and local generalized travel cost (Eq. 5).

$$C_V = \int_0^{2\pi}\int_0^{R}\left(f_V^c(r,\theta)\cdot T\cdot c_V^c(r) + f_V^r(r,\theta)\cdot T\cdot c_V^r(r,\theta)\right) r\,dr\,d\theta \tag{5}$$

3.3.3. Arriving cost to the destination

The density of users ($[veh/km^2\cdot h]$) that arrive at a circular ($f_A^c(r,\theta)$) or a radial road ($f_A^r(r,\theta)$) is calculated (Medina-Tapia and Robusté, 2018).

Average cost function per vehicle at the destination has four elements (Eq. 6). Firstly, the cost of driving by secondary roads from a main road to the destination, and without cruising for a parking spot ($(d_c(r) - d_p)/4$) multiplied by generalized cost ($\Psi^F = \mu/v_f + \varphi^t$). Secondly, the cost of cruising for a parking site depends on the average distance where there is a vacant parking ($1/\lambda_P$) and the generalized cost ($\Psi^P = \mu/v_p + \varphi^t$). Thirdly, the walking cost from the parking site to the destination point depends on the expected walking distance that is multiplied by the generalized cost ($\Psi^A = \mu/v_a$). Arnott and Rowse (1999) determined the expected walking distance from parking ($(2\cdot e^{-\lambda_P\cdot d_p})/\lambda_P + d_p - 1/\lambda_P$); if a driver parks before destination point ($x < d$), he will step $d - x$ km; in another case, the driver will walk $x - d$ km. Finally, the last component is the car parking fee (φ^p).

$$c_A^k(r) = \begin{cases} \left(\dfrac{d_c(r)-d_p}{4}\right)\cdot\Psi^F + \dfrac{1}{\lambda_P}\cdot\Psi^P + \left(\dfrac{2\cdot e^{-\lambda_P\cdot d_p}}{\lambda_P} + d_p - \dfrac{1}{\lambda_P}\right)\cdot\Psi^A + \varphi^p & k = c : circular \\ \left(\dfrac{r\cdot\Phi(\theta)-d_p}{4}\right)\cdot\Psi^F + \dfrac{1}{\lambda_P}\cdot\Psi^P + \left(\dfrac{2\cdot e^{-\lambda_P\cdot d_p}}{\lambda_P} + d_p - \dfrac{1}{\lambda_P}\right)\cdot\Psi^A + \varphi^p & k = r : radial \end{cases} \tag{6}$$

In case of AVs, these vehicles should impact on local cost function in three aspects:

- Drivers in a Smart City will get out of the car neither before the destination nor after it ($d_p = 0$).
- The generalized cost of AVs will decrease (Ψ^F and Ψ^P), and the component μ/v_p is null in the generalized cost Ψ^P.
- The component ($(2\cdot e^{-\lambda_P\cdot d_p})/\lambda_P + d_p - 1/\lambda_P$) is null because they do not have to walk from the parking spot.

The total cost of cruising for parking, parking on the spot, and walking to the destination (C_A) is obtained (Eq. 7) through the integration of the demand in rush hour and the average cost per vehicle at the destination.

$$C_A = \int_0^{2\pi}\int_0^{R}\left(f_A^c(r,\theta)\cdot T\cdot c_A^c(r) + f_A^r(r,\theta)\cdot T\cdot c_A^r(r,\theta)\right) r\,dr\,d\theta \quad (7)$$

4. Quantitative estimation of AV effects

We model a circular city with five zones: a Central Business District (CBD) and four external zones. The radius of the city is 15 km (R), and the CBD has a radius of about 6.7 km ($R_c = R/\sqrt{5}$). The city has 500,000 car users of MVs distributed homogeneously (Medina-Tapia and Robusté, 2018).

Table 1. Parameters in each analyzed scenarios.

Parameters		Manual vehicle Case	Autonomous vehicle Case	Parameters		Manual vehicle Case	Autonomous vehicle Case
$d_c(r)$	[km/street]	1.0	1.0	a		2	2
$\Phi(\theta)$	[radian/street]	0.12	0.12	b		3	3
T	[h]	1.5	1.5	c		3	1
μ	[$/hr]	10	[5…10]	k_V	[veh/lane·h]	1,272	3,960
v_f	[km/h]	20	20	τ_V	[h/veh·street]	0.0125	0.0125·70%
v_c	[km/h]	45	50	λ_P	[parking/km]	5	5
v_p	[km/h]	10	10	d_s	[km]	0.2	0.2
v_a	[km/h]	3	3	φ^t	[$/km]	0.1	0.1·70%
d_p	[km]	0.2	0.0	φ^p	[$/veh·h]	1	1

In the current scenario (MVs), the road capacity is 1,272 per lane (k_V). In a future scenario (AVs), the road capacity will be 3,960 (k_V); it is three times bigger than the current scenario (Lioris et al., 2017).

4.1. Influence of AV implementation

4.1.1. Influence of direct effects

In the discussion previously made about AV impacts on urban mobility, we presented five direct effects, but three of them we have analyzed in this paper.

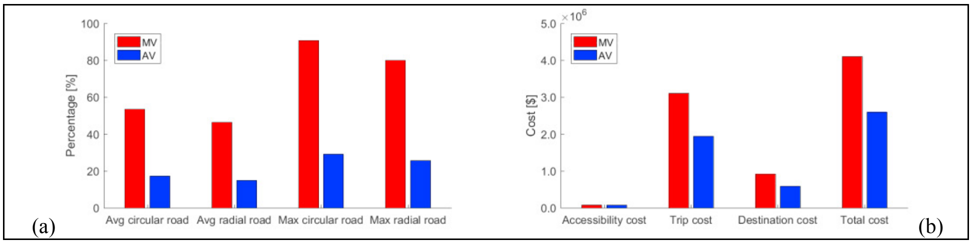

Fig. 1. Impacts of direct effects: (a) MV and AV saturation percentage; (b) Travel stage cost of MVs and AVs

- Congestion reduction. If the driving of AVs is more efficient than MVs, the road capacity per lane will increase, and the congestion will decrease (Fig. 1(a)).
- Travel cost reduction. If VTTS take the same value of the base scenario ($\mu = 10$ [$/h]), the total cost will decrease 33.7%, but the travel cost reduction will be more significant, 37.1% (Fig. 1(b)). The accessibility cost also decreases in a lower percentage than other trip stages (5%).
- Parking cost reduction. Costs of looking for parking in the AV scenario also decrease notoriously regarding the MV case (28.8%), because AVs look for parking without passengers; hence there are only operational costs.

4.1.2. Influence of indirect effects

In a complementary way to the previous point, AVs also cause indirect effects on the urban transport system; positive results of direct effects are compensated for indirect effects (Bahamonde-Birke et al., 2016).

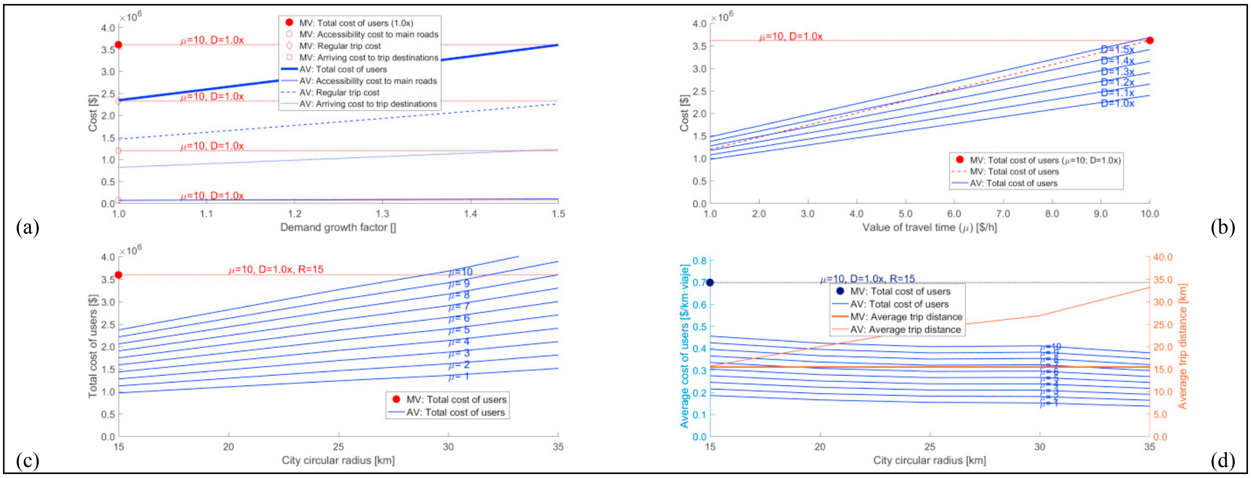

Fig. 2. Impact of demand increment and urban structure (a) Impact of demand increment on the total cost in each travel stage; (b) Impact of variation in the value of travel time and demand increment on the system total costs; (c) Effect of the urban radius on the total cost of users; (d) Effect of the urban radius and the average travel distance on the average cost of users.

- VTTS reduction. Kohli and Willumsen (2016) have pointed the VTTS could decrease 20% in the AV scenario; hence, if $\mu = 8$ in our model, the total cost is reduced in 40.6% and the travel cost in 46.6%. There is a trade-off between longer trips without drivers (AVs), and an increment of walking time (MVs).
- VKT increment. After the user arrives at the destination, AVs will look for a parking spot without passengers, and the Smart City (V2I) will assign the nearest free spot. Our model indicates AVs will travel 66,722.9 km more than the MVs, because these cars begin to look for parking before the destination (d_p).
- Travel distribution pattern changes. If value of travel time and congestion decrease, new users will use AVs. According to the model (Fig. 2(a)), a significant increment of demand density could compensate for the reduction of costs by direct effects. Figure 2(b) simultaneously shows the value of travel time and the increment of the demand on the total cost with AVs (blue lines) in comparison to the total cost using MVs (red symbol and lines).
- Travel distribution and urban structure changes. City size affects the length of trips and, therefore the total cost of the system. Figure 2(c) shows that the total cost will increase if the urban radius also increases, but this value will be similar to the cost of the base scenario (MVs) at the radius about 35 km with $\mu = 8$ [$/h]. It could be inferred that the city size effects are more significant on the total cost value than the effects of the induced demand. In Figure 2(d), the average user cost per kilometer will slightly decrease if the urban radius increases and average costs of AVs are smaller than the costs of the base scenario (blue point). In other words, if the generalized costs are smaller included the value of time, the trips will tend to be longer, and the users will change the destination. This reduction will cause urban problems, and the urban structure could also change in the long term; in other words, these problems are early phases of profound urban problems as spatial segregation and urban sprawl.

5. Conclusions

The paradigm shift in urban mobility is a broad and dynamic concept in which AVs play a relevant role. They present direct and indirect effects. Our results show that the direct effects will be positive for the urban system. However, the indirect effects will change the equilibrium between transport supply and demand, with externalities reaching far beyond the private transport system, as it also influences the urban structure and the urban activity system. According to our results, the effect of system user costs due to urban growth is more significant than the increment of users by induced demand. These impacts will deteriorate the current negative externalities that already encourage private transportation (vicious circle of public transportation). Moreover, a city with only AVs and without other complementary modes (private, public, and shared transportation) is unsustainable in the long run.

The proposed model is considered as a contribution to the analysis of AVs' impacts on urban structure, but it also allows the analysis of a broad spectrum of scenarios, possibilities, measures, or strategies to improve the urban transport system and strategic-level infrastructures of real cities. Therefore, according to our results, if Administrations do not implement regulatory measures and urban planning, the urban problems will be multiplied twice or three times in comparison to the current state. Urban planners and transport engineers should design policies and actions that anticipate problems of the AV implementation in mainly four aspects. Firstly, the governments should design transport demand policies such as incentives or restrictions on private and public transportation. Secondly, they should design types of transport system such as private or sharing AVs, and the complementarity with others freight and passenger transportation systems. Thirdly, urban infrastructure should adapt to new systems or a complete urban redesign. Finally, urban policies should be designed in accordance with the type of urban development—dense or dispersed cities—and the size and form of cities. This last point is the least studied and, at the same time, a key factor for the correct functioning of a new transport system.

New technologies such as AVs, Smart Cities, and MaaS will be implemented neither in the short run nor simultaneously. Instead, there will be a transitional period in which AVs and MVs will share the streets. For this reason, our analysis and modeling in future works will deepen in alternative scenarios such as non-homogeneous demand multi-modes (private, public, and freight transportation); different type of roads; the mobility as a service (MaaS); and finally, the optimization of the system.

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