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Reconsidering AVs future: A socio-spatial perspective

Juhyun Lee [a,1], Tae-Hyoung Tommy Gim [b,*,2]

[a] Department of Urban Planning and Design, Xi'an Jiaotong Liverpool University, China
[b] Graduate School of Environmental Studies, Seoul National University, Republic of Korea

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ABSTRACT

Can Autonomous Vehicles (AVs) contribute to a balanced distribution of accessibility? Despite optimism regarding technological advancements in transport, social outcomes from AVs are highly uncertain, dependent on unknowns including technology and transport mode. We aim to critically consider how different AVs' future situations influence accessibility, grounded on continuous debates on the socio-spatial implications of transport development. Referring to the two key uncertain factors, we deliberated spatial changes that could be induced by AVs, and reflect how such changes might influence accessibility and equity. Our research indicated that high automation and strong shared mobility together can enhance accessibility for all if shared autonomous vehicles are affordable and available for disadvantaged areas. High automation without shared mobility can have negative impacts in inner cities, due to increasing congestion and limited opportunities for effective land development. With limited automation and strong shared mobility, we may see better distribution of accessibility across a wider area, owing to advanced public transport and mobility hub development. We posit that, despite high expectations, the socio-spatial consequences of AVs are far from certain and critical conditions necessary for accessibility for all in varied mobility futures should be carefully considered.

1. Introduction

Across the globe, there has been continued investment in transport to achieve a socially, environmentally, and economically sustainable city and region [1,2]. However, transport development has not necessarily guaranteed enhanced accessibility and quality of life for all (Geurs et al., 2007; [3,4]). Differential outcomes from transport development (e.g. differential accessibility across a city) are often identified, due to the long-term spatial changes induced by such development [5,6]. The planning and evaluation of equitable transport provision are increasingly being emphasized to achieve broader sustainability outcomes of transport development [7,8].

In the 21st century, we have witnessed different forms of technological advancement and innovation in transport. While shared forms of transport have been on the rise, automation is one facet that is increasing and expected to increase [9]. There has been optimism regarding the effects of future mobility, particularly autonomous vehicles (AVs) – e.g. improved safety and sustainable use of resources [10, 11] however, its wider societal impacts have been increasingly questioned (e.g. Sparrow and Howard, 2020). Some scholars (e.g. Ref. [12, 13]) highlighted that the contribution of the possible futures of AVs to *accessibility for all* is highly uncertain, being dependent on factors such as the levels of technological development and shared use of vehicle. Different transport futures could lessen or exacerbate the existing unbalanced distribution of accessibility [14]. Overall, it is questionable whether AVs will contribute to tackling the wicked problem related to accessibility or to making it worse.

In practice, discussion on potential impacts of AVs (e.g. Ref. [15]) often concentrates on technological aspects such as traffic flow efficiency and road capacity while impacts on or emerging from urban and social contexts are relatively understudied (Faisal et al., 2020). Recent studies on the social outcomes from AVs (e.g. Ref. [16,17]) have increasingly stressed the importance of understanding if and how AVs will contribute to a balanced distribution of accessibility across a city (and region) and social groups. However, there has been limited investigation into this issue across all possible situations that could arise

* Corresponding author.
E-mail addresses: juhyun.lee@xjtlu.edu.cn (J. Lee), taehyoung.gim@snu.ac.kr (T.-H. Tommy Gim).
[1] Postal address: No.111 Renai Road, Suzhou Dushu Lake Higher Education Town, Suzhou Industrial Park, Suzhou, P.R. of China 215123.
[2] Postal Address: Graduate School of Environmental Studies, Integrated Program in Regional Studies and Spatial Analytics, Interdisciplinary Program in Landscape Architecture, Institute for Sustainable Development, and Environmental Planning Institute, Seoul National University, Gwanak-ro 1, Gwanak-gu, Building 82, Room 222, Seoul 08826, Republic of Korea

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from varying degrees of automation and shared mobility [13,14,18].[3] We see the need for reflections on the spatial changes occurring under various potential situations, and the different implications of such changes for *accessibility for all*.

This paper aims to critically consider how AVs might affect accessibility[4] from a socio-spatial perspective. Our inquiry is based on the ongoing debates on the socio-spatial implications of transport, which concerns the spatial changes induced by transport development, and the influence of such changes on accessibility and (in)equity[5] [19,20]. We consider four potential AV situations that can arise from two key uncertain factors affecting the AVs social outcomes – i.e. the level of automation technology (high or low level) and the degree of shared mobility (high or low) [14,21]. Using a conceptual model, in each situation, we unpack spatial changes that can be brought by AVs and explore the implications of such changes for accessibility and equity. Furthermore, we discuss critical elements necessary for a balanced distribution of accessibility in each situation.

The remainder of this paper is structured in four sections. Section two revisits an overview of discussions on the socio-spatial implications of transport development (2.1) and discusses key uncertain factors affecting the future of AVs (2.2). These two sections serve as the theoretical basis for a conceptual model used in this paper. Then we explain methodology (2.3) including a conceptual model that describes the socio-spatial implications of AVs under four potential situations derived from the two key uncertain factors. Section three, the main part of the paper, presents the result of analysis, which includes possible changes induced under each situation and their implications for accessibility and equity. Section four discusses critical conditions for greater accessibility of all, followed by the Conclusion.

2. Understanding the socio-spatial implications of transport and AVs

2.1. Socio-spatial implications of transport development

Transport studies have increasingly discussed the socio-spatial implication of transport projects, especially focusing on distribution of accessibility across varied localities and social groups (e.g. Ref. [22]; Smeds et al., 2019). Many scholars – e.g. Pereira et al. [23] and Lubitow et al. [24] – argued that investment in transport development does not necessarily lead to enhanced life opportunities for all, questioning its social sustainability benefit. Lee et al [19] emphasized that long-term spatial changes (e.g. changes in spatial structure) induced by transport development could be attributed to differential accessibility across a city and region.

Transport development has a strong influence on spatial structure (e.g. polycentric or monocentric development) and form (e.g. high-density commercial development around transport nodes), eventually affecting accessibility to opportunities (e.g. time/distance to reach a range of jobs and services[6]) [25–27]. Over a longer period, differential distribution of accessibility (e.g. across center and peripheral areas; urban and sub-urban areas) is often observed, due to the varied level of transport development as well as associated spatial development across a city and region[7] [28,29]. Such spatially differentiated outcomes are often closely related to socially differential distribution of benefits [5,30]. For example, people living in the most disadvantaged areas (e.g. low-income groups living in the periphery) are likely to experience only minimal benefits of transport projects, whereas the least deprived groups in the inner city may benefit from the increasing accessibility [7]. This differential distribution could lead to spatial mismatches between low-income groups and accessibility to job opportunities, affecting social equity [31].

Overall, current discussion on the social outcomes from transport development indicates that the socio-spatial implications of such development are closely related to: (i) spatial changes induced by transport development – e.g. changes in spatial structure, and land use patterns and local environment over time, (ii) how transport development and the associated spatial changes together influence the differential distribution of accessibility across varied localities (e.g. center and peripheral area; urban and sub-urban), and (iii) equity (accessibility for all) (Fig. 1).

2.2. AVs future and uncertainties

The introduction of autonomous vehicles can be one of the most significant technological advances of the 21st century. The technological innovation in transport creates numerous benefits to society including enhancement in road capacity, improved traffic safety, reduced congestion, and greater mobility options [13]. In practice, AVs' impacts on society are uncertain, as they depend on many factors. For example, the potential impacts of AVs on accessibility are closely related to the level of technological advancement (e.g. full or low automation) and the degree of shared use of transport (e.g. shared or non-sharing mobility services) [13,21,32]. These factors can be influenced by external conditions such as consumer acceptance [33], government policy and regulation for automation and shared mobility [34], and broader socio-economic contexts[9] (Thing and Wu, 2016).

Above all, the future of AVs will be directly related to the levels of the emerging technology (automation). The Society of Automotive Engineers (SAE) (2014) distinguishes six levels, ranging from 'no automation (Level 0)' to full automation (Level 5). In Level 5, cars drive fully automatically in any situation (e.g. urban and rural settings) and a driver does not need to control a vehicle. In Levels 1 and 2, drivers must carefully monitor roads, whereas in Level 3 (conditional automation), the technology does this task, although drivers must still be 'fall back ready' [21]. The European Road Transport Research Advisory Council

[3] For example, some studies investigate AVs' impacts on accessibility, only considering full automation and/or shared mobility, rather than holistically consider all possible situations (high or low automation and high or low shared mobility).

[4] By accessibility, we mean 'the extent to which land use and transport system enable individuals to reach activities or destinations using transport modes' as defined by Geurs and van Wee (2004).

[5] This refers to accessibility (in)balance among social groups. For example, people living in the most disadvantaged areas (e.g. low-income groups living in the periphery) can experience only minimal benefits of transport projects, whereas wealthy groups living in the inner city may benefit from increasing accessibility [7]. This differential distribution could lead to spatial mismatches between low-income groups and accessibility to job opportunities, affecting social equity [31].

[6] This includes local facilities and amenities include schools, libraries, basic medical services, sport facilities, parks, and security services, and local stores, which are vital for the livability of a local community (Yhee et al., 2020).

[7] In a city center, continuous investment in transport leads to the spatial concentration of economic and social activity in the area (i.e. high-density mixed-used development around transport nodes), resulting in further transport projects, thus increasing accessibility [78]. In the periphery, with low demands for land development and limited investment in transport projects, the level of accessibility increase can be limited. The differential accessibility between urban and sub urban areas can be also attributed to the differential level of transport development and associated spatial development between two.

[9] It should be noted that this research considered AVs' futures in the general context of developed countries, rather than contexts of both developed and developing countries.

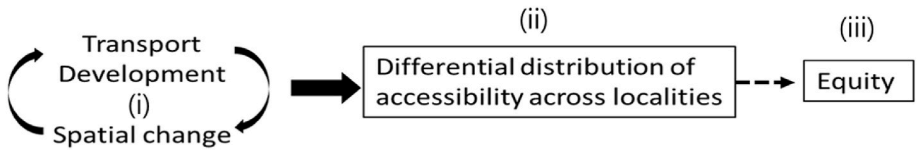

Fig. 1. Perspective of socio-spatial implications of transport development.[8].

[8] It should be noted that in this figure, the socio-spatial model of transport development is rather simplified on purpose to be better integrated into the conceptual model of the research in Section 2.3.

(2021) estimated that in 2050, all newly registered vehicles will have automation but at different levels. However, in practice, it is difficult to predict the future of AVs, especially when and if the full automation will be possible. Years of testing and regulatory approval will be necessary before they are acceptable and commercially available in most jurisdictions (Litman, 2021). Hopkins and Schwanen (2021) alerted that the progression among Levels is not linear and could be varied depending on user groups, historical and geographical contexts, vehicle types, and ownership models.

Another key factor affecting AVs future is the degree of shared mobility [14,35]. The rise of the sharing economy has influenced mobility, enabling new forms of transport that were previously small scale or informal in nature (e.g. ridesharing, rider-sourcing) (George and Julsrud, 2017 [36]). Thanks to advances in technology, one of the phenomena expected in the future can be an increase in supply and demand in shared mobility services, and vehicles might entail less responsibility for individual drivers [37,38]. People may shift in greater numbers to using the shared vehicles if such shared services are affordable and reliable [39,40]. However, if they are uncomfortable or pricey, more households will continue to own private vehicles [41]. Shared autonomous vehicles (SAVs) could provide convenient and comfortable mobility on-demand services to diverse groups while contributing to sustainable development of a city (e.g. shared electric automated mobility services) [42,43]. Overall, the success of SAVs will be dependent on travel cost and time, travel purpose, health and security implications, as well as socio-cultural contexts ([44,45]; Liridona et al., 2020).

Overall, with these uncertain factors, it is difficult to predict whether AVs will necessarily create positive or negative impacts on accessibility and quality of life for all. More people could travel easily and longer distance if the service is efficient and affordable, serving the needs of various users. AVs may well have more negative than positive implications for equity when only few can enjoy the up-to-date service [46]. In this context, we need to map the key uncertain factors – i.e. the level of automation and degree of shared use of vehicles that could directly affect AVs social outcomes – to establish different potential situations. In each potential situation, the socio-spatial implications of AVs can be critically considered and reflected. The details of a methodological approach will be explained in the next section.

2.3. Methodological approach underpinning a conceptual model

Following the discussion above, we propose a conceptual model to critically consider the socio-spatial implications of various potential AV situations, drawn from varying levels of automation and shared mobility (see Fig. 2). This model concerns spatial changes that can be induced by AVs and the implications of such changes for accessibility and equity. It is grounded on the continuous debates on the socio-spatial implications of transport development and takes an exploratory approach to future thinking (Banister and Hickman, 2013 [47]).[10] It should be noted that our focus is not to establish specific scenario(s) that is more likely to happen or more desirable, but to unpack various socio-spatial implications and explore critical issues of the different potential AV situations. This approach considers the possible wicked problems and opportunities within various situations, rather than focusing or advocating for a single situation [48].

As seen in Fig. 2, we mapped the key uncertain factors into four potential situations: 1. high automation + high shared mobility; 2. high automation + low shared mobility; 3. low automation + high shared mobility; and 4. low automations + low shared mobility. High automation refers to SAE Level 5 (full automation), and low automation refers to SAE Levels 3–4 (conditional automation requiring drivers still ‘fall back ready’). For each situation, we deliberated on: (a) spatial changes that can be induced by AVs over time, (b) how such changes and AVs together can affect accessibility across varied localities, including center and periphery; urban and sub-urban areas, and (c) long-term implications for equity.

To identify the socio-spatial implications of AVs, this paper involved an extensive literature review and our own analytical thinking, based on the conceptual model in Fig. 2. The extensive review focused on AVs potential impacts on accessibility and equity, based on various assumptions (e.g. SAE Levels, deployment schemes).[11] We reviewed numerous studies related to potential impacts of AVs on spatial structure and form (e.g. sub-urbanization, (re)densification) as well as transport (e.g. traffic volumes and costs), and wider long-term impacts (e.g. impacts on different groups). These studies used a range of methods including systematic literature review, scenario-building, simulation studies, experts survey or interviews, or combination of more than two of these. Some studies provided more detailed analyses than others.

Relevant peer-reviewed papers (journal articles, conference proceedings, and books) published in English between2015[12] and 2023 were collected from the Web of Science and Google Scholar. The key words for AVs (e.g. vehicle automation, autonomous vehicle(s), autonomous car(s)), “accessibility”, and “equity” have been used jointly through the Boolean operator AND. We also used combinations of keywords for AVs, and keywords for the impacts of AVs (see Table 1), supplemented by forward and backward snowball techniques. Papers

[10] The main aim of the exploratory approach is to identify plausible futures and key challenges, and to examine potential implications of the futures for policy and practice. It is based on plausibility rather than probability or projection. It typically takes two dimensions of factors, within which four potential situations can be constructed. Such an approach is appropriate for this research in that our focus is not to identify specific event or course of action(s) that is most probable or desirable, but to unfold various potential socio-spatial implications each situation and relevant critical issues.

[11] Some papers use only one assumption (e.g. high automation) while others use more than one. A few papers which do not clarify which automation levels and/or degree of shared mobility are assumed are not included in the review.

[12] Milakis et al. [46] highlight that discussion on AVs have expanded from the focus on technical aspects to broader societal impacts since 2015.

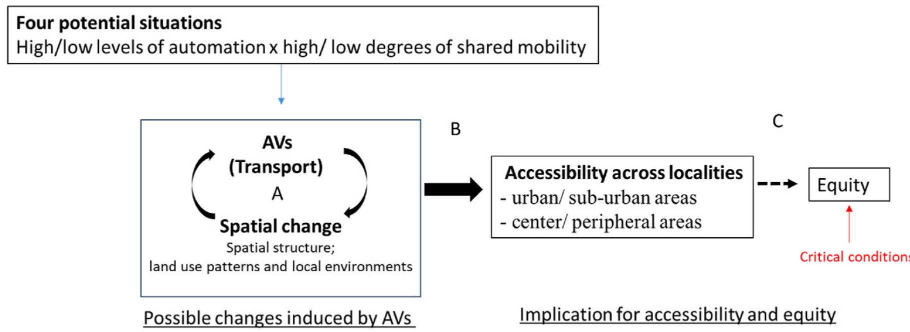

Fig. 2. A conceptual model to examine the socio-spatial implications of potential AV situations.

Table 1
Key words and examples of impacts of AVs.

	Key words	Examples of impacts
AVs	vehicle automation, autonomous vehicle(s), autonomous car(s), self-driving vehicle(s), self-driving car(s)	N/A
Impacts - spatial changes	Urban form, urban structure, built environment, city, land use, environs	Changes in density and diversity of land use, clustering, densification, sub-urbanization, and re-densification of inner cities
Impact -transport changes	Cost, capacity, traffic volumes, modes, comforts, accessibility	Changes in vehicle kilometer traveled, road capacity, volume of car traffic, travel time, and travel cost
Wider impacts on society	Social, equity, social impact(s), wider impacts, society	Differential impacts on high- and low-income groups; differential impacts across the least and most advantaged areas in cities

exploring the impacts of AVs with various assumptions in great details (e.g. Ref. [14,21]) were included using backward snowballing. Once the literature review was completed, the results were grouped according to the four potential situations of AVs used in this research. The implications for accessibility and equity, and critical conditions for accessibility for all are explored based on our own analytical thinking as well as the literature review.

3. Analysis of the socio-spatial implications of different AV situations

3.1. Situation 1: high automation and high shared mobility

In Situation 1, the assumption is that automation technology is developed to a high level (Level 5), and people are extremely willing to share their transport modes (high level of shared mobility). With full automation, a driver does not need to control a vehicle at all on all roads and in every situation.

3.1.1. Possible changes

If full automation and high degree of shared mobility are achieved, AVs could potentially offer efficiency, affordability, and comfort [49]. People can enjoy cheaper services (due to car- and ridesharing) while an increase in IoT capability contributes to improving traffic behavior (Athanasopoulou et al., 2019 [50]). Thanks to the productive use of time during a trip, affordable travel cost, and an increase in road capacity [51], many people might move out from cities, resulting in sub-urbanization ([17]; Gelauff et al., 2017; [52,53]). In city centers, due to the high degree of shared mobility services, the needs for parking space and transport infrastructure may decrease while the chances for newly available land use increase [14,43]. This can create opportunities for the re-densification of inner cities if the available land is planned for more compact use. The densification, in turn, can further boost the demand for a well-functioning shared transport system (Yu and Peng, 2019 [54]).

3.1.2. Implications for accessibility and equity

With the spatial changes (i.e. sub-urbanization and re-densification of inner cities) and the increase in efficiency of transport system, Situation 1 is likely to contribute to enhancing accessibility to opportunities across a wider area. People living in both urban and sub-urban areas can access more services in the redeveloped and newly developed areas efficiently. Moreover, more diverse groups (e.g. children, the elderly, people with disabilities) could enjoy travelling.[13] In this context, a more balanced distribution of opportunities across space and possibly among social groups can be expected. However, we noted that in practice, a privatized SAV service could focus on areas where many people live or work (e.g. city centers) in order to maximize profits of the service (Sparrow and Howard, 2020 [55]). Such a case may create negative impacts on social equity because people living in the disadvantaged areas, which are often deprived [7], could experience on average longer travel times than affluent areas. This situation will worsen if public transport completely disappears because of competition between the public and private services [56]. In the long term, some areas (communities) could suffer due to decreased housing affordability [29,57]. Increased demands for land (especially when former parking spaces are replaced with commercial or residential uses) can increase land prices, resulting in displacement of lower income groups [58].

3.2. Situation 2: high automation and low shared mobility

In Situation 2, the assumption is that automation technology is developed to a high level (Level 5), and a majority of users are reluctant to car share. People are attached to car ownership and want to enjoy the various benefits of the advanced technology.

3.2.1. Possible changes

If the full automation is achieved and the level of vehicle ownership is high, more people might prefer to drive on their own more frequently and over longer distances, thanks to the high-level privacy and comfort [21]. Certain types of collective transport (e.g. self-driving minivans) will exist since not everyone can afford luxurious AVs ([59]; Schluter al., 2021). In this situation, overall congestion levels are expected to be high, especially in a city, due to the high level of volume of traffic and

[13] It should be also noted that in Situation 1, as more diverse groups (e.g. children, the elderly) can travel, the total level of vehicle kilometers traveled might increase [21], and, in this context, the gains in the reduction of the number of vehicles and the need for parking space might not be as much as expected.

the high demand for parking places [21,60]. With the increasing traffic pressures and the lower livability in cities (due to the traffic congestion and pollution), some businesses might decide to relocate to sub-urban areas. Moreover, thanks to the comfort and convenience of the fully automated vehicles, some residents may move to countryside areas that were previously unpopular or inaccessible in order to enjoy a better living environment (Gelauff et al., 2017; Jeong et al., 2015). Gradually, suburbanization of some commercial, residential and recreational functions are expected [14].

3.2.2. Implications for accessibility and equity

In Situation 2, while people enjoy leisure or practical activities in AVs, the accessibility benefit in urban areas could be limited due to heavy traffic congestion resulting from induced demand for travel and parking in the city. Some urban residents might experience decreasing accessibility to jobs as well as services, especially if they need to travel to workplaces that have been relocated to sub-urban areas. In the long-term, the inner city may suffer from various health and safety issues stemming from high levels of traffic and congestion [61]. In contrast, suburban and rural areas may see increasing accessibility, especially if full automation helps induce more efficient use of transport infrastructure and productive use of time during trips [62,63]. In this situation, AVs can contribute to spatially balanced distribution of opportunities, rather than increasing the disparity between urban and sub-urban areas. However, in a broader context, this is likely to have negative impacts on social equity. People who cannot afford luxurious AVs or transport services could be excluded from the benefits of vehicle automation, which are mainly accessible to people with higher incomes [13,17]. Vulnerable social groups, especially those living in low-demand areas without cars, could receive limited accessibility benefits. Moreover, in the long-term, further sub-urbanization of urban activities could lead to higher travel times and costs, decreasing accessibility for certain disadvantaged groups [64,65].

3.3. Situation 3: low automation and high shared mobility

In Situation 3, we assume that the advancement of automation technology is limited (conditional automation – Levels 3,4), and that the majority are extremely willing to share their transport modes. Drivers must still be 'fall back ready' especially in congested cities with many different types of road users.

3.3.1. Possible changes

In this context, automation could trigger innovation in the mass transit system (e.g. trains, metro, and trams), which travels along separate routes, resulting in higher frequency of travel, lower travel cost, shortened waiting times, and seamless transit [21,66]. Thanks to the great use of sharing vehicles and autonomous mass transit, fewer cars and less traffic congestion are expected. The efficient multi-modal systems could lead to population clustering and densification of land use around key transport nodes (Gelauff et al., 2017 [67]). Gradually, mobility hubs can be (re)created around these key nodes and key socio-economic activities can be (re)organized around the hubs. In this context, a city is likely to gradually (re)transform into a polycentric urban structure [27,68]. Such a polycentric structure could induce further concentration of activities around the hubs, triggering land (re) development and transport projects [19]. With the space that is no longer required for car parking, further densification of inner-city areas is also expected [14].

3.3.2. Implications for accessibility and equity

Due to the advanced transit system and the (re)development of land around mobility hubs across the city and region, accessibility could increase across a wide area. People living in both the periphery and the center could benefit from easier access to jobs and services [69]. In this context, diverse social groups may benefit from the enhanced accessibility. However, we noted that the cutting-edge mass transit and the development of multi-modal transport hub might not always guarantee greater accessibility for all. For example, if there are no affordable ride-sourcing services linked to mass transit [56], those who live in disadvantaged areas might experience only minimal accessibility benefits. People living in peripheral areas, which are often deprived [7], could end up spending more time and cost on reaching transport than those living in the center ([70]; Li et Zhao, 2022). In the longer run, increasing demands for land development around key transport nodes might drive land prices higher [7], especially with the gradual change to a polycentric spatial structure [68]. Such situations can trigger a gradual gentrification process in the area (Grube-Cavers and Patterson, 2014 [29]). Some people, especially low-income groups, could suffer from decreased housing affordability, consequently being displaced from those areas.

3.4. Situation 4: low automation and low shared mobility

In Situation 4, the assumption is that automation technology is limited (conditional automation) while the majority is attached to car ownership. Vehicles could drive autonomously to a limited extent (e.g. highways) and drivers must still be 'fall back ready' most of the time.

3.4.1. Possible changes

If technological advancement is limited and car ownership is high in the future, there might be an increase in traffic volume, travel time, and lack of parking space due to the easy use of private cars. In this situation, limited spatial changes are expected both in urban and sub-urban areas.

3.4.2. Implications for accessibility and equity

With limited spatial changes, AVs are unlikely to particularly affect accessibility nor deepen equity issues. Limited accessibility in peripheral areas will persists. People who cannot afford a car and live in sparsely populated areas will likely suffer from limited access to jobs and services located in cities. Overall, compared to the other situations, the socio-spatial effect of Situation 4 can be limited.

4. Discussion on critical conditions for accessibility for all

Our critical investigation indicates that in any of the four potential situations, accessibility for all is not guaranteed despite the optimism regarding the effects of future mobility [48]. In each situation, we can anticipate 'wicked' problems [11] as well as opportunities to address issues related to accessibility (in)equity. In this context, critical conditions necessary for social benefit in various situations should be carefully considered. All the relevant wicked problems and opportunities should be thoroughly interrogated, rather than one situation being focused or advocated. Based on the socio-spatial implications of AVs identified in this research, we discuss critical elements for ensuring "accessibility for all" and the related policy implications.

One may consider that the combination of advanced technology and shared mobility (Situation 1) is crucial for enhancing accessibility across a city among different social groups. However, the existing equity could be exacerbated or reduced, depending on the extent to which shared AVs cover wider areas (e.g. low-demand areas including the edge of satellite cities) [32]. *Affordability and availability of shared mobility innovation* are critical conditions necessary for greater accessibility for all. The business model of shared mobility services can play a role in either increasing or decreasing accessibility inequity, eventually contributing to either integrating or segregating urban space [71]. Moreover, it is critical that land use policy considers using the newly available lands for varied purposes in accordance with societal needs [72]. For example, some of the former parking space and infrastructure can be transformed into open green space or bicycle parking (Lee and Anderson, 2014). A compact city policy focusing on public interest and social justice over a longer period [73] can also contribute to (re)creating attractive and livable environments.

Limited advancement of technology (conditional automation) with shared mobility (Situation 3) could be the most realistic situation, in which AVs contribute to both a socially and spatially balanced distribution of accessibility. Thanks to autonomous transit services and land (re)development around mobility hubs, we can expect an increase in accessibility across social groups and a wider area. However, such effects will be affected by the extent to which last mile connections are available, especially for those who live in peripheral areas. Without *affordable last-mile connections*, there might be an increase in the accessibility gap between the advantaged group (e.g. those living in the wealthy inner city) and the disadvantage group (e.g. those living in the peripheral areas, mainly replying on public transport) [7]. To achieve greater accessibility for all, we need to consider low-cost, demand-responsive ride-sourcing schemes [59] that are connected to the advanced transport system. The societal benefits could be even more secured if the transit system operates dynamically, increasing or reducing supply according to real-time demand [12]. To maintain accessibility benefits for a long time, transport planning and policy may need to consider measures to prevent a modal shift of users from public transport to shared AVs [32]. For example, competition between shared AVs and transit services is monitored and mediated to ensure that affordable seamless transit service is continually provided.

Our paper identifies that AVs will not always bring the greatest benefits to the advantaged area (group) (e.g. city center), which contrasts with the results of previous studies (e.g. Ref. [12,17]). In the context of full automation and high car ownership (Situation 2), accessibility in urban areas (especially in inner cities) may decrease due to increasing traffic and congestion and limited opportunities for effective (re)development of land. We note that various measures are needed to tackle such issues. For example, the congestion problems in the center can be partially prevented by higher parking fees or parking on the outskirts of the city [74]. Land use policy also needs to consider separating pedestrians and cyclists from motorized travel and establishing measures to monitor and control the quality of pedestrian and cycling infrastructure [75,76]. Ultimately, for the balanced distribution of accessibility among all the social groups, the provision of *affordable collective AV services* for those commuting between urban and sub-urban areas is critical. Effective automated transit service to those commuting from the peripheral areas to the commercial centers of a city also needs to be arranged.

Based on the socio-spatial implications of AV situations this research identified, we posit that the most vulnerable group can differ according to potential situations, and that attention should be given to each group. For example, in situations when technology is developed to an advanced level and the degree of shared mobility is low (Situation 2), the most disadvantaged group can be those who live in the periphery of cities without cars and commute to jobs in sub-urban areas. In situations when technological advancement is limited and shared mobility culture is weak (Situation 4), the most vulnerable group can be people living in the periphery of sub-urban areas, who do not have cars and have to commute to cities. It is essential that policy makers and planners identify different vulnerable groups in different situations and explore the critical conditions to maintain sufficient accessibility for them [65]. Fundamentally, future mobility planning needs to be critically evaluated against its inclusion (or exclusion) of different users' needs in order to ensure equal access to livelihood opportunities for all [8,77].

5. Conclusion

Our paper provides clear indications that the social outcome from future mobility is far from certain. Understanding these outcomes requires critical analysis of the socio-spatial effects of AVs in different potential situations that can be drawn from the key uncertain factors. Spatial and social changes that can be induced under different levels of automation and degrees of shared mobility have varying implications for accessibility and equity. We argue that all the possible situations and relevant problems and opportunities should be thoroughly interrogated, rather than focusing or advocating for one particular situation. Ultimately, creating truly sustainable and equitable cities and regions largely depends on "to what extent" and "how" critical elements for accessibility for all are considered in practice.

We anticipate that this paper will contribute to stimulating debates and critical thoughts about the possible futures of AVs, based on the potential socio-spatial implications we have identified. As a follow-up, there are various areas of research that deserve particular attention. To advance studies on the broader social outcomes of AVs, we suggest that future research establish different scenarios, focusing on differential accessibility among different social groups. Our review reflected on the differential outcomes across different locations, considering people living in low-demand areas as the disadvantaged group. Comprehensive studies on whether and how technological advancements in transport will increase or decrease the accessibility gap among different social groups (e.g. different gender, age, and income groups) in different scenarios can be of great value. Moreover, to develop more comprehensive scenarios based on the socio-spatial implications, focus groups can be conducted with various stakeholders including various social groups. Focus group discussions can be organized to identify their perceived impacts in each situation as well as their most or least preferred situations. In each scenario, critical conditions including policy and regulations for accessibility for all can be also further discussed. Furthermore, although we mainly considered two extreme cases (urban and sub-urban and center and periphery), further investigation into the grey areas (e.g. varied localities across a city) not identified in this research is needed. We also suggest further in-depth investigation into spatial changes at a more detailed level (e.g. types of dwelling) and in different socio-cultural contexts. Since our study mainly focused on the general contexts of developed countries (e.g. Europe and the U.S.), further research based on specific contexts of different places (e.g. rapidly developing cities) would be of high value.

CRediT authorship contribution statement

Juhyun Lee: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Tae-Hyoung Tommy Gim:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

No potential conflict of interest was reported by the authors.

Data availability

No data was used for the research described in the article.

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