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An Overview of the Impacts of Autonomous Vehicles on Urban Spatial Form

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Abstract: Based on a review of urban planning literature, this paper analyzes the impacts of autonomous vehicles on population distribution, parking land use, regional accessibility, street facility environment, and other features of urban spatial form. With variations in different cities and among different population groups, private autonomous vehicles are more likely to induce suburban migration than shared autonomous vehicles. While the use of autonomous vehicles may reduce parking space needed in cities and improve flexible layout of parking infrastructure, it can also lead to increased vehicle miles traveled. Compared with large cities, autonomous vehicles can greatly improve the regional accessibility in rural or suburb areas. With narrowed lanes, reduced road signs, and less traffic lights, more public spaces become available in the era of autonomous driving. However, intersections with reduced traffic control by traffic lights, along with increased passenger pick-up and stopping spaces, may become barriers for the smooth use of walking and cycling network. The paper also suggests planning policies for autonomous vehicles to address traffic congestion issues and environmental challenges in Chinese cities. **DOI:** 10.13813/j.cn11-5141/u.2022.0501-en

Keywords: intelligent transportation; autonomous driving; urban spatial form; accessibility

0 Introduction

As one of the major development directions of transport, autonomous vehicles (AVs) have attracted much attention both in China and abroad in recent years. According to relevant research, autonomous driving technology means not only a safer experience on the road [1–2] and more comfortable travel [3] but also lower travel costs [4] and higher socioeconomic benefits [5]. Having formulated or perfected the laws and regulations related to AVs, more than a dozen countries are fully committed to deploying autonomous driving demonstration areas and experimental sections, thus setting the stage for the era of unmanned driving. China attaches great importance to the development of AVs, with road testing and regulation legislation already taken in Beijing, Shanghai, Guangzhou, Shenzhen, and other cities, and plans for the pilot demonstration of intelligent connected vehicles (ICV) have been proposed by Chengdu, Chongqing, Xi'an, and other cities in the 14th Five-Year Plan in comprehensive transportation. In the *New Energy Vehicle Industry Development Plan (2021–2035)* issued in 2020, the General Office of the State Council identified the commitment to "commercial application of highly AVs in limited areas and specific scenarios by 2025" and "large-scale application of highly AVs by 2035". All this makes the era of autonomous driving just around the corner.

The influence of autonomous driving technology on the transportation system is self-evident. When it comes to planning and design, the reconstruction of road space brought by AVs and the changes in land use and urban structure caused by new travel behaviors will have a profound impact on cities. Autonomous driving technology works on transportation, space, and society in a sequential and conductive manner, which can be summarized by the ripple model [6]. In the ripple model of autonomous driving technology, the first circle presents the influence on transportation and travel behaviors, including travel cost, travel choice, carrying

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capacity of traffic, etc.; the second circle refers to the influence on various urban elements, including road facilities, land use, workplace and residence distribution, etc.; the third circle indicates the influence on the economy and society, including air quality, social equity, and public health, etc. Through a comprehensive study of the three circles, D. Milakis et al. [6] and Qin et al. [7] have found the influence of AVs on transportation, cities, and society.

Focusing on the relevant literature about the second circle, this paper aims to sort out the latest progress of international research on the influence of AVs on the urban spatial form. In terms of distribution of resident population, parking land, regional accessibility, and street facility environment, this paper discusses in detail the differences and similarities of research methods, objects, and conclusions, analyzes the influences that may be brought by AVs, and discusses how urban planning and policy-making respond to the changes brought by AVs by reference to the challenges faced by China's large cities in development.

The second circle in the ripple model of autonomous driving technology mainly involves road infrastructure, as well as facilities for parking, walking, and cycling, factors such as the location selection and land use for employment, housing, and leisure, and vehicle-related elements such as vehicle design, ownership, and use form [6]. From the perspective of urban planning, this paper will focus on the distribution of resident population, parking land, regional accessibility, and street facility environment based on the importance level of the elements of urban spatial form and the number of relevant studies.

1 Classification of AVs

The Society of Automotive Engineers has divided AVs into six levels from the perspective of automation level [8]: Level 0 stands for "no driving automation", Level 1 for driver assistance, Level 2 for partial driving automation, Level 3 for conditional driving automation, Level 4 for high driving automation, and Level 5 for full driving automation. Due to the insignificant influence of low-level AVs on travel behaviors, most of the existing studies focus on higher-level AVs, i.e., vehicles that do not require manual intervention and can independently drive under specific (Level 4) or all conditions (Level 5).

In terms of ownership form, AVs can be divided into private AVs (PAVs), shared AVs (SAVs) operated by enterprises, and autonomous buses operated by the government [9]. This paper mainly summarizes the former two AVs. Among them, there is no significant difference between PAVs and traditional private cars in terms of ownership form and mode of use, only except the participation of the driver; SAVs operated by enterprises can be interpreted as responsive autonomous taxis, which can serve multiple persons (carpooling) simultaneously or only one or more fellow passengers, with no ownership enjoyed by users.

2 Influence on the distribution of resident population

There are two main methods in the existing literature to study the influence of AVs on the distribution of the urban resident population. 1) Understanding the housing location preference of the respondents in the autonomous driving scenario through the questionnaire and inferring the changes in the population distribution in the city by reference to other factors (such as the respondents' current housing locations, socioeconomic statuses, and demographic characteristics, etc.) [10–12]. 2) Substituting new travel costs into the existing land use and transport interaction model or using the agent-based simulation model and other computer simulation tools to analyze the changes in urban population and land distribution based on the data about current urban transportation and the assumption that AVs can change the commuting costs [13–14].

Theoretically, AVs enable other activities during travel, which can improve comfort while reducing time costs of travel, increase acceptable commuting distance, and encourage people to move to the outskirts of the city. However, different studies report varied influences of AVs on the distribution of resident population, which mainly depend on the form of vehicle use, urban location, the status of the built environment, and individual factors of residents.

In terms of the use form of AVs, PAVs are more inclined to encourage people to move to the outskirts of the city than SAVs, thus causing urban sprawl and bringing about high vehicle kilometers travelled (VKT) and traffic congestion. P. Thakur et al. [14] studied the urban area of Melbourne in Australia and proposed that if all cars were PAVs, the outer suburbs would see a significant increase in population density and 30% rise in the passenger kilometer of cars in the morning peak hours; if all cars were SAVs, the central suburbs would see the most significant increase in population density but 9% decrease in the passenger kilometer of cars under the assumption that AVs reduced the typical value of travel time savings (VTT) by 50%. S. Carrese et al. [11] studied Rome in Italy and proposed that when the penetration rate of AVs reached up to 50%, there was a significant increase in the population density of the suburbs, which was accompanied by a decrease in the population density of the city center. In the case of a low penetration rate of SAVs in carpooling mode, only the commuting time of urban residents was reduced, and suburban residents would face more serious traffic congestion, with the overall commuting time of the city increasing by 13% (the penetration rate of carpooling is 0%) at most and the VKT increasing by 7%; when all AVs were SAVs in carpooling mode, the overall commuting time of the city would decrease by 19%, and the VKT would reduce by 2%. Compared with PAVs, SAVs are not inclined to lead to urban sprawl, which can be best explained by the following factors: 1) SAVs involve varied waiting times in different urban areas [13], making the travel time cost relatively high in areas far from the city center; 2) the single cost of an online taxi is believed to be higher than that of a private car [14] and is positively related to the travel distance, which hinders people's inclination to the outer suburbs to some certain extent.

In terms of urban location and built environment, AVs are more likely to bring about suburbanization in densely populated large cities. S. H. Kim et al. [10] conducted a questionnaire survey on 15 urban areas in Georgia, the United States and proposed that if AVs were widely applied, residents in Atlanta, the capital of Georgia in the United States, were more inclined to move to places farther away from their usual destinations than those in other regions. This can be explained by the wider area of activities in Atlanta where people are more likely to trade a longer commuting distance for their favorite residence; besides, there are more significant differences in the density of the built environment in the suburbs of Atlanta and the city center, compared with other regions, and relocation can meet the "pro-suburban" inclination of some groups.

In terms of individual factors, the current housing location, age, income, and family structure of people act on their choice of residence in the era of autonomous driving. As AVs can reduce commuting costs, people will emphasize factors such as housing quality and educational resources when choosing houses. In western countries, groups living in densely populated areas and families with one or more children are more inclined to move away from the city center. In addition, familiarity with electronic devices also represents a major factor behind the housing choice in the era of AVs. S. Carrese et al. [11] conducted a questionnaire study in Rome, Italy and proposed that residents in the city center were more inclined to move to the suburbs in the era of autonomous driving than those in the periphery, and residents' moving experiences had some influences. P. Bansal et al. [15] conducted a questionnaire survey among residents in Austin, the United States and noted that groups having more children, living in densely populated communities, driving and commuting alone, and showing strong educational backgrounds, were more likely to move out of the city center, while those familiar with electronic devices such as mobile phones were more likely to move closer to the city center for better SAV services. Zhang et al. [13] carried out a simulation study in Atlanta, the United States and noted that if the penetration rate of SAVs reached up to 100%, families aged over 40 years old (usually with higher economic capacity) tended to move closer to the city center for shorter waiting time for SAVs and more urban resources, while those aged below 40 years old would move further away from the city center for higher-quality houses or better public education.

Notably, the above conclusions about the influence of AVs on the distribution of the resident population are largely based on the assumption that autonomous driving technology can reduce commuting time. However, R. Krueger et al. [12] noted through an intention survey of residents in the urban area of Sydney that AVs would not significantly change the perceived value of travel time, and P. A. Singleton [16] noted that as most activities in the travel process were designed to kill time rather than to carry out efficient production, the influence of AVs on travel and residence choice also depended on time use preferences and travel activities of individuals [17–18]. Therefore, in order to study the influence of AVs on the distribution of the resident population, it is necessary to carry out social surveys tailored to specific cities to identify the needs and preferences of different groups for housing and travel.

3 Influence on parking land

Existing studies mainly focus on the area and distribution of parking land, but some studies have also further explored the influence of changes in the parking location of AVs on transportation and carbon emissions. Computer simulation tools such as the agent-based simulation model and the discrete event simulation model are common research methods. In other words, on the basis of current travel data, the parking behaviors of AVs under different scenarios are simulated with different parameters (such as the penetration rate of AVs, rules of charge for parking, etc.), and the influence on parking land is analyzed then.

In terms of the area of parking land, most studies show that SAVs can reduce the number of small- and medium-sized vehicles in cities through more intensive use, thus reducing the parking land. D. J. Fagnant et al. [19] conducted a simulation study on SAVs and noted that for a grid city of 10 miles × 10 miles (approximately 16 km × 16 km), if 3.5% of trips are taken by SAVs instead of traditional cars, one SAV was equivalent to 12 private cars to serve the travel and could save 11 parking spaces. L. Martinez et al. [20] made a transportation simulation study in Lisbon, Portugal and noted that 100% of the penetration rate of SAVs could reduce about 80%–90% of cars and save 84%–95% of parking spaces in the city, and the parking spaces required under the scenarios of carpooling and public transportation were even less. Zhang et al. [21] conducted a simulation study of SAVs and pointed out that for a grid city of 10 miles × 10 miles grid city, if 2% of the residents (about 10 000 people) used SAVs instead of private cars for travel, one SAV was equivalent to 14 private cars to serve the travel demand, with the parking demand of these SAV users reduced by about 90%. Besides, if carpooling service was introduced, or some passenger-less driving time was allowed, the parking demand would be further reduced. Zhang et al. [22] carried out a simulation study on the parking behaviors of SAVs in Atlanta and found that when 5% of families used SAVs to replace private cars, the parking land in urban areas could be reduced by about 4.5%. In addition, under the scenarios of free parking, pay-per-view, and pay-per-hour, the required parking land would be reduced in turn. Compared with traditional cars, AVs require smaller parking spaces and do not need facilities that serve people, such as elevators and signs, thus further cutting the area of the parking lot [23–24].

In terms of the distribution of parking land in urban areas, under different scenarios of charge for parking, SAVs tend to choose parking lots in different locations and with different land use properties [22]. When there is no charge for parking, SAVs are mainly parked in areas featuring frequent vehicle use, i.e., the city center and prosperous commercial districts; in the case of pay-per-view, SAVs will park themselves in areas with a lower land price; in the case of pay-per-hour, SAVs will be parked in underdeveloped communities, which may further weaken their land value and development potential. In addition, under the scenario of charge for parking, the demand of parking in central business district (CBD) and office land will be transferred to that in areas dominated by land for mixed purposes or residential land.

According to the above research, AVs can lead to the reduction or transfer of parking land in urban areas and have a positive impact on crowded urban core areas. However, reduced parking demand and flexible choice of parking location are often associated with higher VKT, which is especially evident for PAVs. A. Millard-Ball [25] noted that the parking of AVs represented essentially an economy-oriented behavior. By calculating the parking fee and the charge of driving to the parking lot (if any), it was found that PAVs could be parked at the public parking lot or at home or ran continuously (without parking) after they delivered passengers to the destination. Studying the data of travel and parking of cars in downtown San Francisco, the United States, A. Millard-Ball noted that in the era of autonomous driving, most of the private vehicles paying for parking tended to continue driving on the road after the delivery of their passengers and reduce the driving cost per unit time by deliberately creating traffic congestion, with the average single VKT increasing by 2.7 km; in addition, a few tended to park free of charge in the residential area near the destination during limited hours or drove home, with the average single VKT increasing by 10.3 km and 5.2 km, respectively. Through a simulation study of the parking behaviors of AVs in Seattle, the United States, C. D. Harper et al. [26] noted that when the penetration rate of AVs was relatively low (5%–25%), a PAV would travel an additional mileage of more than 3.5–4.0 miles (about 5.6–6.4 km) every day to find cheap parking space outside the CBD; when the penetration rate was relatively high (50%–100%), as low-cost parking space became in dire need, a PAV would travel an additional mileage of more than 5.6–8.4 miles (about 9.0–13.5 km) every day to find low-cost parking space, which resulted in an overall VKT growth of 0.9%–2.5% in urban areas. In addition, after the rush hour, traffic congestion may occur when AVs were moving to the parking lot outside the CBD. Through the mathematical analysis and research of the influence of AVs, R. Zakharenko [27] conducted a mathematical analysis and research on the impact of AVs and noted that in an imaginary semicircular city with a single center, as many as 97% of PAVs were parked in the "parking belt" outside the urban employment area, with the rest parked in the residential area. In view of the carbon emissions and traffic congestion due to the parking transfer of AVs, some studies believed that road pricing could serve as a restraint to some extent, and reserved transportation may divert the traffic flow. Furthermore, traffic congestion can be avoided through higher certainty of travel time [5, 25, 28–30].

4 Influence on regional accessibility

Regional accessibility depends on the number and distribution of various activities and the transportation convenience of the region [31–33]. AVs can work on regional accessibility by influencing the efficiency and cost of the transportation system and urban land distribution and changing the travel modes of various groups [34]. In terms of land distribution, AVs can act on regional accessibility by changing people's choices of housing location. Travel mode involves the elements in the third circle concerning social equity, e.g., affordability and availability of AVs. This chapter focuses on the transportation system. Mainly based on traffic simulation or travel activity simulation, the existing research analyzes the influence of AVs on regional accessibility by calculating the changes in travel costs they've brought.

According to relevant studies, AVs enable higher regional accessibility through larger road capacity, more flexible travel services, and fewer travel costs [4]. However, the increased traffic demand may weaken or even offset such benefits [3], and the relationship between public transportation and AVs represents a key element. J. Meyer et al. [35], based on the Swiss national traffic forecast model, studied the change in accessibility based on the travel time of motor vehicles in different administrative regions under different scenarios of AV application and noted that when SAVs (without carpooling) were applied in all aspects, large cities featuring prosperous public transportation systems would report an accessibility decrease of up to 29% due to the significant increase in travel demand caused by the shift of travel by public transport to cars, while rural areas weighed down by underdeveloped public transportation registered an accessibility increase. Similarly, according to research based on travel data in Singapore, SAVs may divert part of public transport flows and increase travel costs, thus weakening the accessibility of areas closer to CBD and equipped with prosperous public transportation systems [36].

In addition, compared with large cities, rural areas or suburbs weighed down by low transportation convenience and small road traffic volume are more likely to benefit from the improvement of regional accessibility by AVs [37]. Relevant studies show that rural areas see the improvement of accessibility in three scenarios: the use of PAVs on highways, the full use of PAVs, and the full use of SAVs; while in large cities, as the increase in travel demand exceeds the rise of road capacity in the latter two scenarios, the regional accessibility improves slightly or even decreases [35]. Through a simulation study on the accessibility of Gunma Prefecture, Japan, L. Luo et al. [38] noted that when traditional cars, PAVs, SAVs, walking, and bicycles were mixed, the prefecture reported an average accessibility increase of 23%–36%, which was higher in remote areas than in urban areas as AVs were applied. Through a simulation study of the travel behaviors in Seattle, the United States, S. Childress et al. [29] noted that in the optimistic case where AVs reduced travel time, increased road capacity, and lowered parking costs, all areas would see an improvement of accessibility, with a higher increase reported in the suburbs and rural areas distant from cities. Studying the travel demand model of Columbus, the United States, G. Vyas et al. [39] noted that AVs could enhance the accessibility of non-commuting travel by reducing travel time costs, with a higher increase to be seen in suburban areas currently dominated by travel by cars.

5 Influence on street facility environment

According to the thought of planners, government officials, and automobile practitioners on autonomous driving technology, a few studies have summarized the possible influences of AVs on street layout and facility environment from the perspectives of right-of-way distribution, road signs, pick-up & drop-off space, walking space, and cycling space [24].

1) Smaller lane width

AVs can narrow the motorway or cancel the safety separation belt between two-way lanes via more accurate driving, thus saving much road space for public space, sidewalks, non-motor lanes, and passenger pick-up & drop-off; according to relevant studies, with the same traffic volume, AVs can save 11%–12% of road space compared with traditional vehicles [40]. However, more efficient right-of-way distribution is based on the separation of AVs and traditional vehicles, which may take a long period of implementation and call for the cooperation of the government and autonomous driving industry to coordinate the research & development of Internet-of-Vehicles (V2X) technology and the construction of related road facilities [41].

2) Fewer road traffic signs and signal lights

Traffic signs and signal lights make up an important part of the transportation infrastructure and occupy some road space at the moment. In the future, vehicle-to-vehicle and vehicle-to-infrastructure (V2I) technologies will change the way transportation information is conveyed, thus reducing the demand for physical signs and signal lights and allowing more room for other purposes such as walking and cycling. However, at the stage featuring the coexistence of AVs and traditional cars, more road traffic signs may be there, so as to guide the driving of traditional cars.

3) More pick-up & drop-off space

AVs shift the pick-up & drop-off place from parking lots to places nearest to the destination, thus leading to the increased demand for pick-up & drop-off space in the city. Efficient, safe, and comfortable pick-up & drop-off space design will be one of the priorities for future urban designers and road engineers. In crowded space such as the city center, existing on-road parking space can be transformed into a pick-up & drop-off space, but its relationship with the traffic lane will significantly affect traffic safety and driving efficiency.

4) Possible influence on bicycles and pedestrians

AVs can reduce the driving space of motor vehicles and make it possible to broaden sidewalks and non-motor lanes, add more guidance signs for walking and cycling, and expand public space on the street, which can thus enhance the attractiveness of walking and cycling for transportation. However, AVs may also have negative effects. For instance, after the cancellation of traffic signal lights, AVs may not stop automatically, and the traffic flow will not be interrupted for a long time, which means a long waiting time for pedestrians and bicycles to cross the street on the ground. Setting exclusive time for pedestrians and bicycles at road intersections and using pedestrian overpasses, underpasses, and other three-dimensional crossing facilities may be major means in the future [42]. In addition, the pick-up & drop-off areas for AVs may fragment the pedestrian and bicycle network, which will leave walking and cycling interfered.

6 Policy and planning response of large cities in China

Through the above review of the research on the influence of AVs on the urban spatial form (Fig. 1) and in view of the main problems faced by large cities in China, such as intensified road traffic congestion, higher carbon emissions, and worsening travel environment, this paper gives the following suggestions for planning and policy-making of large cities in the era of AVs.

1) Carry out reasonable regulation of VKT of AVs

Due to the imbalance between workplace and residence and the gap between urban and suburban areas in housing prices, Chinese residents living in large cities are generally plagued by relatively long commuting distances. AVs, especially PAVs, may drive a large number of residents in central urban areas to move to the periphery, leading to longer average commuting distances and increasing the share of small- and medium-sized vehicles in medium and long commuting distances. In addition, high parking fees in the central urban area may make AVs parked in some far away places. Accordingly, AVs are likely to significantly increase the trips and VKT of cars in large cities and worsen traffic congestion and carbon emissions. Therefore, it is very important to carry out reasonable regulation of the VKT via traffic demand management. Cities like Singapore, London, and Stockholm have implemented a congestion charge policy for many years, which can control car travel and reduce traffic congestion by charging cars passing through specific areas during rush hours. Large cities in China have yet to implement such policies due to political influence and techniques, and the arrival of AVs offers an opportunity. For one thing, congestion charge, especially road use charge based on VKT, is necessary for controlling the passenger-load and no-load VKT of AVs; for another, V2X technology has also made the charge by VKT more feasible. Congestion charge should serve as an important means of transportation demand management in the era of AVs, so as to scientifically control car travel in cooperation with parking charge policies.

2) Encourage and standardize the use of SAVs

SAVs contribute positively to the control of urban sprawl and the reduction of VKT and parking land. Unlike traditional shared vehicles, SAVs do not need to be borrowed and returned at designated places, which can be understood as unmanned online taxis. As there is no driver, SAVs involve lower travel costs than traditional online taxis and eliminate the potential safety hazard from driver-passenger contact, so they are expected to have a larger market in large cities in the future. Therefore, the efficient and fair operation mechanism of SAVs will be of much significance. The government and enterprises providing SAV service should actively cooperate to develop a reasonable allocation mechanism to achieve the optimal balance between fleet size and waiting time, formulate scientific driving rules to avoid excessive VKT, and rationally allocate vehicle supply in different regions to take into account social equity and market benefits.

3) Build a transportation system featuring reasonable division of labor for high-capacity public transportation and SAVs

As SAVs represent an important form of future transportation, a clear and mutually complementary division of labor with traditional public transportation enables a more intensive and efficient transportation system. On the one hand, the passenger flow of buses in large cities in China decreases year by year [43], and many lines have low passenger volume, which results in long departure interval, high no-load rate, and a waste of resources. SAVs can replace buses with low load factor, offer more flexible services in an intensive way, and reduce VKT and carbon emissions. Particularly in the suburbs plagued by underdeveloped public transportation, SAVs will ensure easier access to ride than public transportation. On the other hand, under high population density in large cities, a significant shift from travel by public transportation to SAVs will increase road traffic volume, which thus exacerbates traffic congestion and reduces regional accessibility. Therefore, large-volume urban rail transit should always maintain its dominant role, while SAVs can serve as a more flexible and efficient mode to supplement the passenger flow of the urban rail transit and thus achieve seamless connection.

4) Value the construction of the facilities for pedestrian and bicycle crossing the street and roadside pick-up & drop-off

Although the reduction of vehicle driving space brought by AVs has provided more opportunities for the construction of walking and cycling transportation systems, the absence of traffic signal lights for controlling the vehicle flow at road intersections will affect pedestrians and cyclists' efficiency in crossing the street, and the lack of crossing facilities has always been the weakness of the urban walking and cycling transportation systems in China. Due to different implementation subjects and uncoordinated construction time sequence of the road sections, there is usually a lack of facilities for pedestrians and cyclists at road intersections; besides, large-scale blocks are also weighed down by the lack of crossing facilities, which makes walking and cycling inconvenient. As the era of autonomous driving tends to set higher standards for crossing facilities for pedestrians and cyclists, it is crucial to provide high-quality crossing facilities and guidance signs and formulate the rules for AVs to give others the right of way. In addition, the era of AVs also shows greater demand for roadside pick-up & drop-off facilities, which poses more serious challenges to space and design. Despite the small size of pick-up & drop-off space for AVs compared with that for bus stops, vehicles will stop more frequently, and the relationship with traffic flow will be more complex. As a result, separating travel and parking flows, providing safe and convenient waiting facilities, and avoiding conflicts with walking and cycling traffic flows, are important links of improving the travel experience of AVs.

5) Coordinate the construction of road infrastructure and the research & development of autonomous driving technology.

Autonomous driving technology will inevitably usher in a mature development, but it will take a long period before the all-round application of AVs. The stage of technology development and market penetration rate both work on the effectiveness of AVs. Infrastructure such as smart roads represents not only a prerequisite but also a necessary requirement for the widespread application of AVs. The government and R&D vehicle enterprises should keep close communication, coordinate the time sequence of the construction of road infrastructure and research & development of autonomous driving technology, and avoid the waste of resources on both sides, so as to minimize the negative impact on the city during the popularization of AVs.

6) Improve traffic data collection and carry out social surveys

Most of the existing international studies are based on high-precision urban travel data, with different conclusions drawn under varied assumptions and scenarios. Furthermore, there are significant differences between foreign cities and Chinese cities in terms of population density, residential mode, travel volume, and share rate of travel, which makes the conclusions obtained not totally consistent with China's national conditions. However, the collection of basic traffic data in Chinese cities has yet to be perfect and transparent, which makes it difficult for the academic community to carry out empirical research and has hindered the simulation of the application of AVs in cities. In addition, as people's travel behaviors and lifestyles in the era of AVs are closely related to the cultural and social environment and individual factors, extensive social surveys lay a foundation for understanding and prediction. Accordingly, it is necessary to improve the collection of traffic data and conduct social surveys for the planning response of the era of AVs.

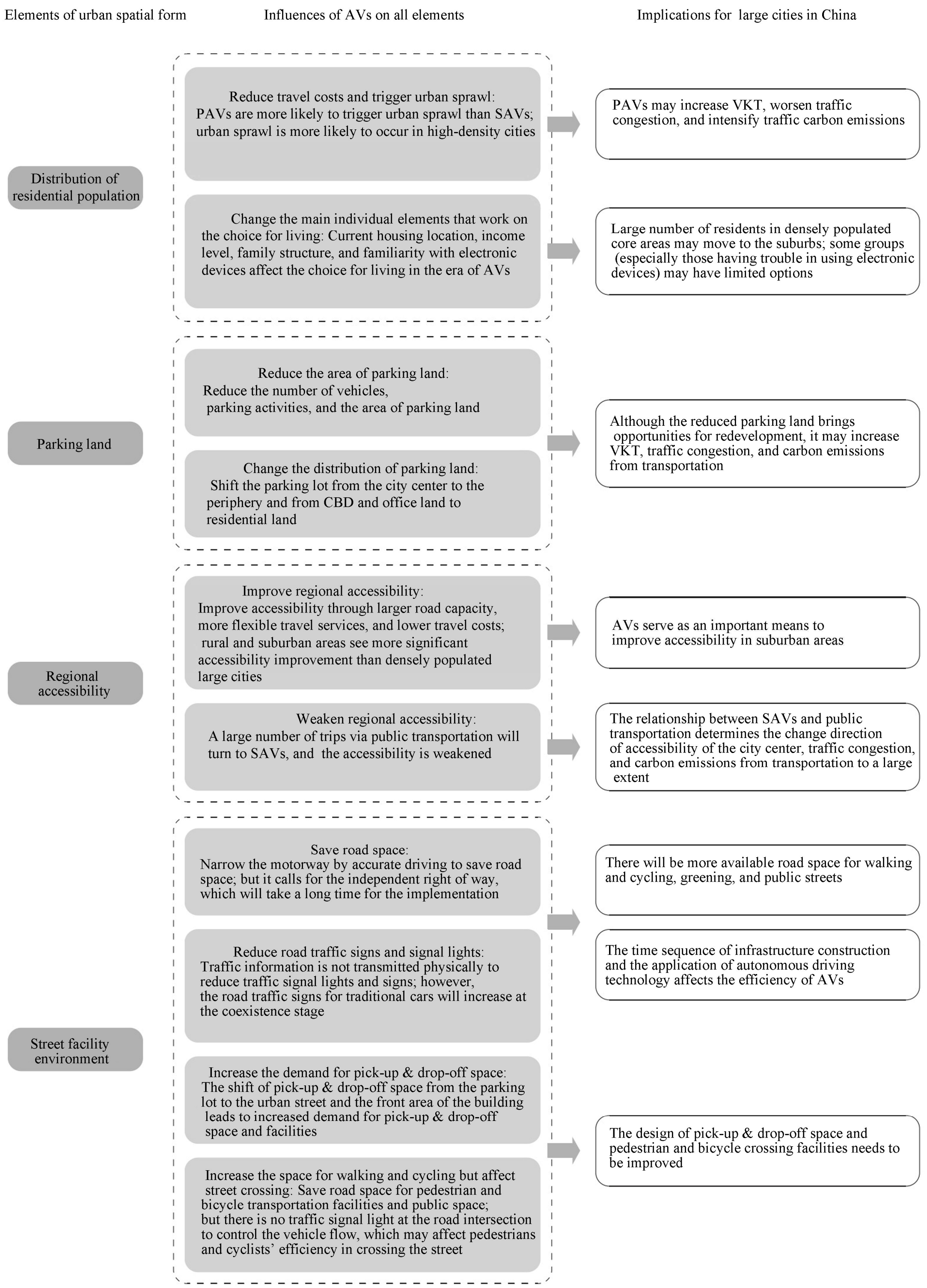

Fig. 1 Influences of AVs on four types of elements of urban spatial form and implications for large cities in China

7 Conclusions

Like other technological progress, AVs will have a profound influence on cities, which is diverse and complex. Focusing on the four elements of urban spatial form, this paper reviews foreign literature and comes to the following conclusions. 1) AVs may lead to urban sprawl and worsen traffic congestion and carbon emissions by changing travel costs and parking modes, and this negative impact can be weakened by reasonable transportation demand management. 2) AVs can enhance the accessibility of underdeveloped areas, but in densely populated areas, they may increase travel demand and thus weaken the accessibility of transportation, so it is crucial to build a transportation system with a reasonable division of labor between public transportation and SAVs. 3) AVs can release more road space for other modes of transportation and public life in urban areas, but the change in road layout requires a high market penetration rate and independent right of way of AVs. Accordingly, the government and planning practitioners should give positive responses and work to promote the wide application of autonomous driving technology in terms of the construction of smart infrastructure, street design for AVs, etc.

With the advent of new technologies, the government and planners should earnestly carry out scientific research and social surveys to find support for the design of planning policies, avoid another urban disease due to motor vehicles, and make new technologies available to cities, so as to make them as strong tools boosting cities' response to climate change, environmental quality, and social equity.

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