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Autonomous vehicles, parking, and urban spatial structure

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Abstract

This paper provides a theoretical analysis of the effects of autonomous vehicles (AVs) on the spatial structures of future cities. We consider two types of AVs, private AVs (PAVs) and shared AVs (SAVs). We assume that AVs have a lower marginal travel cost than human-driven traditional vehicles (TVs) due to additional utility caused by free activities in AVs, and PAVs have a lower marginal travel cost than SAVs due to better privacy and comfort. The land that SAVs release due to exemption of parking land is used for firm production and household residential uses. We also assume that the type of housing is regulated and designed by the government, and households rent houses from the government. Two urban spatial models, one for TVs and the other for PAVs / SAVs, accounting for the competition for land among firm production, household residence, and parking, are presented and compared. The government aims to determine the optimal housing sizes to maximize the social welfare of the city system. The finding shows that after introducing AVs, the city size may expand or shrink, depending on the marginal travel costs of AVs and the SAV market share in the AV market. The firm production rises for a full SAV city. Household utility and social welfare may increase or decrease, depending on the maturity level of AV technologies.

Keywords: Private autonomous vehicles; shared autonomous vehicles; parking; urban spatial model; fixed cost; marginal travel cost.

JEL classification: R13, R14, R48, R52

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1. Introduction

It has been widely recognized that autos play an important role in shaping the cities. In the past decades, rapid progress in auto technologies, particularly autonomous vehicle technologies, significantly promotes the urban developments. Autonomous taxis (robotaxis) and autonomous buses are currently being deployed and tested in some cities around the world. For instance, in August 2023, Waymo and Cruise were authorized to operate their paid robotaxi services in San Francisco, US.[1] Baidu company's newly launched robotaxi, called "Apollo Go", has over 600 robotaxis operating in Wuhan China from 6 am to 2 am the next day, and the number will be increased to over 1000 robotaxis by the end of 2024.[2] Navya, a French company, is currently deploying autonomous shuttle buses in Paris to solve the first- and last-mile problems.[3] As autonomous technologies continue to mature, autonomous vehicles (AVs) are becoming part of the mobility landscape, and will possibly replace human-driven traditional vehicles (TVs) as a main mode of urban transportation in the future. Naturally, this raises one important and intriguing issue: How will AVs reshape the urban spatial structure? This paper will address this issue.

The emergence of AVs can bring significant changes to the transportation industry and people's lifestyle. On one hand, compared to TVs, AVs can drive themselves automatically without need for drivers, and thus vehicle users can carry out various activities freely in the vehicles, such as eating, sleeping, or meeting. The in-vehicle activities can incur extra utility to vehicle users and thus reduce their aversions to staying in the vehicles for a long time (Pudāne, 2020; Wu and Li, 2023). AVs are also likely to reduce commuters' parking cursing time because they could find a parking space automatically. On the other hand, with the development of shared mobility services, people can get shared AVs (SAVs) conveniently via APP installed in cellphone, anytime, anywhere. SAVs can run on the road through the daytime and park outside the city in the nighttime, and thus do not need parking land within the city or at least the number of parking spaces required is reduced (Zhang, 2017; Larson and Zhao, 2020). The land freed up can be used for other purposes, such as firm production and household residence. It was reported that on average, 20% of land in the US city centers is dedicated to parking, and even 30% in some

[1] https://en.wikipedia.org/wiki/Robotaxi.
[2] https://www.baiguan.news/p/baidu-apollo-go-robotaxi-wuhan-launch.
[3] https://www.navya.tech/en.

cities, e.g., 39% for Arlington Texas, and 33% for Las Vegas.[4] Therefore, it is plausible that AVs will reshape spatial structures of future cities. This paper aims to provide a theoretical analysis of the AV effects on the urban spatial structure, household utility, firm production, and social welfare of future cities. For simplicity of analysis, this paper focuses on the case of traffic congestion-free and surface parking.[5]

We begin by establishing a benchmark urban model that takes into account the competition for land among firm production, TV household residence and parking, and the behavior of the government. In this model, we assume that the type of housing in this city is regulated and designed by the government due to technological restriction on housing production, and households rent houses from the government. We consider a linear monocentric city corridor, in which all import / export good trades occur at the city center. Firms use land and labor to produce goods, households choose residential location and worksite with parking land demand, and the land of the city is allocated to the highest bidder among households and/or firms. Firms prefer to locate near the central business district (CBD) due to its approach to the trade market, whereas households prefer to locate near the workplace due to low commuting cost. Using the benchmark urban model, the border between industrial (or employment) area and residential area and their respective size are determined endogenously, together with the wage and land rent gradients. From the government's perspective, the optimal housing size is determined to maximize the social welfare of the city system.

These are significant extensions to the classical Alonso-type urban models (Alonso, 1964), in which the wage is exogenously given, and the employment or industrial area is treated as a single point without area such that the change of land use in the industrial area and the interrelationship between the land uses of the industrial and residential areas cannot be analyzed. In this regard, Ogawa and Fujita (1980) and Fujita and Ogawa (1982) made a pioneering contribution. They have been extended to general equilibrium models (Lucas and Rossi-Hansberg, 2002; Berliant et al., 2002; Malykhin and Ushchev, 2018; Mossay et al., 2020), which have subsequently led to the development of quantitative urban models (e.g., Ahlfeldt et al.,

[4] https://bigthink.com/strange-maps/parking-lots-eat-american-cities.

[5] The assumption of surface parking has been adopted in some previous studies about parking land use, such as Zakharenko (2016), Franco (2017), and Brueckner and Franco (2018). For land use modeling of other parking facility types, like underground parking and structural parking (i.e., multi-storey car park), please refer to Brueckner and Franco (2017).

2015; Redding and Rossi-Hansberg, 2017; Allen and Arkolakis, 2022). However, these studies did not consider the parking land use and the AV role in reshaping urban spatial structure. Moreover, they assumed that household housing size was exogenously given, but not endogenously determined by the model, and thus the household utility achieved is not maximized. We extend their work to address the issues of the TV / AV parking land use and the optimal housing size.

In order to reveal the AV effects, we then extend the benchmark urban model to account for the behavior of firms and AV households. Two types of AVs, private AVs (PAVs) and shared AVs (SAVs), are considered. For simplicity of analysis, we assume that SAVs do not need to occupy parking land, and the land released by SAVs is used for firm production and household residential uses. Each PAV, like a TV, needs a parking space at the industrial area for daytime parking and a parking space at the residential area for nighttime parking.[6] Compared to TVs, AVs have a lower marginal travel cost due to additional utility caused by free activities in AVs. Moreover, the marginal travel cost of PAVs is lower than that of SAVs due to its better privacy and comfort. Two extreme cases of full PAVs and full SAVs in the urban system are discussed in detail. With the assumption that housing type is regulated and designed by the government, the optimal housing sizes that maximize the social welfare is determined. We find that after introducing AVs, the housing size of PAV households increases, whereas the housing size of SAV households may increase or decrease. The size of the industrial area becomes smaller due to the decreased demand for parking land with SAVs. As a result, the city size may expand or shrink, depending on the marginal travel costs of AVs and the SAV market share in the AV market. We have analytically derived the critical condition for city expansion or contraction. Our result is comparable to the previous studies, such as Zakharenko (2016), Larson and Zhao (2020), and Zhong and Li (2023). All of them adopted a numerical simulation method due to analytical intractability, and showed that after introducing AVs, the city would expand. In addition, we find that after introducing AVs, the household utility and social welfare may increase or decrease, relying on the AV fixed cost, marginal travel cost, and SAV market share. The firm production increases for a full SAV city. We also discuss the AV regulation issue, and determine the optimal SAV market share in terms of social welfare.

[6] It should be pointed out that PAVs may be able to find a parking space automatically with AV techniques, e.g., return automatically to the parking space at residential location. This case will reduce the land for parking, but increase the travel cost. This is left for a further study.

The remainder of this paper is organized as follows. In the next section, related literature is reviewed. In Section 3, a benchmark urban model with TV households is presented to endogenously determine the sizes of household residential area and firm production area with parking consideration. The optimal housing size that maximizes the social welfare is also determined. Section 4 extends the benchmark model to account for the PAV/SAV effects on urban land uses (including parking land use), together with determinations of optimal housing size and optimal SAV market share. Section 5 further analyzes two special cases of full PAVs and full SAVs. In Section 6, numerical examples are provided to illustrate the model properties. Section 7 concludes this paper and provides suggestions for further studies.

2. Literature review

Our work is closely related to the studies of the urban model with household residential and work location choices. The literature related to this topic can be categorized into two classes in terms of modeling method: one considers a monocentric city structure with exogenously given city center; and the other focuses on endogenous formation of urban configurations, including determinations of residential and industrial areas (i.e., city center is endogenously determined). As far as the first-class method is concerned, Straszheim (1984) presented a segregated model of land and labor markets (with exogenously given city center as import / export market) to determine the border between industrial and residential areas, and wage and rent gradients. A closed-form solution cannot be obtained for this formulation because the model is too complex. Sasaki and Kaiyama (1990) extended it to evaluate the effects of transportation system improvements on urban spatial structure. Ross and Yinger (1995) performed analytically comparative static analysis of open urban models considering the firm's and household's competitive behavior (with land and labor as inputs to housing production and consumption goods). Ross (1996) further incorporated capitals as an input to housing production and as a consumption good. Although these studies provided a useful approach for modeling household residential location and worksite choices in a monocentric city, they ignored the effect of agglomeration economies on firm's location. Moreover, an analytical solution cannot generally be obtained, and thus a simulation method must be adopted.

As far as the second-class method is concerned, Ogawa and Fujita (1980) made a pioneering work. They endogenously determined urban land use patterns, in which neither employment nor residence needs to be specified a priori. Three types of urban land use patterns were considered: monocentric urban configuration, partially mixed urban configuration, and completely mixed urban configuration. Fujita and Ogawa (1982) extended it to the cases of duocentric and tricentric urban configurations and analyzed the conditions for the structural transition of urban configurations. For simplicity of analysis, both studies assumed that the commuting cost is a linear function of travel distance between household residence and worksite. The modeling frameworks of Ogawa and Fujita (1980) and Fujita and Ogawa (1982) have been widely extended through relaxing some assumptions. For example, Berliant and Tabuchi (2018) relaxed the assumption of a linear commuting cost to a nonlinear case. Garrido-da-Silva et al. (2022) further considered the resident's travel cost of visiting the city center in the model, besides the resident's cost of commuting to work and the firm's cost of shipping industrial goods to the city center. Lucas and Rossi-Hansberg (2002) allowed substitution between land and labor in firm's production technology and substitution between land and goods in household consumption. Osawa and Akamatsu (2020) addressed the emergence of polycentric city structures as a result of tradeoff between agglomeration economies and congestion effects, based on the theory of potential games.

Our work is also closely related to integrated issues of parking land use and urban spatial model. In this regard, only a few studies can be found in the literature. Voith (1998) presented a general equilibrium model to examine the effects of parking and transit subsidy on CBD size, CBD land value, and market shares of cars and transit. However, his model only focused on CBD area, but did not considered the spatial details of the city. Anderson and de Palma (2007) integrated parking in a monocentric city model, in which land can be used for residences or parking lots, and land rents are endogenously determined. They showed that at equilibrium, residents close to CBD walk to work, whereas residents further out drive to parking lot, and then walk to work; and the social optimum is identical to an equilibrium when parking lots are monopolistically competitively priced. Their model did not consider the firm production behavior and the competition for land between households and firms. Franco (2017) explored the effects of change in downtown parking supply on welfare, mode choice, and urban spatial structure using a monocentric city model with two transport modes, endogenous residential surface parking, and bottleneck congestion at the CBD. Brueckner and Franco (2017) further investigated the effects of different regimes for provision of parking spaces on urban form, including surface parking, underground parking, and structural parking. However, all these studies did not involve AVs and their effects on land use and parking.

To the best of our knowledge, Zakharenko (2016) was the first to address the AV effects on urban form from the perspective of urban economics. In his study, the equilibrium solution of household residential and work location choices with parking land use incorporated was endogenously determined. However, his study did not concern the firm behavior and the behavioral difference between PAVs and SAVs. Zakharenko (2023) further considered the travelers' choice equilibrium issue of PAVs and SAVs based on a trade-off between vehicle capital cost and search cost. However, he did not concern the effects of PAVs / SAVs on urban spatial structure. Larson and Zhao (2020) used classic monocentric urban model with fixed CBD land area to model the effects of AVs on urban sprawl, energy consumption, and housing affordability. More recently, Zhong and Li (2023) adopted counterfactual analysis techniques to examine the effects of AVs on urban expansion for metropolitan areas in the US if autonomous vehicles had been introduced. Dantsuji and Takayama (2024) utilized a bathtub model to examine the effects of AVs on the spatial structures of a hyper-congested city, without considering firm behavior and auto parking. These studies assumed that the worker wage was exogenously given, and showed that introduction of AVs would cause urban expansion using numerical simulation methods.

This paper presents analytical models for exploring the effects of AVs on the urban spatial structure in a linear monocentric city with a consideration of interactions among households, firms, and the government. The parking land occupancies for TVs and PAVs and the land released by SAVs for production and residential uses are explicitly considered. The optimal housing size and optimal SAV market share are analyzed. This study provides many new insights into the AV effects on the future urban spatial structure, household utility, firm production, and social welfare. The proposed model can serve as a useful tool for modeling AV impacts on urban system and evaluating various urban policies.

3. Urban model with TVs only

3.1. Urban configuration with TVs only

The focus of this paper is on the effects of AVs on urban spatial structure, and thus we attempt to develop simple urban models based on some reasonable assumptions. We first consider a linear, closed, symmetric, monocentric city with TVs only, in which all import / export trades occur in the city center. There is one unit of land available at every location of the linear city. There are three stakeholders in the city: households, firms and the government. Households provide labor to firms, and conversely, firms pay wages to households. Firms interact with each other, generating agglomeration economies. In the benchmark case, it is assumed that all households travel by TVs, and each of them needs a parking space to be provided at the residential location for nighttime parking and at the work location for daytime parking, causing parking rents paid to the land owner (i.e., the government) due to parking land occupancies. Households and firms compete for land for their activities' purposes, including residential and parking uses for households and production uses for firms. The locational competitions among households, among firms, and between households and firms create an urban configuration of the spatial economy. With the assumption that all import / export trades occur in the city center (i.e., y = 0), the transportation costs of goods and the agglomeration economies among firms make the land at the city central area more attractive to the firms. As a result of competition for land, the firms choose to implement production activity in the CBD area of the city due to its approach to the trade market, whereas households choose to reside in the outer part of the city and commute to the worksite. This leads to a segregated city pattern in which employments are located in the CBD area, whereas residents are located in the peripheral area.

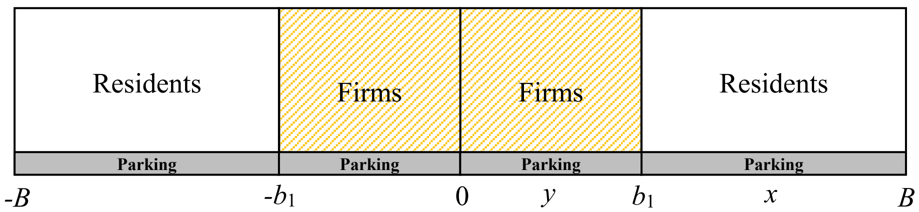

Fig. 1. Symmetric monocentric urban configuration with TVs only.

For illustration purpose, Fig. 1 shows a symmetric monocentric urban configuration with TVs only. In Figure 1, B is the city boundary, $[-b_1, b_1]$ is the industrial or employment area, $[-B, -b_1]$ and $[b_1, B]$ are residential areas, and b_1 and $-b_1$ are the borders between industrial area and residential area. We assume that the type of parking provided in the city is surface parking, thus causing parking land occupancy. The land in the industrial area is used for firm production and parking, whereas the land in the residential area is used for household residence and parking. The government regulates and designs the housing size to maximize the social welfare. In the following, we compute an equilibrium for households and firms and determine the optimal regulatory policy for the government. Considering the city's symmetry, we only focus on right-half of the city.

3.2. Households

Suppose that there are N homogeneous households with identical preferences for land and (numéraire) composite goods. Each household provides one unit of labor to a firm to earn the income in return. The utility of each household is derived from housing consumption and composite non-housing good consumption. For simplicity of analysis, following some previous studies, such as Ogawa and Fujita (1980), Fujita and Ogawa (1982), Berliant and Tabuchi (2018), Regnier and Legras (2018), and Kyriakopoulou and Picard (2021, 2023), we assume that the housing size consumed by each household is a positive uniform size s_h across residential areas. That is, the housing size in the city is regulated and designed by the government, and all households rent houses from the government. In this paper, we adopt a quasi-linear form of household utility function, expressed as

$$U\left(z(x)\right) = z(x) + \gamma \ln s_h,\ x \in [b_1, B], \tag{1}$$

where $U(\cdot)$ is the household utility level, x is the residential location of a household, $z(x)$ is the quantity of numéraire composite non-housing goods consumed by the household residing at location x, and s_h is the quantity of land consumed by a household. The government determines the optimal housing size s_h to maximize the social welfare of the city system, presented later. The positive constant γ represents household preference for land. A larger value of γ indicates a stronger preference, and vice versa. The quasi-linear utility function has been adopted in some previous studies, such as Song and Zenou (2006), Kono et al. (2012), Regnier and Legras (2018), and Li et al. (2024a, b).

A TV has to park at worksite during the day and at residential location during the night, thus causing parking land occupancies at both occasions. Suppose that each TV needs s_p units of land for parking at each occasion, which is assumed to be a constant. We assume $s_h > s_p$, which goes along with usual observation. Household income is spent on housing rent, composite non-housing good consumption, parking fees or rents at residence and worksite, fixed vehicle ownership cost, and commuting cost between residence and worksite. The budget constraint for a household residing at location x and working at location y is given as

$$w(y)-\alpha_0^{\mathrm{TV}}-\alpha_1^{\mathrm{TV}}\left(x-y\right)-\left(r(x)+r(y)\right)s_p=z(x)+r(x)s_h,\ x\in[b_1,B],y\in[0,b_1], \tag{2}$$

where the superscript "TV" represents traditional vehicles. $w(y)$ is the wage paid to workers by the firm locating at *y*, $x-y$ is the commuting distance of a worker from residence *x* to worksite *y*. α_0^{TV} is the vehicle ownership cost, including purchase cost, depreciation cost, insurance and registration fees etc. α_1^{TV} is the marginal travel cost per unit of distance by TV. $r(x)$ and $r(y)$ are the land rents at residence *x* and workplace *y*, respectively. The left-hand side of Eq. (2) represents the disposable income of a household residing at *x* and working at *y*, which is equal to the household income deducted by the vehicle fixed cost, commuting time cost between residence and worksite, and the parking land rents at both residence and worksite.

Each household maximizes its own utility $U(\cdot)$ by choosing the amount of composite goods $z(x)$, residential location *x*, and worksite *y* within its budget constraint. The household utility maximization problem for determining $z(x)$, *x* and *y* can be formulated as

$$\max_{z(x),x,y} U\left(z(x),x,y\right)=z(x)+\gamma\ln s_h, \tag{3}$$

$$\text{s.t.}\ \ w(y)-\alpha_0^{\mathrm{TV}}-\alpha_1^{\mathrm{TV}}\left(x-y\right)-\left(r(x)+r(y)\right)s_p=z(x)+r(x)s_h,\ x\in[b_1,B],y\in[0,b_1]. \tag{4}$$

Substituting Eq. (4) into Eq. (3), one immediately obtains that household utility $U(\cdot)$ is a function of *x* and *y*. From the first-order optimality condition $\partial U(\cdot)/\partial x=0$, one can derive the equilibrium land rent $r(x)$ at residential location *x* as

$$r_h(x)=R_A+\frac{\alpha_1^{\mathrm{TV}}}{s_h+s_p}(B-x),\ x\in[b_1,B], \tag{5}$$

where the subscript "*h*" represents the "household" at the residential area. R_A is the agricultural rent with $r_h(B)=R_A$. Eq. (5) shows that the residential land (or housing) rent linearly decreases with an increase in the distance from the city center.

From the first-order optimality condition $\partial U(\cdot)/\partial y=0$, one can derive the relationship between the wage $w_f(y)$ at the best worksite *y* chosen by the household residing at *x* and its commuting cost, as follows:

$$w_f(y)=w_f(0)-\alpha_1^{\mathrm{TV}}y-\left(r(0)-r(y)\right)s_p,\ y\in[0,b_1], \tag{6}$$

where the subscript "*f*" represents the "firm" at the industrial area. The term

$\alpha_1^{\mathrm{TV}} y + \left(r(0) - r(y)\right) s_p$ represents the total commuting cost savings due to choosing to work at location *y* but not at city center ($y = 0$), including travel cost and parking cost. Hence, Eq. (6) means that the wage, $w_f(y)$, at the best worksite *y* equals the wage at the city center minus the total cost savings due to reduced distance between residence and worksite.

Substituting Eqs. (5) and (6) into Eq. (4), one obtains the equilibrium composite non-housing good consumption as

$$z = w_f(0) - \alpha_0^{\mathrm{TV}} - \alpha_1^{\mathrm{TV}} B - r(0) s_p - R_A \left(s_h + s_p\right). \tag{7}$$

Eq. (7) shows that the equilibrium composite good consumption *z* and thus equilibrium household utility $U(\cdot)$ in terms of Eq. (3) depends on housing size s_h to be determined by the government.

As previously stated, each TV household needs to occupy s_h units of land for residence and s_p units of land for parking at the household residential area, implying a total of $s_h + s_p$ units of land occupancy per household. Hence, the household residential density (i.e., the number of households per unit of residential land area), $m(x)$, at location *x* is given as

$$m(x) = \frac{1}{s_h + s_p}, \ \text{for } x \in [b_1, B]; \ \text{and } 0, \ \text{otherwise}. \tag{8}$$

In the above, we have derived the residential location choice equilibrium of TV households, including the equilibrium land rent $r_h(x)$, the equilibrium composite good consumption *z*, and the relationship between best worksite $w_f(y)$ and commuting cost savings $\alpha_1^{\mathrm{TV}} y + \left(r(0) - r(y)\right) s_p$. Observe that $r_h(x)$ and $w_f(y)$ are dependent on the marginal travel cost α_1^{TV}, but are independent of vehicle fixed cost α_0^{TV}; *z* and thus $U(\cdot)$ is dependent on both α_0^{TV} and α_1^{TV}.

3.3. Firms

We now look at the firm's behavior. Suppose that all firms have the same land and labor inputs and the same production technology. They produce the composite goods that are shipped and sold at a unitary price in the trade market using land and labor as inputs. Following Ogawa and Fujita (1980), Fujita and Ogawa (1982), Berliant and Tabuchi (2018), Regnier and Legras (2018), and Kyriakopoulou and Picard (2021, 2023), we assume that the quantities of land and labor used for production for each firm are, respectively, fixed as s_f units of land and l_f units of labor, and there is no unemployment in the city. Therefore, the number of firms, denoted by M, can be expressed as

$$M = N/l_f \, . \tag{9}$$

According to the previous related studies, such as Berliant and Tabuchi (2018), Regnier and Legras (2018), and Kyriakopoulou and Picard (2021, 2023), firm's production function, $F(y)$, depends on spillover, communication, and economic interactions, defined as

$$F(y) = \int_{-\infty}^{+\infty} \left(\beta - \delta |t - y|\right) m(t) dt \, , \tag{10}$$

where β is a parameter reflecting firm productivity, $m(t)$ is the firm density at location t, and $|t-y|$ is the distance between firms locating at t and y. δ is the transaction cost of unit distance between firms. The term $\beta - \delta|t-y|$ can be interpreted as knowledge or information spillover effects of a firm at location t on a firm at location y, that is, the contribution or agglomeration externality of the firm at t to the production of the firm at y. Clearly, $\beta - \delta|t-y|$ should be positive under the agglomeration economy effects.[7] This implies a positive interaction among firms, and a positive firm production. The higher the mass of firms around y, the higher the production of the firm at y, and vice versa. Empirical studies in regional and urban economics provide evidences of such an agglomeration force (see Ciccone and Hall, 1996; Rosenthal and Strange, 2008).

In the TV era, each worker entails s_p units of land for daytime parking at the worksite, and each firm needs s_f units of land for production. The total quantity of land consumed by each firm with l_f units of labor is the sum of the land for all workers' parking uses and for the firm production use, i.e., $s_p l_f + s_f$. Thereby, the firm density (i.e., the number of firms per unit of

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[7] A sufficient condition is $\beta > 2\delta b_1$, under which two firms are, respectively, located at both ends of the industrial area. We assume that β is high enough or δ is low enough for this inequality to be satisfied, as assumed in Kyriakopoulou and Picard (2021, 2023).

industrial land area), $m(y)$, at worksite y is

$$m(y) = \frac{1}{s_p l_f + s_f}, \text{ for } y \in [0, b_1]; \text{ and } 0, \text{ otherwise}. \tag{11}$$

In terms of Eqs. (10) and (11), the firm's production function can be calculated as

$$F(y) = \int_{-b_1}^{b_1} \left(\beta - \delta|t - y|\right) m(t) dt = \frac{-\delta y^2 - \delta b_1^2 + 2\beta b_1}{s_p l_f + s_f}, \; y \in [0, b_1]. \tag{12}$$

Eq. (12) shows that the firm production function $F(y)$ is concave on $[0, b_1]$ and reaches its maximum value of $2\beta b_1 - \delta b_1^2$ at the city center (i.e., $y = 0$). This means that the firm production is higher when firms are close to each other due to agglomeration externality effects, particularly around the city center.

Each firm maximizes its own net profit by choosing its location. The firm's net profit maximization problem is represented as

$$\max_y \; \Pi(y) = F(y) - w_f(y) l_f - r_f(y) s_f, \; y \in [0, b_1], \tag{13}$$

where $\Pi(y)$ is the firm profit at y, and the production function $F(y)$ is given by Eq. (12).

We assume a perfectly competitive product market, i.e., each firm can freely enter or exit the city. Accordingly, at equilibrium each firm's net profit is equal to 0, i.e., $\Pi(y) = 0$. Combining it and Eq. (13), one obtains the bid-rent, $r_f(y)$, of the firm at location y as

$$r_f(y) = \frac{1}{s_f}\left(F(y) - w_f(y) l_f\right), \; y \in [0, b_1]. \tag{14}$$

According to Eq. (14), the firm's bid-rent $r_f(y)$ is positively related to the firm production but negatively related to the wage.

3.4. Equilibrium

Competition for land among households, among firms, and between households and firms leads to an equilibrium spatial structure of the city, which is described by the following variables: land rent profile at industrial area $r_f(y)$, land rent profile at residential area $r_h(x)$, wage profile $w_f(y)$, border, b_1, between industrial and residential areas, city boundary B, and common household utility level *U*. These variables are determined by the following equilibrium conditions:

$$2\int_{0}^{b_1} m(y)dy = M \ , \tag{15a}$$

$$2\int_{b_1}^{B} m(x)dx = N \ , \tag{15b}$$

$$r_f(b_1) = r_h(b_1), \tag{15c}$$

$$r_h(B) = R_A \, . \tag{15d}$$

Eqs. (15a) and (15b) are the labor market equilibrium conditions, and Eqs. (15c) and (15d) are the land market equilibrium conditions. Specifically, Eq. (15a) is the conservation constraint about the total number of firms, requiring that all firms are located at the industrial area of the city. Eq. (15b) is the conservation constraint about the total number of households, requiring that all households are accommodated in the residential area of the city. Eq. (15c) represents that the bid-rent of firms equals that of households at border b_1. Eq. (15d) states that the market land rent at the city boundary equals the agricultural rent. The number "2" in Eqs. (15a) and (15b) is due to the city's symmetry.

From the equilibrium conditions (15a)-(15d), one can derive border, b_1, between industrial area and residential area, city boundary *B*, wage curve $w_f(y)$, and firm's bid-rent curve $r_f(y)$, as follows:

$$b_1 = \frac{M}{2}\left(s_p l_f + s_f\right), \ \ B = \frac{M}{2}\left(s_p l_f + s_f\right) + \frac{N}{2}\left(s_h + s_p\right), \tag{16a}$$

$$w_f(y) = \frac{l_f s_p F(y) + s_f F(b_1) - l_f s_f \alpha_1^{\mathrm{TV}} y}{l_f\left(s_f + l_f s_p\right)} - \frac{s_f}{l_f} R_A, \ y \in [0, b_1], \tag{16b}$$

$$r_f(y) = \frac{F(y) - F(b_1) + \alpha_1^{\mathrm{TV}} l_f y}{s_f + l_f s_p} + R_A, \ y \in [0, b_1]. \tag{16c}$$

Eq. (16b) shows that the wage function $w_f(y)$ is concave and decreasing on $[0, b_1]$, and reaches its maximum value of $\frac{s_p l_f F(0) + s_f F(b_1)}{l_f\left(s_f + s_p l_f\right)} - \frac{s_f}{l_f} R_A$ at the city center (i.e., $y = 0$). Eq. (16c) shows that the firm's bid-rent function $r_f(y)$ is a concave and quadratic function of *y*.

3.5. Optimal housing size under social welfare maximization

So far, we have formulated the household's and firm's behavior for a TV city. We now look at the behavior of the government. As previously stated, housing type in the city is designed and constructed by the government, and households rent houses from the government. The government determines the optimal housing size s_h, aiming to maximize the social welfare (*SW*) of the system, which is the sum of consumer surplus and producer surplus (zero profit for perfectly competitive firms). The social welfare maximization problem for optimizing the housing size s_h can be expressed as

$$\begin{aligned}\max_{s_h}\ SW^{\mathrm{TV}} &= NU^{\mathrm{TV}}(s_h) \\ &= N\left(w_f(0)-\alpha_0^{\mathrm{TV}}-\alpha_1^{\mathrm{TV}}B-r(0)s_p-R_A\left(s_h+s_p\right)+\gamma\ln s_h\right).\end{aligned} \tag{17}$$

According to Eq. (17) and the equilibrium solutions $w_f(0)$, $r(0)$, and B (see Eq. (16)), one can derive the optimal housing size s_h^{TV} as

$$s_h^{\mathrm{TV}} = \frac{2\gamma}{\alpha_1^{\mathrm{TV}}N+2R_A}. \tag{18}$$

Therefore, city boundary B and common household utility U are given by

$$B=\frac{M}{2}\left(s_p l_f+s_f\right)+\frac{N}{2}\left(\frac{2\gamma}{\alpha_1^{\mathrm{TV}}N+2R_A}+s_p\right), \tag{19}$$

$$U=w_f(0)-\alpha_0^{\mathrm{TV}}-\alpha_1^{\mathrm{TV}}B-r(0)s_p-R_A\left(\frac{2\gamma}{\alpha_1^{\mathrm{TV}}N+2R_A}+s_p\right)+\gamma\ln\frac{2\gamma}{\alpha_1^{\mathrm{TV}}N+2R_A}. \tag{20}$$

Note that the marginal travel cost α_1^{TV} and the parking land size s_p are two crucial parameters influencing the urban model solution. Hence, it is important to carry out the comparative statics analyses of these two parameters, as shown in Table 1.

Table 1 Comparative statics results.

Parameter	$F(y)$	$r_f(y)$	$r_h(x)$	$w_f(y)$	s_h^{TV}	b_1	B
α_1^{TV}	null	+	?	–	–	null	–
s_p	–	?	+	?	null	+	+

Note: "+" means a positive correlation, "–" means a negative correlation, and "null" means no effect.

The results presented in Table 1 are summarized as follows.

Proposition 1. Considering the comparative statics results of marginal travel cost α_1^{TV} and parking land size s_p, we have

(i) Smaller marginal travel cost of TVs α_1^{TV} decreases firm land rents $r_f(y)$, increases wages $w_f(y)$, household housing size s_h^{TV} and city size B, but has no effect on firm production $F(y)$ and industrial area's size b_1.

(ii) Smaller parking land size s_p decreases residential land rent $r_h(x)$, industrial area's size b_1 and city boundary B, thereby causing an increase in firm production $F(y)$.

According to Proposition 1, a decrease in the marginal TV travel cost α_1^{TV} through vehicle technological innovation can lead some households to move outwards to enjoy bigger housing size, thus causing urban sprawl. As a result, the firm land rents decreases and household disposable wage increases. On the other hand, a decrease in the parking land size s_p leads more land to be used for firm production and household residence, thus causing a more compact city and an increased firm production due to the more intense agglomeration economy effects. This completes our study of the interactions among TV households, firms, and the government for a city with TVs only.

4. Urban model with PAVs and SAVs

In this section, we study the effects of introducing AVs on the urban system.

4.1. Urban configuration with PAVs and SAVs

With a rapid progress in artificial intelligent technology and autonomous vehicle technology, it is anticipated that TVs in the city will probably be entirely replaced by AVs in the future. AVs can drive themselves automatically without need for drivers, and the in-vehicle activities can bring extra utility to vehicle users. It is reasonable to expect that the marginal travel cost of commuters in AVs be lower than that in TVs, thus leading to a significant change in household behavior and in urban system performance.

With convenient ride-hailing services via a shared mobility platform, residents can easily use SAV services with no obligation to purchase a vehicle, facing therefore a lower fixed cost than PAVs. With adoption of SAVs, the land area required for parking in a city is decreased, which is dedicated to the use of firms and households. By contrast, PAVs can provide better privacy, more convenient and comfortable services due to better accessibility than SAVs, and thus the marginal travel cost of PAVs is lower than that of SAVs.

We assume that the marginal travel cost of TVs is the highest, that of PAVs is the lowest, and that of SAV is in between, i.e.,

$$\alpha_1^{PAV} < \alpha_1^{SAV} < \alpha_1^{TV}, \tag{21}$$

where the superscripts "PAV" and "SAV" represent PAVs and SAVs, respectively. α_1^{PAV} and α_1^{SAV} are the marginal travel costs of PAVs and SAVs, respectively.

To analyze the effects of AVs on the urban spatial structures of future cities, we consider a linear, closed, symmetric, monocentric city with AVs; θ proportion of households take SAV services, whereas $1-\theta$ proportion of households own their PAVs. The competitions for land between firms and households, among households, and among firms reshape the urban spatial configuration. With the assumption that all good trades take place in the city center and using condition Eq. (21), it can be shown that at equilibrium, the urban configuration after introducing AVs has the following properties (the proof is relegated to Appendix A).

Proposition 2. Considering the competition for land between households and firms, we have

(i) Households are located at the outer area of the city, and PAV and SAV households' residences are segregated, with PAV households' residences being at the most peripheral area.

(ii) Firms are located at the inner area of the city, and PAV and SAV households' worksites are segregated, with the SAV households' worksites being at the most central area.

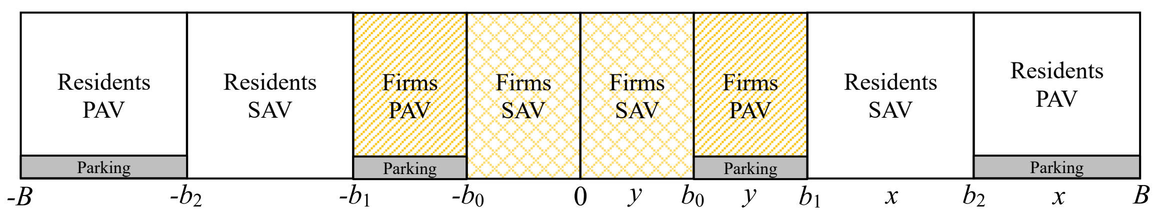

Fig. 2. Symmetric monocentric urban configuration after introducing PAVs and SAVs.

Considering different residential locations and different wage levels for PAV and SAV households, their optimal housing sizes, denoted as s_h^{PAV} and s_h^{SAV} respectively, may be different from the perspective of the social optimum. Both are determined by the government, aiming to maximize the social welfare. Fig. 2 illustrates the urban configuration of the city with PAVs and SAVs. In this figure, b_1 and $-b_1$ are the borders between industrial area and residential area, b_2 and $-b_2$ are the borders between residential areas of PAV and SAV households, and b_0 and $-b_0$ are the borders between employment areas of PAV and SAV households. The urban model with PAVs and SAVs aims to determine the following quantities at equilibrium: borders b_0, $-b_0$, b_1, $-b_1$, b_2 and $-b_2$, city boundary *B*, wage profile $w_f(y)$, land rent profiles $r_h(x)$ and $r_f(y)$, and household utility level *U*. Again, considering the city symmetry, we focus only on the right-half of the city in the following analysis.

4.2. Households

4.2.1. PAV Households

We first look at the behavior of PAV households. Similar to TVs, PAVs need to park at both household residential location during the night and worksite during the day. The PAV household income is spent on the fixed vehicle ownership cost, commuting time cost, parking cost, composite non-housing good consumption, and housing consumption. Suppose that a PAV has the same vehicle size as a TV, and thus needs an identical land area of s_p for parking at both trip origin and destination. Again, we assume that the housing consumption of all PAV households in the city is a uniform quantity of s_h^{PAV} (with $s_h^{\text{PAV}} > s_p$). The PAV household utility maximization problem for choices of composite good consumption $z(x)$, residential location *x*, and worksite *y* subject to the budget constraint is given as

$$\max_{z(x),x,y} U\left(z(x),x,y\right) = z(x) + \gamma \ln s_h^{\text{PAV}}, \tag{22}$$

s.t. $w_f(y) - \alpha_0^{\text{PAV}} - \alpha_1^{\text{PAV}}\left(x-y\right) - \left(r(x)+r(y)\right)s_p = z(x) + r(x)s_h^{\text{PAV}},\ x \in [b_2, B], y \in [b_0, b_1]$. (23)

where α_0^{PAV} is the (fixed) ownership cost of PAV. The differences of the PAV household's model (Eqs. (22) and (23)) and the TV household's model (Eqs. (3) and (4)) lie in the fixe cost, marginal travel cost, and the residential and industrial areas.

Applying the method presented in Section 3.2 to solve the maximization problem Eqs. (22) and (23), one obtains the equilibrium residential land rent $r_h^{\mathrm{PAV}}(x)$, equilibrium composite good consumption of PAV households z^{PAV}, and the relationship between wage $w_f^{\mathrm{PAV}}(y)$ at the best worksite y and commuting cost savings $\alpha_1^{\mathrm{PAV}}(y-b_0)+(r(b_0)-r(y))s_p$, as follows:

$$r_h^{\mathrm{PAV}}(x)=R_A+\frac{\alpha_1^{\mathrm{PAV}}}{s_h^{\mathrm{PAV}}+s_p}(B-x),\ x\in[b_2,B], \tag{24a}$$

$$z^{\mathrm{PAV}}=w_f(b_0)-\alpha_0^{\mathrm{PAV}}-\alpha_1^{\mathrm{PAV}}(B-b_0)-r(b_0)s_p-R_A\left(s_h^{\mathrm{PAV}}+s_p\right), \tag{24b}$$

$$w_f^{\mathrm{PAV}}(y)=w_f(b_0)-\alpha_1^{\mathrm{PAV}}(y-b_0)-\left(r(b_0)-r(y)\right)s_p,\ y\in[b_0,b_1]. \tag{24c}$$

Eq. (24a) shows that equilibrium residential land rent $r_h^{\mathrm{PAV}}(x)$ is linearly decreasing with distance from the city center.

4.2.2. SAV Households

SAVs, contrarily to TVs and PAVs, do not occupy land for parking. The SAV household income is spent on the ticket price by SAV, commuting time cost, composite non-housing good consumption, and housing consumption. The utility maximization problem for the SAV households' choices of the amount of composite goods, residence, and worksite is represented as

$$\max_{z(x),x,y} U\left(z(x),x,y\right)=z(x)+\gamma\ln s_h^{\mathrm{SAV}}, \tag{25}$$

$$\text{s.t.}\ \ w_f(y)-\alpha_0^{\mathrm{SAV}}-\alpha_1^{\mathrm{SAV}}(x-y)=z(x)+r(x)s_h^{\mathrm{SAV}},\ x\in[b_1,b_2], y\in[0,b_0], \tag{26}$$

where α_0^{SAV} is the ticket fare by SAV. From the maximization problem Eqs. (25) and (26), one can derive the equilibrium residential land rent profile $r_h^{\mathrm{SAV}}(x)$, equilibrium composite good consumption z^{SAV}, and the relationship between wage $w_f^{\mathrm{SAV}}(y)$ at the best worksite y and commuting cost savings $\alpha_1^{\mathrm{SAV}}y$, as follows:

$$r_h^{\mathrm{SAV}}(x)=r(b_1)-\frac{\alpha_1^{\mathrm{SAV}}}{s_h^{\mathrm{SAV}}}(x-b_1),\ x\in[b_1,b_2], \tag{27a}$$

$$z^{\mathrm{SAV}}=w_f(0)-\alpha_0^{\mathrm{SAV}}-\alpha_1^{\mathrm{SAV}}b_1-r(b_1)s_h^{\mathrm{SAV}}, \tag{27b}$$

$$w_f^{\text{SAV}}(y) = w_f(0) - \alpha_1^{\text{SAV}} y,\ y \in [0, b_0]. \tag{27c}$$

Note that each SAV household at the residential area needs only s_h^{SAV} units of land for residential use without need of land for parking, whereas each PAV household needs s_h^{SAV} units of residential land and s_p units of parking land. This means that each PAV household residing at the most peripheral area $[b_2, B]$ requires a total of $s_h^{\text{PAV}} + s_p$ units of land, whereas each SAV household residing at the area $[b_1, b_2]$ occupies s_h^{SAV} units of land. The household residential density function, $m(x)$, at location x can thus be given as

$$m(x) = \begin{cases} 1/\left(s_h^{\text{PAV}} + s_p\right),\ x \in [b_2, B], \\ 1/s_h^{\text{SAV}},\ x \in [b_1, b_2], \\ 0,\ \text{otherwise}. \end{cases} \tag{28}$$

4.3. Firms

In order to represent the firm production function, we first define the firm density function. Note that in the future AV era, the SAV commuters do not need to occupy the land for parking due to use of shared services. The land released by the SAVs in the industrial area is used for firm production. But, the PAV commuters need s_p units of land for daytime parking at the worksite, like TV commuters. On the other hand, each firm requiring l_f units of labor needs s_f units of land for production. Therefore, the quantities of land consumed by each firm in $[0, b_0]$ and $[b_0, b_1]$ are, respectively, s_f and $s_p l_f + s_f$ (referring to Fig. 2). One thus obtains the firm density, $m(y)$, at worksite y as

$$m(y) = \begin{cases} 1/s_f,\ y \in [0, b_0], \\ 1/\left(s_p l_f + s_f\right),\ y \in [b_0, b_1], \\ 0,\ \text{otherwise}. \end{cases} \tag{29}$$

Similar to Section 3.3 and according to Eq. (10) and Fig. 2, the production function of firms for a city with PAVs and SAVs can be expressed as

$$F(y)=\int_{-b_1}^{b_1}\left(\beta-\delta|t-y|\right)m(t)dt$$

$$=\begin{cases}\dfrac{1}{s_p l_f+s_f}\left(2\beta\left(b_1-b_0\right)+\delta\left(b_0{}^2-b_1{}^2\right)\right)+\dfrac{1}{s_f}\left(-\delta y^2+2\beta b_0-\delta b_0{}^2\right),\ y\in[0,b_0],\\ \dfrac{1}{s_p l_f+s_f}\left(-\delta y^2+2\delta b_0 y-\delta b_1{}^2+2\beta\left(b_1-b_0\right)\right)+\dfrac{2b_0}{s_f}(\beta-\delta y),\ y\in[b_0,b_1].\end{cases}\tag{30}$$

Eq. (30) shows that the firm production function is concave and decreasing on $[0,b_0]$ and $[b_0,b_1]$. Moreover, the production of SAV households is higher than that of PAV households.

Again, we assume that all firms are identical with the same inputs of labor and land. Under the perfect competition, each firm's net profit is 0, i.e., $\Pi(y)=0$, where $\Pi(y)$ is defined by Eq. (13). One thus obtains the bid-rent, $r_f(y)$, of firm at location *y* as

$$r_f(y)=\frac{1}{s_f}\left(F(y)-w_f(y)l_f\right),\ y\in[0,b_0]\cup[b_0,b_1].\tag{31}$$

4.4. Equilibrium

Given the market share of SAV (or PAV) commuters as θ (or $1-\theta$), the spatial structure of the urban system is endogenously determined by these variables: b_0, b_1, b_2, *B*, $w_f(y)$, $r_f(x)$, and $r_h(x)$. They can be calculated by the following equations which represent the equilibrium conditions of the system:

$$2\left(\int_0^{b_0}m(y)dy+\int_{b_0}^{b_1}m(y)dy\right)=M\ ,\tag{32a}$$

$$2\int_{b_1}^{b_2}m(x)dx=\theta N\ ,\ 2\int_{b_2}^{B}m(x)dx=(1-\theta)N\ ,\tag{32b}$$

$$r_f^{\mathrm{SAV}}(b_0)=r_f^{\mathrm{PAV}}(b_0)\ ,\ r_f^{\mathrm{PAV}}(b_1)=r_h^{\mathrm{SAV}}(b_1),\ r_h^{\mathrm{SAV}}(b_2)=r_h^{\mathrm{PAV}}(b_2)\ ,\ r_h^{\mathrm{PAV}}(B)=R_A.\tag{32c}$$

Eqs. (32a) and (32b) are the labor market equilibrium conditions for the SAV and PAV households, respectively. Eq. (32c) is the land market equilibrium conditions for the industrial and residential areas.

From the equilibrium conditions (32a)-(32c), one can derive

$$b_0=\frac{N\theta s_f}{2l_f},\ b_1=\frac{N}{2l_f}\left((1-\theta)l_f s_p+s_f\right),\ b_2=\frac{N}{2l_f}\left(\theta s_h^{\mathrm{SAV}}l_f+(1-\theta)s_p l_f+s_f\right),\tag{33a}$$

$$B=\frac{N}{2l_f}\left((1-\theta)l_f s_h^{\text{PAV}}+\theta l_f s_h^{\text{SAV}}+2(1-\theta)l_f s_p+s_f\right), \tag{33b}$$

$$r_h(x)=\begin{cases} R_A+\frac{\alpha_1^{\text{PAV}}}{s_h^{\text{PAV}}+s_p}\left(B-b_2\right)+\frac{\alpha_1^{\text{SAV}}}{s_h^{\text{SAV}}}\left(b_2-x\right),\ x\in[b_1,b_2], \\ R_A+\frac{\alpha_1^{\text{PAV}}}{s_h^{\text{PAV}}+s_p}\left(B-x\right),\ x\in[b_2,B], \\ R_A,\ x\in[B,+\infty), \end{cases} \tag{33c}$$

$$r_f(y)=\begin{cases} \frac{1}{s_f}\left(F(y)-F(b_1)+l_f\alpha_1^{\text{SAV}}y\right)+\frac{l_f s_p\left(F(b_1)-F(b_0)\right)}{s_f\left(s_f+s_p l_f\right)}+R_A,\ y\in[0,b_0], \\ \frac{F(y)-F(b_1)+l_f\alpha_1^{\text{PAV}}\left(y-b_0\right)}{s_f+s_p l_f}+\frac{N\theta\alpha_1^{\text{SAV}}}{2}+R_A,\ y\in[b_0,b_1], \end{cases} \tag{33d}$$

$$w_f(y)=\begin{cases} \frac{s_p l_f F(b_0)+s_f F(b_1)}{l_f\left(s_f+s_p l_f\right)}-\frac{s_f}{l_f}R_A-\alpha_1^{\text{SAV}}y,\ y\in[0,b_0], \\ \frac{s_p l_f F(y)+s_f F(b_1)-l_f s_f\alpha_1^{\text{PAV}}\left(y-b_0\right)}{l_f\left(s_f+s_p l_f\right)}-\frac{s_f}{l_f}\left(\frac{N\theta\alpha_1^{\text{SAV}}}{2}+R_A\right),\ y\in[b_0,b_1]. \end{cases} \tag{33e}$$

Eqs. (33a) and (33b) show that the borders b_0 and b_2 increase with the SAV market share θ (due to $s_h^{\text{SAV}}>s_p$), while b_1 and B decrease with θ, i.e., both the industrial area and the city become more compact due to the reduced parking land demand with SAVs. Eqs. (33c) and (33d) show that the household's land rent $r_h(x)$ is linearly decreasing with the distance from the city center, while the firm's land rent $r_f(y)$ is concave on $[0,b_1]$. Eq. (33e) indicates that the wage function $w_f(y)$ is linearly decreasing on $[0,b_0]$, but concave and decreasing on $[b_0,b_1]$. Therefore, the wage of the SAV workers is higher than that of PAV workers.

4.5. Optimal housing size under social welfare maximization

The government regulates and designs the housing sizes for the PAV and SAV households, aiming to maximize the social welfare. The social welfare maximization problem for determining the optimal housing sizes s_h^{PAV} and s_h^{SAV} is

$$\begin{aligned} \max_{s_h^{\text{PAV}},s_h^{\text{SAV}}}\ SW^{\text{AV}} &=\theta N U^{\text{SAV}}\left(s_h^{\text{SAV}}\right)+\left(1-\theta\right)NU^{\text{PAV}}\left(s_h^{\text{PAV}}\right) \\ &=\theta N\left(w_f(0)-\alpha_0^{\text{SAV}}-\alpha_1^{\text{SAV}}b_1-r(b_1)s_h^{\text{SAV}}+\gamma\ln s_h^{\text{SAV}}\right) \\ &\quad+\left(1-\theta\right)N\left(w_f(b_0)-\alpha_0^{\text{PAV}}-\alpha_1^{\text{PAV}}\left(B-b_0\right)-r(b_0)s_p-R_A\left(s_h^{\text{PAV}}+s_p\right)+\gamma\ln s_h^{\text{PAV}}\right). \end{aligned} \tag{34}$$

The first-order optimality condition of maximization problem (34) leads to the optimal solutions of s_h^{PAV} and s_h^{SAV} as

$$s_h^{\text{PAV}} = \frac{2\gamma}{\alpha_1^{\text{PAV}} N(1-\theta) + 2R_A}, \quad s_h^{\text{SAV}} = \frac{2\gamma}{2(1-\theta)N\alpha_1^{\text{PAV}} + \theta N \alpha_1^{\text{SAV}} + 2R_A}. \tag{35}$$

Therefore, an increase in the SAV market share θ leads to an increase in the optimal housing size s_h^{PAV} for PAV households. Howevere, the optimal housing size s_h^{SAV} for SAV households may increase or decrease, depending on the relationship between α_1^{SAV} and $2\alpha_1^{\text{PAV}}$. As $\alpha_1^{\text{SAV}} > 2\alpha_1^{\text{PAV}}$, an increase in θ causes a decrease in s_h^{PAV}; and an increase in s_h^{SAV}, otherwise.

The resultant city boundary *B* is

$$B = \frac{N}{2l_f}\left(\frac{2\gamma(1-\theta)l_f}{\alpha_1^{\text{PAV}} N(1-\theta) + 2R_A} + \frac{2\gamma\theta l_f}{2(1-\theta)N\alpha_1^{\text{PAV}} + \theta N\alpha_1^{\text{SAV}} + 2R_A} + 2(1-\theta)l_f s_p + s_f\right). \tag{36}$$

In the above analysis, the SAV market share θ is exogenously given. Naturally, what the government cares for is to find the optimal θ to maximize the social welfare. When there is an interior solution, the condition $\partial SW^{\text{AV}}(\theta)/\partial\theta = 0$ should hold. The expression for the optimal θ is complicated, and its detailed derivation is provided in Appendix B.

We now look at the change of the social welfare before and after introducing the AVs, defined as

$$\begin{aligned} \Delta SW &= SW^{\text{AV}} - SW^{\text{TV}} \\ &= \theta N U^{\text{SAV}}(\cdot) + (1-\theta) N U^{\text{PAV}}(\cdot) - N U^{\text{TV}}(\cdot), \end{aligned} \tag{37}$$

where $U^{\text{SAV}}(\cdot)$, $U^{\text{PAV}}(\cdot)$, and $U^{\text{TV}}(\cdot)$ are determined by Eqs. (25), (22), and (3), respectively.

Note that $U^{\text{SAV}}(\cdot)$, $U^{\text{PAV}}(\cdot)$, and $U^{\text{TV}}(\cdot)$ are the functions of fixed vehicle ownership cost, marginal travel cost, and SAV market share. At the early stage of the AV technology development, the vehicle fixed costs of PAVs and SAVs are too high; but their marginal travel costs are close to that of TVs, ΔSW may thus become negative, showing a decrease in the social welfare after the introduction of AVs. However, when the AV technologies are mature such that the vehicle fixed costs of PAVs and SAVs are low (e.g., close to that of TVs), ΔSW

in Eq. (37) is thus positive, implying that the introduction of AVs increases the social welfare.

According to the above discussions and the comparison of the results before and after introducing AVs, we obtain the following properties.

Proposition 3. After introducing AVs,

(i) The housing size of PAV households increases, i.e., $s_h^{\mathrm{PAV}} > s_h^{\mathrm{TV}}$; and the housing size of SAV households increases if and only if $\alpha_1^{\mathrm{TV}} > 2(1-\theta)\alpha_1^{\mathrm{PAV}} + \theta\alpha_1^{\mathrm{SAV}}$.

(ii) The industrial area b_1 gets more compact; and the city expands if and only if $(1-\theta)s_h^{\mathrm{PAV}} + \theta s_h^{\mathrm{SAV}} > s_h^{\mathrm{TV}} + 2\theta s_p$.

(iii) The social welfare may increase or a decrease, depending on the vehicle fixed cost, marginal travel cost, and SAV market share.

It should be pointed out that the critical condition $\alpha_1^{\mathrm{TV}} > 2(1-\theta)\alpha_1^{\mathrm{PAV}} + \theta\alpha_1^{\mathrm{SAV}}$ in Proposition 3(i) can be derived from $s_h^{\mathrm{SAV}} > s_h^{\mathrm{TV}}$. Proposition 3(i) shows that the housing size of SAV households may increase or decrease, depending on the marginal travel costs of PAVs, SAVs, and TVs and the SAV market share. The critical condition of $(1-\theta)s_h^{\mathrm{PAV}} + \theta s_h^{\mathrm{SAV}} = s_h^{\mathrm{TV}} + 2\theta s_p$ in Proposition 3(ii) can be directly obtained by taking a difference of the city boundaries before and after introducing AVs (i.e., Eq. (36) minus Eq. (19)). Proposition 3(ii) shows that after introducing AVs, the size of the industrial area becomes smaller because the land demand for parking with SAVs is reduced; the city boundary may expand or contract, depending on the marginal travel costs of AVs and the SAV market share. Proposition 3(iii) highlights the critical role of the maturity level of AV technologies in enabling the widespread adoption of autonomous vehicles in real-world applications.

5. Two special cases: full PAVs and full SAVs

In this section, we consider two extreme cases: full PAVs ($\theta = 0$) and full SAVs ($\theta = 1$). The case of full PAVs is similar to the TV case, in which all vehicles need to park at residential location and work location, and the main differences are the fixed cost and marginal travel cost of vehicles. Therefore, the expressions for the urban model with the full PAVs are basically consistent with those with TVs, and the optimal housing size, equilibrium city boundary, and equilibrium household utility are, respectively, given as

$$s_h^{\text{PAV}} = \frac{2\gamma}{\alpha_1^{\text{PAV}} N + 2R_A}, \tag{38a}$$

$$B = \frac{M}{2}\left(s_p l_f + s_f\right) + \frac{N}{2}\left(\frac{2\gamma}{\alpha_1^{\text{PAV}} N + 2R_A} + s_p\right), \tag{38b}$$

$$U = w_f(0) - \alpha_0^{\text{PAV}} - \alpha_1^{\text{PAV}} B - r(0)s_p - R_A\left(\frac{2\gamma}{\alpha_1^{\text{PAV}} N + 2R_A} + s_p\right) + \gamma \ln \frac{2\gamma}{\alpha_1^{\text{PAV}} N + 2R_A}. \tag{38c}$$

In order to look at the effects of introducing PAVs, we compare the equilibrium solutions for the city with TVs and with full PAVs, as summarized below.

Proposition 4. Compared to the TV city,

(i) For a city with full PAVs, the size of industrial area remains unchanged. However, the land rent of firms decreases, leading to an increased wage level.

(ii) The housing size increases, and the size of the city with full PAVs expands.

Proposition 4 shows that the full PAVs lead to a decreased firm land rent, but a higher wage level, which benefits all workers. On the other hand, a decrease in the marginal travel cost of PAVs and an increase in the wage allow households to afford larger housing spaces, thus causing urban sprawl.

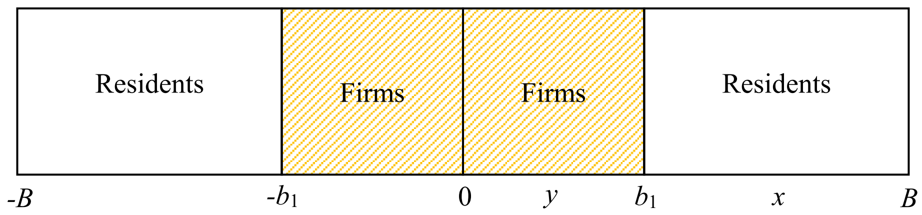

Fig. 3. Symmetric monocentric urban configuration with full SAVs.

For a full SAV system, there is no need of land for parking, and all land of the city is used for industrial production and residential uses, as shown in Fig. 3. Hence, the household residential density function, $m(x)$, at location x is

$$m(x) = \frac{1}{s_h^{\text{SAV}}}, \text{ for } x \in [b_1, B]; \text{ and } 0, \text{ otherwise}. \tag{39}$$

The firm density, $m(y)$, at worksite y is

$$m(y) = \frac{1}{s_f}, \text{ for } y \in [0, b_1]; \text{ and } 0, \text{ otherwise}. \tag{40}$$

Similar to the previous sections, from the urban equilibrium conditions and the social welfare maximization model for determining the optimal housing size, one can derive the border, b_1, between industrial and residential areas, city boundary *B*, firm's bid-rent curve $r_f(y)$, wage curve $w_f(y)$, housing rent curve r_h^{SAV}, and the optimal housing size s_h^{SAV} for the full SAV system, as follows:

$$b_1 = \frac{M}{2} s_f, \quad B = \frac{M}{2} s_f + \frac{\gamma N}{2R_A + \alpha_1^{\text{SAV}} N}, \tag{41a}$$

$$r_f(y) = \frac{F(y) - F(b_1) + l_f \alpha_1^{\text{SAV}} y}{s_f} + R_A, \; y \in [0, b_1], \tag{41b}$$

$$w_f^{\text{SAV}}(y) = \frac{F(b_1) - s_f\left(0.5N\alpha_1^{\text{SAV}} + R_A\right)}{l_f} + \alpha_1^{\text{SAV}}\left(b_1 - y\right), \; y \in [0, b_1], \tag{41c}$$

$$r_h^{\text{SAV}}(x) = r(B) + \frac{\alpha_1^{\text{SAV}}}{s_h}(B - x), \; x \in [b_1, B], \tag{41d}$$

$$s_h^{\text{SAV}} = \frac{2\gamma}{2R_A + \alpha_1^{\text{SAV}} N}, \tag{41e}$$

$$z^{\text{SAV}} = w_f(0) - \alpha_0^{\text{SAV}} - \alpha_1^{\text{SAV}} B - R_A \frac{2\gamma}{2R_A + \alpha_1^{\text{SAV}} N}, \tag{41f}$$

$$U^{\text{SAV}} = w_f(0) - \alpha_0^{\text{SAV}} - \alpha_1^{\text{SAV}} B - R_A \frac{2\gamma}{2R_A + \alpha_1^{\text{SAV}} N} + \gamma \ln \frac{2\gamma}{2R_A + \alpha_1^{\text{SAV}} N}. \tag{41g}$$

By comparing the results before and after introducing SAVs, one can find the effects of SAVs on the future urban spatial structure as follows.

Proposition 5. Compared to the TV city, for a city with full SAVs, the size of industrial area decreases, and the firm production rises. However, the residential land size increases. Introducing SAVs leads the city to expand if and only if $\alpha_1^{\text{SAV}} < \frac{2}{N}\left(\frac{\gamma}{s_h^{\text{TV}} + 2s_p} - R_A\right)$.

Proposition 5 shows that introduction of SAVs leads the size of the industrial area to contract, inducing a higher firm density within this area. This enhances the agglomeration externalities, such as the knowledge or information spillover effects. As a result, the firm production increases. On the other hand, the housing size increases due to introduction of SAVs. As a result, the size of the city with SAVs may expand or shrink. Specifically, as the marginal travel cost by SAVs is relatively low, the city expands after introducing SAVs. This is because the increased residential land size outweighs the decreased parking land size due to introduction of SAVs.

6. Numerical illustrations

In this section, numerical examples are provided to further illustrate the economic consequences of AVs. We examine the effects of AVs on the future city size, household utility, and social welfare; and compare the land rent, wage, and firm production profiles before and after introducing AVs.

6.1. Parameter specifications

We assume a population size of 2000 households (i.e., $N = 2,000$) in the linear monocentric city corridor. Each firm has an average of 32 workers and 200 meters of land, i.e., $l_f = 32$ and $s_f = 200$. The parameters in the firm production function are set as: $\beta = \$50,000/\text{year}$ and $\delta = \$2/m/\text{year}$. The annual agricultural rent is \$1,000 per meter. Households have a land preference valued at \$10,000, i.e., $\gamma = 10,000$. The parking land occupancy per vehicle is 4.0 meters. The annual ownership costs of a TV and a PAV are \$3159 and \$9951 per year, respectively. The annual ticket price by SAV is \$6318 per year. The annual marginal travel costs by TVs, PAVs, and SAVs are assumed to be \$0.83, \$0.45, and \$0.70 per meter, respectively. Table 2 summarizes the baseline values of all the input parameters.

Table 2 Values of input parameters.

Parameter	Description	Baseline value
N	Number of households	2,000
γ	Preference for land of households ($)	10,000
s_p	Land for parking (m)	4.0
α_0^{TV}	Annual ownership cost of TV ($/veh/year)	3159
α_1^{TV}	Marginal travel cost by TV ($/m/year)	0.83
α_0^{PAV}	Annual ownership cost of PAV ($/veh/year)	9951
α_1^{PAV}	Marginal travel cost by PAV ($/m/year)	0.45
α_0^{SAV}	Annual ticket price by SAV ($/year)	6318
α_1^{SAV}	Marginal travel cost by SAV ($/m/year)	0.70
s_f	Land used for production per firm (m)	200
l_f	Units of labor	32
β	Parameter reflecting firm productivity ($/year)	50,000
δ	Transaction cost of unit distance between firms ($/m/year)	2
R_A	Agricultural rent ($/m/year)	1,000

Note: The values of some parameters are from Zakharenko (2016), Reginer and Legras (2018), and Kyriakopoulou and Picard (2023).

6.2. Effects of AVs on future urban spatial structure

To illustrate the AV effects on the urban spatial structure, we conduct a sensitivity analysis of city boundary B with regard to SAV market share θ after introducing AVs, as shown in Fig. 4. Fig. 4 indicates that the size of city with TVs only is 19.71 km. After introducing AVs, the size of city decreases by about 9 km from 21.15 km to 12.13 km with the change of SAV market share θ from 0 to 100%. There exists a critical vaule of $\theta = 18.65\%$ such that the city expands at its left-hand side, and shrinks at its right-hand side, compared to the city with TVs (i.e., before introducing AVs). This illustrates the trade-off between decreased marginal travel cost after the introduction of AVs and reduced parking land demand due to increased SAV market share. In fact, the introduction of AVs will induce some households to move outwards to enjoy large housing size due to a lower marginal travel cost. Meantime, it also causes a reduced parking land demand. As the increased residential land size exceeds the reduced parking land size, the city expands, and contracts otherwise. These results are consistent with those of Proposition 3.

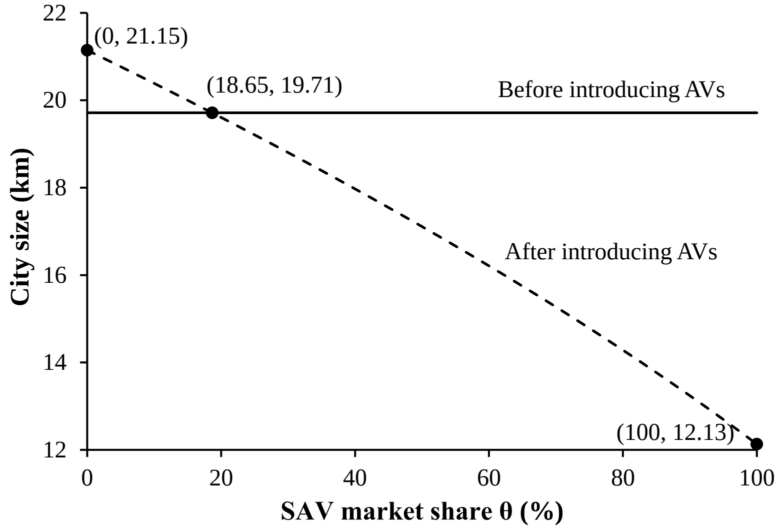

Fig. 4. Change of city size *B* with SAV market share θ.

6.3. Effects of AVs on household utility and social welfare

We now look at the effects of AVs on the household utility and the social welfare. Fig. 5 shows the changes of household utility before and after introducing AVs with the SAV market share θ and the PAV/SAV fixed costs (μ is the scaling factor of baseline values of PAV/SAV fixed costs). The horizontal axis in Fig. 5 represents the household utility with TVs only (its value is \$73.03 thousand). It can be seen in Fig. 5 that after introducing AVs, the utility of AV households may be higher or lower than that of TV households, depending on the fixed costs of AVs and the SAV market share. When the fixed costs of AVs are relatively low (i.e., $\mu = 1$), the houshold utility curves for PAV and SAV households are above the horizontal axis, implying that all households benefit from the introduction of AVs. Particularly, at a low SAV market share ($\theta < 29.02\%$), SAV households gain more from AVs than PAV households, and otherwise, PAV households benefit more. When the fixed costs of AVs are relatively high (i.e., $\mu = 3$), PAV households still always benefit from AVs, but SAV households may suffer a loss once its market share falls below 19.75%. For example, as $\theta = 0$ (i.e., the case of full PAVs), such a loss is \$6.96 thousand (from \$73.03 thousand under the case of TVs to \$66.07 thousand under the case of full PAVs).

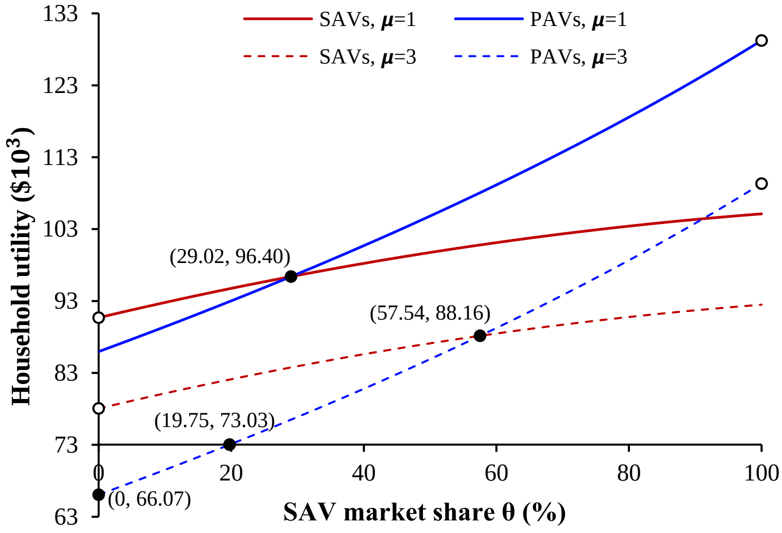

Fig. 5. Household utility before and after introducing AVs (red lines represent utility of SAV households, and blue lines represent utility of PAV households. μ is scaling factor of baseline values of PAV/SAV fixed costs).

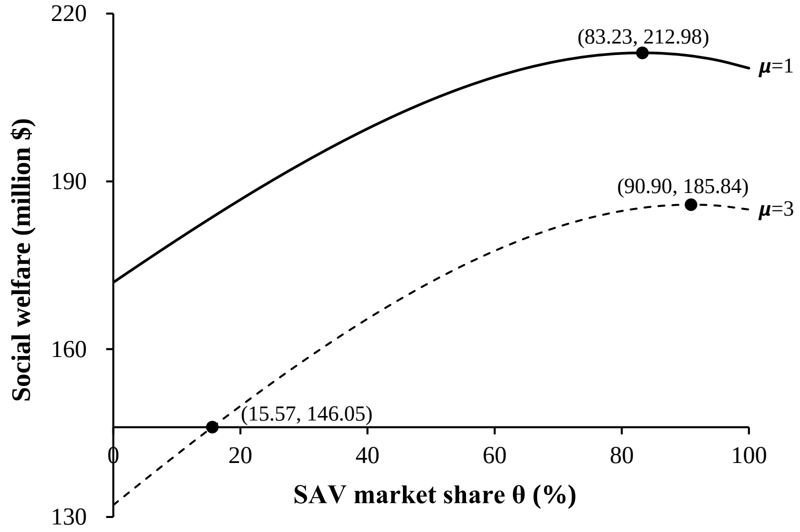

Fig. 6. Social welfare before and after introducing AVs.

Fig. 6 shows the social welfare before and after introducing AVs when the SAV market share θ and the PAV/SAV fixed costs change. The horizontal axis in Fig. 6 represents the social welfare with TVs only (its value is $146.05 million). It can be seen that as $\mu = 3$ (a high AV fixed cost, e.g., at an early stage of AV development), the introduction of AVs may cause an increase or a decrease in the social welfare. As shown in Fig. 6, as $\theta < 15.57\%$, the social welfare decreases after the introduction of AVs, implying a welfare loss. The welfare curve is concave with regard to θ, and thus there exists a unique optimal θ that maximizes the social welfare of the AV city (this is consistent with the solution of Eq. (B.3)). Specifically, the optimal SAV market share θ is 90.9%, resulting in a welfare increase by \$39.79 million (from TV city's social welfare of \$146.05 million to AV city's social welfare of \$185.84 million). However, as $\mu = 1$ (a low AV fixed cost, e.g., at a mature stage of AV development), the introduction of AVs can enhance the social welfare of the system. Therefore, as the maturity level of AV technologies inceases, the AV fixed cost decreases and the social welfare increases, and thus AVs deserves to be widely applied in practice.

6.4. Effects of AVs on land rent, wage, and firm production

In order to examine the effects of AVs on the land rent, wage, and firm production, we plot the land rent, wage, and production profiles for the city with TVs and with hybrid AVs of $\theta = 50\%$, as shown in Fig. 7. Fig. 7a and c show that in the TV city, firms are concentrated at the CBD area, while households are located at the outer areas. The firm's land rent, wage, and production profiles are concave on $[-b_1, 0]$ and $[0, b_1]$, while the household's land rent profile is linearly decreasing with the distance from the city center. Fig. 7b and d show that in the AV city, firms remain at the inner area of the city, which is partitioned into the worksites of SAV and PAV households from the CBD outwards. PAV and SAV households reside at the outer area of the city, particularly with PAV households being at the most peripheral area. Moreover, the wage profile for the SAV workers on $[-b_0, b_0]$ decreases linearly with the distance from center (see Fig. 7d). These results are consistent with those of Proposition 2.

It can be seen in Fig. 7 that the size of the industrial area $[-b_1, b_1]$ becomes smaller after introducing AVs. This is because SAVs do not occupy parking land, and the land released is used for firm production. Hence, the density of firms in the industrial area increases, which enhances the knowledge or information spillover effects due to agglomeration externalities. As a result, the production per capita and thus wage level enhances (comparing Fig. 7c and d). Meanwhile, the land rents for both industrial and residential areas decrease (comparing Fig. 7a and b). These results further illustrate Propositions 4 and 5.

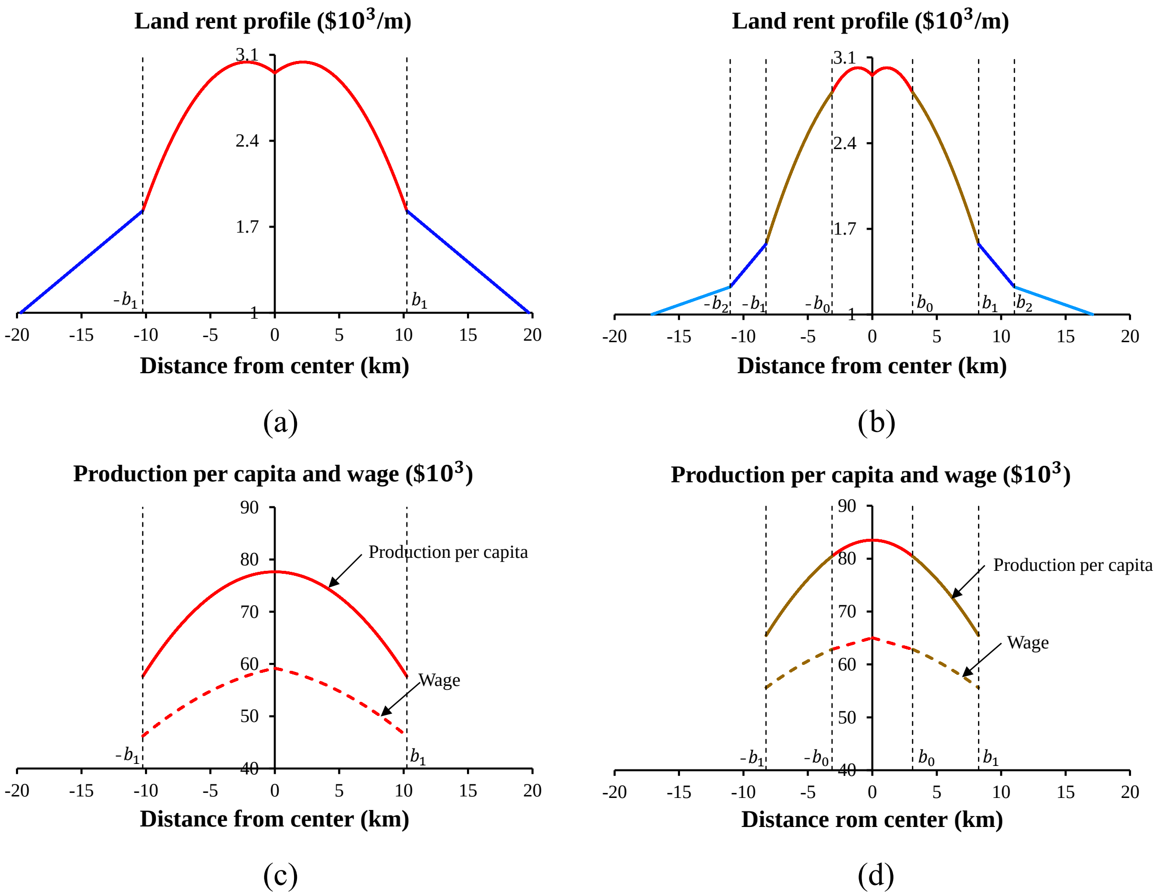

Fig. 7. Land rent, wage, and production profiles: (a) and (c) represent the city with TVs, and (b) and (d) represent the city with AVs ($\theta = 0.5$).

7. Conclusion and further studies

In this paper, a theory for analyzing the AV effects on future cities was presented. Two types of AVs, namely PAVs and SAVs, were considered. Compared to human-driven TVs, AVs have a lower marginal travel cost due to additional utility caused by free activities in AVs. SAVs have a higher marginal travel cost than PAVs due to poor privacy and comfort. The land released by SAVs is used for firm production and household residential uses. The housing type in the city is regulated and designed by the government, aiming to maximize the social welfare of the city. Households rent houses from the government. A benchmark urban model accounting for the competition of land among firm production, TV household residences, and parking was presented to determine the sizes of industrial and residential areas and the wage and land rent profiles. In order to reveal the AV effects on the urban spatial structure, an urban model incorporating the competitive behavior of firms and PAV / SAV households was presented and compared with the benchmark urban model. The AV regulation issue was also discussed through determining the optimal SAV market share. The findings showed that after introducing AVs, the housing size of PAV households increases, while the housing size of SAV households may increase or decrease. The size of industrial area contracts due to the reduced parking land demand with SAVs. The firm production rises for a full SAV city. The city size may become more centralized or decentralized, depending on the marginal travel costs of AVs and the SAV market share. Household utility and social welfare may increase or decrease, depending on the maturity level of AV technologies. The proposed approach in this paper provided a useful tool for modeling the AV effects on the urban system and for evaluation and design of various urban and transportation policies.

Some directions for further extensions are listed as follows. First, we considered an auto city, in which the auto is the main mode of transportation. This is the case in many U.S. cities. However, in many Asian and European cities (e.g., Beijing, Hong Kong, Tokyo, Paris), public transportation has a big market share in the urban transportation. Therefore, it is important to explore the evolving effects of AV technology development on the modal share. Second, we focused on a linear monocentric urban configuration. However, many realistic cities have radial or circular structures (Li et al., 2013, 2024a) or polycentric urban configurations (Fujita and Ogawa, 1982). Therefore, it is worthwhile to extend the proposed framework to account for other urban forms. Third, the AV effects on traffic congestion, industrial pollution, and traffic emission were not considered. However, it is meaningful to extend to take into account such effects in a further study. Finally, for simplicity, parking of PAV commuters was assumed to be identical with that of TV commuters. It is anticipated that PAVs may be able to find a parking space automatically away from the worksite, thus significantly reducing the commuter parking search time, which would further favor AVs, and reduce the congestion induced by cruising for parking (Anderson and de Palma, 2004; Fagnant and Kockelman, 2015). There is, therefore, a need to incorporate the automatic parking behavior of PAVs in the model in future study.

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Appendix A: Proof of Proposition 2

First, we identify the locations of firms and households. With the assumption that all good trades take place in the city center, firms are located at the CBD area (i.e., industrial area), whereas households are located at the peripheral area (i.e., residential area), leading to border b_1 (or $-b_1$) between industrial area and residential area, as shown in Fig. 2.

Then, we look at the residential locations of PAV and SAV households. With the assumption of $\alpha_1^{\mathrm{PAV}} < \alpha_1^{\mathrm{SAV}}$, PAV households have incentives to reside at more peripheral locations in order to enjoy bigger housing spaces, cheaper housing / land rents and lower parking rents, compared to SAV households. This creates a critical location, represented by b_2 (or $-b_2$), such that the SAV households reside at the locations close to the industrial area, whereas the PAV households reside at the peripheral area, as indicated in Fig. 2.

Finally, we analyze the work locations of PAV and SAV households. Considering that PAVs need to occupy land for parking at both residence and worksite, whereas SAVs do not occupy parking land. For a given household residing at location *x* and working at location *y*, the disposable income of choosing to use PAVs and SAVs can, respectively, be defined as

$$\Lambda^{\mathrm{PAV}}(y|x) = w_f(y) - \alpha_0^{\mathrm{PAV}} - \alpha_1^{\mathrm{PAV}}(x-y) - \big(r(x)+r(y)\big)s_p, \tag{A.1}$$

$$\Lambda^{\mathrm{SAV}}(y|x) = w_f(y) - \alpha_0^{\mathrm{SAV}} - \alpha_1^{\mathrm{SAV}}(x-y). \tag{A.2}$$

Owing to $\alpha_0^{\mathrm{SAV}} < \alpha_0^{\mathrm{PAV}}$ and $\alpha_1^{\mathrm{PAV}} < \alpha_1^{\mathrm{SAV}}$, for a work location at the CBD area (implying a short commuting distance), the disposable income of SAV households is higher than that of PAV households, i.e., $\Lambda^{\mathrm{SAV}}(y|x) > \Lambda^{\mathrm{PAV}}(y|x)$. It is just reversed for a work location at the outer area (meaning a long commuting distance), i.e., $\Lambda^{\mathrm{SAV}}(y|x) < \Lambda^{\mathrm{PAV}}(y|x)$. By the intermediate value theorem, there exists a critical location, represented by b_0 (or $-b_0$), such that the SAV households choose to work at a more central area than the PAV households, as shown in Fig. 2. This completes the proof of Proposition 2.

Appendix B: Derivation of optimal SAV market share

The social welfare maximization problem for determining the optimal SAV market share θ can be formulated as

$$\begin{aligned}\max_{\theta}\ SW^{\text{AV}} &= \theta N U^{\text{SAV}}(\theta)+(1-\theta)NU^{\text{PAV}}(\theta)\\ &=\theta N\left(w_f(0)-\alpha_0^{\text{SAV}}-\alpha_1^{\text{SAV}}b_1-r(b_1)s_h^{\text{SAV}}+\gamma\ln s_h^{\text{SAV}}\right)\\ &\quad+(1-\theta)N\left(w_f(b_0)-\alpha_0^{\text{PAV}}-\alpha_1^{\text{PAV}}\left(B-b_0\right)-r(b_0)s_p-R_A\left(s_h^{\text{PAV}}+s_p\right)+\gamma\ln s_h^{\text{PAV}}\right).\end{aligned} \tag{B.1}$$

From the first-order optimality condition of maximization problem (B.1), we have

$$\begin{aligned}\frac{\partial SW^{\text{AV}}}{\partial\theta} &= N\left(U^{\text{SAV}}-U^{\text{PAV}}\right)+\theta N\left(\frac{\partial w_f(0)}{\partial\theta}-\alpha_1^{\text{SAV}}\frac{\partial b_1}{\partial\theta}-\frac{\partial r(b_1)}{\partial\theta}s_h^{\text{SAV}}-r(b_1)\frac{\partial s_h^{\text{SAV}}}{\partial\theta}+\frac{\gamma}{s_h^{\text{SAV}}}\frac{\partial s_h^{\text{SAV}}}{\partial\theta}\right)\\ &\quad+(1-\theta)N\left(\frac{\partial w_f(b_0)}{\partial\theta}-\alpha_1^{\text{PAV}}\left(\frac{\partial B}{\partial\theta}-\frac{\partial b_0}{\partial\theta}\right)-\frac{\partial r(b_0)}{\partial\theta}s_p-R_A\frac{\partial s_h^{\text{PAV}}}{\partial\theta}+\frac{\gamma}{s_h^{\text{PAV}}}\frac{\partial s_h^{\text{PAV}}}{\partial\theta}\right).\end{aligned} \tag{B.2}$$

Let $\partial SW^{\text{AV}}/\partial\theta=0$, and after some calculations, we obtain

$$\begin{aligned}&N\left(U^{\text{SAV}}-U^{\text{PAV}}\right)+0.5\delta M^2Ns_p(1-\theta)+0.5\theta N^2\left(\alpha_1^{\text{SAV}}\left(s_p-s_h^{\text{SAV}}\right)+s_h^{\text{SAV}}\alpha_1^{\text{PAV}}\right)\\ &+0.5(1-\theta)NM\left(\alpha_1^{\text{PAV}}\left(s_f-l_f\left(s_h^{\text{SAV}}-s_h^{\text{PAV}}-2s_p\right)\right)-\alpha_1^{\text{SAV}}\left(s_f+s_pl_f\right)+s_p\delta\theta M\right)\\ &-\frac{\theta N^2\gamma\left(\alpha_1^{\text{SAV}}-2\alpha_1^{\text{PAV}}\right)}{\left(2(1-\theta)N\alpha_1^{\text{PAV}}+\theta N\alpha_1^{\text{SAV}}+2R_A\right)^2}\left(\frac{2\gamma}{s_h^{\text{SAV}}}-2r(b_1)-\alpha_1^{\text{PAV}}(1-\theta)N\right)\\ &+\frac{\gamma\alpha_1^{\text{PAV}}N^2(1-\theta)}{\left(\alpha_1^{\text{PAV}}N(1-\theta)+2R_A\right)^2}\left(\frac{2\gamma}{s_h^{\text{PAV}}}-2R_A-\alpha_1^{\text{PAV}}(1-\theta)N\right)=0.\end{aligned} \tag{B.3}$$

The optimal θ satisfies Eq. (B.3). It is difficult to derive a closed-form solution of θ from this equation. One has to use a numerical method to solve it, such as bisection method.