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Long-term effects of autonomous vehicles on the built environment: a systematic scoping review towards conceptual frameworks

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ABSTRACT

The advent of autonomous vehicles (AV) is expected to significantly impact the built environment in the long-term. However, the mechanism through which these effects would occur is not known. This study aims to develop conceptual frameworks in the form of causal loop diagrams to enhance understanding through a systematic scoping review of the literature. The review process followed the PRISMA framework and 82 eligible studies were sourced from the Scopus and Web of Science databases. Data were extracted for six attributes of the built environment (parking, density, land use diversity, destination accessibility, urban sprawl and street design). Both qualitative/speculative and quantitative findings are presented stratified by AV types (i.e. shared-autonomous vehicle and private autonomous vehicles), and geographical contexts (i.e. citywide, suburbs and central business district). The findings show that the long-term effects of AVs on the built environment would not be uniformly distributed across the city and vary by AV types. Built environment effects would occur through changes in accessibility, the redistributive demand for parking spaces and other mechanisms. The study provides a knowledge repository and identifies gaps in knowledge for researchers and practitioners interested in the long-term effects of AVs on the built environment.

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Autonomous vehicles; built environment; land use; parking; accessibility; urban sprawl

1. Introduction

Transportation technologies, such as automobiles and steam engines, have significantly altered the built environment. For instance, a higher demand for parking, urban sprawl and car-oriented urban design has been widely practiced since the human-driven cars have been introduced in most cities (Gehl, 2010). These associations have been investigated in various studies (Aston et al., 2021; Ewing & Cervero, 2010). Their relationships are usually complex, sometime non-linear (Tao & Cao, 2022), and depend on several

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factors such as public policies, transportation costs, socio-demographics, culture, weather, topography, economy and associated technologies.

Likewise, the advent of the autonomous vehicle (AV) may potentially lead to several built environment changes. For instance, experts have speculated that AVs may reduce the demand for parking, encourage urban sprawl and affect road capacity (Gruel & Stanford, 2016; Heinrichs, 2016). Nevertheless, these impacts may rely on several factors, such as transportation and land use policies, socio-demographics, types of AV operation and their levels of automation.

The operation of AVs is expected to be either as a shared-autonomous vehicle (SAV) or private autonomous vehicle (PAV). SAV systems may be defined as a combination of automated car-sharing and autonomous ride-sourcing systems (Kang & Levin, 2021; Narayanan et al., 2020). PAVs, on the other hand, will be privately owned by their users, similar like the private cars today (Heinrichs, 2016). Both SAV and PAV are likely to be used to reach activity destinations as well as to serve as feeder modes for (first/last mile service) public transport (Heinrichs, 2016).

The extent of impacts of AVs on the built environment depends on the driverless capabilities of AVs (Heinrichs, 2016). Automation of AVs is currently categorised into 6 different levels according to SAE (2021): level 0 (no driving automation), level 1 (driver assistance), level 2 (partial driving automation), level 3 (conditional driving automation), level 4 (high driving automation) and level 5 (full driving automation). It is expected that changes in the built environment would only occur if AVs are equipped with high/full automation (Heinrichs, 2016). For example, empty-cruising to find a parking space is only possible with automation levels 4 and 5.

The various forms of AV operation and automation may distinctly affect the built environment in the long-term. However, the types and extents of these changes as well as the mechanisms through which the effects will occur have only sporadically been reported to date. Furthermore, no systematic synthesis of these effects has been performed yet in the literature. **To address this gap, this paper combines a systematic scoping review of the literature synthesising the built environment impacts of AVs, and several conceptual frameworks illustrating the mechanisms by which AV will affect the built environment.**

Several literature review papers have previously been published on AVs including intention to use AVs (Keszei, 2020), AV acceptance (Jing et al., 2020b), AV capabilities, planning and policies (Bagloee et al., 2016; Faisal et al., 2019; Milakis et al., 2017), SAV and urban mobility (Golbabaee et al., 2021; Narayanan et al., 2020), modelling and simulation techniques for AVs (Hawkins & Nurul Habib, 2018; Jing et al., 2020a; Li et al., 2021) and AV impacts on accessibility and transport equity (Dianin et al., 2021). Nonetheless, none of these studies have focused on the built environment impacts of AVs. Moreover, there is limited understanding of the mechanism through which the built environment will likely be affected by AVs, and how this will differ between PAV and SAV, and between urban and suburban regions. This paper aims to conceptualise the mechanisms through which highly/fully AVs are likely to affect the various elements in the built environment and present such findings in an easily understandable manner. Built environment is defined here as the built forms, building types, land uses and open spaces of a city (Lawrence & Low, 1990).

Section 2 presents the methodology applied to address the research aim. In Section 3, findings are presented including a general descriptive review of the literature and a

quantitative assessment of the extent of the built environment effects. Conceptual frameworks capturing the causal links between AVs and the built environment changes are presented in Section 4 in the form of causal loop diagrams (CLD). The section also outlines gaps in understanding such links. Findings are discussed in research and policy terms in Section 5. The paper concludes with a summary of key findings in Section 6.

2. Methodology

2.1. Search for evidence

A systematic scoping review of the literature was performed to investigate the current state of knowledge regarding the potential impacts of AVs on the built environment. A scoping review aims to identify and map existing evidence, explain concepts, characteristics, methods and gaps in a certain field, and be a precursor for systematic review (Munn et al., 2018). The primary difference between a scoping review and a systematic review is that the former does not aim to critically appraise the identified literature on a topic (Munn et al., 2018). Finally, a systematic scoping review comprises of a scoping review that follows a systematic framework (e.g. PRISMA framework) (Peters et al., 2015).

The study used a systematic approach based on the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework to search for evidence (Moher et al., 2009; Page et al., 2021). The PRISMA 2020 statement “provides updated reporting guidance for systematic reviews that reflects advances in methods to identify, select, appraise, and synthesise studies” (Page et al., 2021). The PRISMA critical appraisal requirement for systematic review was not included since it is not part of the aims of a scoping review. Two databases were searched to identify relevant articles for this study: Web of Science and Scopus. The search process was carried out in November 2022.

Given that the study focuses on the built environment impacts of autonomous vehicles, the two main search terms as used were: “built environment” and “autonomous vehicles”. However, a range of synonyms of these two terms were also added to ensure that the results are comprehensive. The synonyms for the built environment were derived from the well-known 5D’s concept, which includes density, destination accessibility, design, diversity of land uses and distance to transit (Ewing & Cervero, 2010). However, the distance to transit term was replaced by distance to CBD to account for potential AV impacts on residential relocation and commute distances. In addition to the 5Ds, parking was specifically included as a built environment attribute in the search term, which is often overlooked in the land use diversity discussion but has been identified to have a great potential to be affected by the AVs (Gruel & Stanford, 2016; Heinrichs, 2016). More specifically, the following search terms were used to identify relevant articles, directed to the Title, Abstract and Keywords:

“autonomous vehicles” OR “driverless vehicles” OR “automated vehicles” OR “self-driving vehicles”

AND

“built environment” OR “land use” OR “urban environment” OR “parking” OR “accessibility” OR “density” OR “urban sprawl” OR “city” OR “cities” OR “urban system” OR “urban planning” OR “urban area” OR “urban design” OR “housing” OR “urban form” OR “urban transport” OR “urban development” OR “neighbourhood”

2.1.1. Eligibility criteria

The resultant search outputs were assessed against the following eligibility criteria:

- a) Reported either quantitative or qualitative/speculative findings in relation to the potential impacts of autonomous vehicles on any of the six aforementioned attributes of the built environment.
- b) Provided empirical or simulation results of AVs with levels 4 and/or 5 automation capabilities as classified by SAE (2021).
- c) Studies reporting built environment effects of only land-based AVs (excluding mass transit and freight) are considered eligible.
- d) Only peer-reviewed publications are considered to extract quantitative findings linking AVs and the built environment;
- e) The peer-review status was relaxed to extract qualitative/speculative findings in relation to AVs and the built environment and included peer-reviewed journals, books, conference proceedings and technical reports. However, studies published on website pages, social media and video platforms were not considered eligible for this research;
- f) Only publications written in English and published between 2011 and 2022 are considered eligible. The year 2011 was selected as the initial period because publications prior to this date focused mostly on AV system engineering with little/no studies assessed the built environment impacts of AVs (Gandia et al., 2019);

2.1.2. Search outcomes

Figure 1 provides a summary of the search outcomes. The searches in both databases resulted in 3247 potentially eligible studies. These were imported to Endnote, and 1137 duplicates were removed, resulting in 2110 unique records. The titles and abstracts of these studies were screened to check their relevance to the aims of this review based on the eligibility criteria.

The screening of titles and abstracts resulted in 96 potentially eligible studies for a full-text review. Furthermore, 2 additional studies were included based on the snowballing of the references listed. After full text reading, 16 studies were found ineligible because their findings were not directly related to AV impacts on the built environment. For instance, some reviewed studies provided findings related to AV impacts on traffic (Legêne et al., 2020; Shatanawi & Mészáros, 2022) and car ownership (Kellett et al., 2019; Ostermeijer et al., 2019) rather than direct impacts on the built environment. The remaining 82 studies formed the overall sample for this review, including 78 peer-reviewed journal articles, two book chapters, one conference paper and one government technical report (see appendix). An additional 33 references are cited in this paper to provide contextual background and methodological justification.

2.1.3. Data extraction

The data extracted from each literature source comprised of study location, study objectives, analytical method, sampling method, model assumptions, scenarios, geographic context, AV types, studied built environment indicators, and the qualitative/quantitative

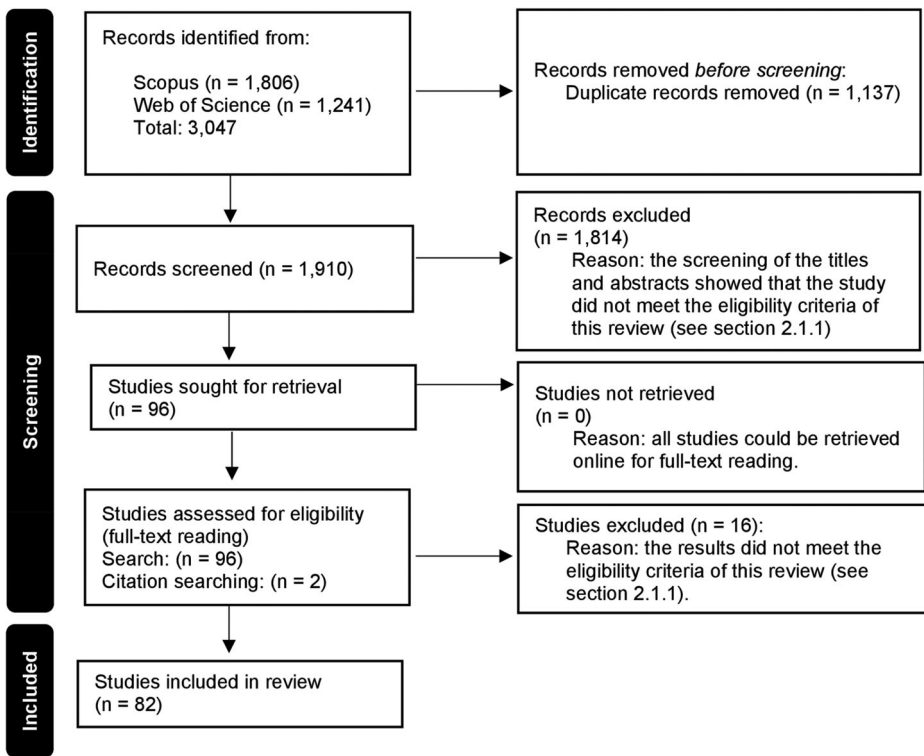


Figure 1. Systematic search process based on the PRISMA framework and search outcomes (Page et al., 2021).

links between AV types and the built environment dimensions. The first, second, and third authors respectively extracted, reviewed and validated the data. The findings are stratified by six built environment dimensions, three AV types (SAV, PAV, mixed AV), and three geographic contexts (CBD, suburbs and citywide), resulting in 54 individual tables, which were later merged for the efficiency of presentation. The three geographical contexts broadly capture the findings of studies that simulated separated scenarios for city centres and suburban areas. The “citywide” category represents studies that have made no distinction between city centre and suburban areas. Any of the six built environment dimensions considered in this study can be represented by many indicators. For example, density can be represented by employment density, dwelling density, population density, floor-area ratio and building height. As a result, it was necessary to define various indicators used to extract the built environment data for this study, as shown in Table 1.

2.2. Data analysis: derivation of causal loop diagrams

Causal loop diagrams (CLD) are developed to synthesise the identified relationships between AVs and the built environment. CLD is a method of visualising the relationships and causal effects among key variables. This method was first adopted to analyse a feedback system in the field of cybernetics (Magoroh, 1963). It has also been used in transportation (Gruel & Stanford, 2016; Sterman, 2000). CLDs are composed of three elements: the

Table 1. Indicators used to extract data for each built environment dimension.

Built Environment Dimension	Data Extraction Indicators
Parking	Demand for both off-street and on-street parking, measured by: 1. Number of parking spaces per vehicle/household. 2. Size of parking spaces per vehicle/household.
Destination Accessibility	Job and residential accessibilities represented by time, monetary and land use indicators.
Density	Population and number of jobs per unit of area.
Distance to CBD	Commute distance/time, average travel distance, urban area and household relocation.
Diversity of Land Uses	Land use entropy and parcel area disaggregated by type (i.e. commercial, residential, industrial, government, civic, education, etc).
Design	Changes in urban geometry and infrastructure, measured by: 1. Intersection density/block sizes. 2. Sizes of sidewalks, car lanes and cycle lanes. 3. Street network density (i.e. street area/total urban study area). 4. Pavement and utilities.

names of the variables; the causal links that are represented by arrows linking the independent variable to the dependent variable; and a positive or negative sign indicating the nature of the relationship. This method has already been applied to assess the long-term effects of autonomous vehicles adoption on traffic flow (Emberger & Pfaffenbichler, 2020; Gruel & Stanford, 2016). However, no CLD has been developed to analyse AV impacts on the built environment.

The quantitative results reported in the section 3 are represented in the CLDs using different colours and signs in the arrows. A blue arrow represents a dominant set of quantitative results found in the literature. It means that all reviewed studies reported consistent findings in terms of the direction of impacts (i.e. all the reported impacts were either positive or negative). A yellow arrow represents a divergent set of results for a specific relationship. A red arrow represents a research gap. This means that existing studies have not yet studied the indicated relationships. In the CLDs, a positive sign means that an increase in the independent variable will lead to an increase in the dependent variable, and a negative sign means an inverse relationship. A total of 9 CLDs are developed in this study, one for each of the three types of AVs and three geographic contexts, outlining the causal mechanisms of AV impacts on the built environment. The detailed colour coding of the results is provided as a supplementary material.

3. Results

Among the 82 studies reviewed, 46 applied mathematical simulations, 12 conducted empirical investigation using data collected through surveys and/or interviews with experts and 24 studies proposed frameworks, design guidelines or policies based on the literature. The case studies investigated in these studies were drawn from various cities across the world: 25 from North America, 15 from Europe and 13 from Asia and Oceania. The remaining 29 studies do not focus on any specific geographical context. The 82 studies included in this review are presented in appendix together with the methods applied, built environment indicators studied, and contextual focus.

Findings are presented under the following headings: parking, urban density, destination accessibility, distance to CBD, urban design and diversity of land uses. Quantitative results demonstrating a specific scale of land use impacts are synthesised in [Tables 2–](#)

5. Results were disaggregated by AV type (i.e. SAV, PAV and mixed-mode), and city location (i.e. central business district, suburbs and citywide) to better represent the scenarios found in the literature. Quantitative findings are presented in tandem with qualitative/speculative findings.

3.1. Parking

Autonomous vehicles are expected to significantly reduce the demand for both curbside and off-street parking since autonomous car-sharing and ride-sharing schemes tend to reduce car ownership (Legacy et al., 2018). In addition, AVs may be capable of cruising empty for vacant parking spots in suburban areas, or even move back to residential home garages (Milakis et al., 2017; Millard-Ball, 2019). This may enable the replacement of parking spaces by other land uses in high-density areas, such as affordable housing (Riggs et al., 2020; Yigitcanlar et al., 2019) and commercial services (Hawkins & Nurul Habib, 2018). For buildings, the total costs of construction may drop by –20 to –25% if structural parking is no longer needed due to the replacement of human-driven vehicles by SAV systems and PAVs (Riggs et al., 2020). Table 2 list the impacts of AVs on parking.

3.1.1. Shared autonomous vehicles & parking

The results suggest that if SAVs become dominant, the demand for parking may significantly drop. Fagnant and Kockelman (2014) estimated that each SAV can replace up to eleven human-driven vehicles. Moreover, Zhang and Guhathakurta (2017) found that each SAV has the potential to eliminate up to 20 parking spaces due to the reduction of car ownership, higher vehicle utilisation and occupancy rates. Parking demand in suburbs may significantly rise due to the empty cruising of AVs in search for vacant parking slots (Milakis et al., 2018; Zhang & Guhathakurta, 2017). Nonetheless, a simulation study in Okinawa, Japan, found that parking spaces at the periphery may drop by 94% owing to more efficient vehicle utilisation in a scenario with travel demand completely served by a SAV fleet (Kumakoshi et al., 2021).

3.1.2. Private autonomous vehicles & parking

Regarding PAVs, the potential impacts on parking are more unclear. PAVs are expected to reduce parking demand in CBDs due to their ability of cruising empty to low-density suburbs (Chapin et al., 2016; Kang et al., 2022), where parking spots are often more vacant, free or cheaper than the CBD. Kang et al. (2022) estimated that, approximately, 25–32% of current parking areas could be repurposed owing to PAV capability of parking at their origins. Furthermore, the adoption of PAVs may increase vehicle ownership owing to lower acquisition and operational costs compared to human-driven vehicles in the long-term (Shatu & Kamruzzaman, 2022). Moreover, car ownership may also rise due to the inclusion of new users who are unable to drive, such as the elderly, disabled people and children (Chapin et al., 2016; Fox, 2016; Truong et al., 2017). Higher individual car ownership normally leads to higher demand for parking. For instance, Zakharenko (2016) forecast an overall increase of 7.4% in parking demand in a scenario with solely single-user PAVs, and, thereby, assuming an increase in car ownership. On the other hand, fully-automated PAVs may provide higher flexibility for household vehicle sharing, which may eventually contribute to a reduction in household

Table 2. Quantitative impacts of AVs on parking.

Parking					
AV Type	Location	Impact	Description	Major Assumptions	Source
SAV	CBD	−90% to −70%	Parking demand reduction range.	SAV fleet size was 60,000 vehicles (i.e. 5.7% of the total number of private vehicles registered in 2018); each traveller performs only one trip during the morning trip hour, and no trip chains were assumed.	Kumakoshi et al. (2021)
SAV	CBD	−67% to −20%	Parking demand reduction range.	Year 2035; different SAV adoption rates (i.e. from 20% to 61%); both car-sharing and ride-sharing are considered as SAVs.	Simons et al. (2018)
SAV	Suburbs	−94%	Parking demand reduction.	SAV fleet size was 60,000 vehicles (i.e. 5.7% of the total number of private vehicles registered in 2018); each traveller performs only one trip during the morning trip hour, and no trip chains were assumed.	Kumakoshi et al. (2021)
SAV	Citywide	−90%	Reduction in parking space demand.	Study Area: UWE Frenchay campus. Scenario with 90% of the travel demand served by SAVs; all SAVs are singly occupied; one SAV is assumed to replace nine non-SAVs.	Okeke (2020)
SAV	Citywide	−4.5%	Parking demand reduction.	5% mode shift from human driven vehicles to SAVs; no induced demand is considered; the cost of SAV system is \$0.5/min for single occupant, and \$0.3/min for ride-sharing; maximum waiting time is 15 min.	Zhang and Guhathakurta (2017)
SAV	Citywide	−83%	Maximum potential reduction in parking.	90% of the travel demand served by SAVs; 50% with single occupancy and 40% ride-sharing; population and land use do not change;	Silva et al. (2021)
SAV	Citywide	−50%	Reduction in parking area.	SAV is used for home-work commuting; 100% of the travel demand served by SAVs; assumed maximum empty-cruising distance is 1.5 km.	Kondor et al. (2019)
SAV	Citywide	−96% to −88%	Parking demand reduction range.	10 × 10mi grid based hypothetical city is used; SAV has a low penetration rate of 2%; peak hour speed is 30mph, and off-peak speed is 21 mph.	Zhang et al. (2015)
PAV	Citywide	−32% to −15%	Parking area reduction range in four different scenarios.	Parking fees vary from \$0 to \$2/h.	Kang et al. (2022)
PAV	Citywide	7.4%	Parking demand change for single-user PAVs.	The commute cost is assumed as 50% of the fixed vehicle ownership cost.	Zakharenko (2016)
PAV + SAV	CBD	−75%	Parking area reduction.	Year 2040; Scenario with PAV (37.35%), SAV (37.35%) and human-driven vehicles (12.65% shared and 12.65% private).	Zhang and Wang (2020)
PAV + SAV	Suburbs	100%	Parking area increase.	Year 2040; Scenario with PAV (37.35%), SAV (37.35%) and human-driven vehicles (12.65% shared and 12.65% private).	Zhang and Wang (2020)
PAV + SAV	Citywide	−62% and −87%	Average and maximum car-park demand reduction.	All vehicles are the same size; car-park operator takes control of all AVs that enter the parking facility; the vehicles arrivals follow a Poisson distribution; only AVs park in this car-park.	Nourinejad et al. (2018)

(Continued)

Table 2. Continued.

Parking					
AV Type	Location	Impact	Description	Major Assumptions	Source
PAV + SAV	Citywide	−50%	Car-park space reduction due to more efficient layout for AVs.	Vehicles can be controlled remotely; they park in same size cells; vehicle exit time is previously known, accurate positioning information.	Azevedo et al. (2020)
PAV + SAV	Citywide	−49% to −11%	Car-park area reduction range due to more efficient layout for AVs.	Single-story parking facility with no interior obstructions; all AVs are the same size; accurate positioning system; vehicles can be independently accessible at all times.	Kong et al. (2018)

vehicle ownership and parking demand (Bin-Nun & Binamira, 2020). For instance, Zhang et al. (2018) estimated a car ownership reduction of between 9.5 and 12.3% due to sharing of PAV's within households in Atlanta, USA.

3.1.3. Off-Street car parks

Off-street parking design for both SAVs and PAVs are expected to generate a more efficient use of space compared to current car-parks (Bischoff et al., 2019; Fraedrich et al., 2019; Heinrichs, 2016). AV car-parks will allow, for instance, more tight distances between side doors, and multiple rows of vehicles stacked, as passengers will not need to access and egress the vehicles on the parking slot since an automated valet systems may be implemented (Azevedo et al., 2020; Nourinejad et al., 2018). Moreover, ramps and aisles will be replaced by lift shafts, reducing parking lot heights and increasing parking density (Heinrichs, 2016). As a result, these high-density AV off-street car-parking layouts are estimated to increase parking capacity from 50% (Azevedo et al., 2020; Kong et al., 2018) up to 87% (Nourinejad et al., 2018).

3.2. Urban density

Several studies have discussed the impacts of AVs on urban density (Table 3). Research suggests that residential and employment densities in city centres and suburbs will be affected by AVs in different ways. Reductions in parking space demands in city centres will permit more housing and commercial land uses, creating denser urban cores (Llorca et al., 2022; Milakis et al., 2018; Stead & Vaddadi, 2019), whereas suburban and exurban areas will likely face more urban sprawl and lower residential density development owing to lower disutility of travel time, and lower transportation costs (Duarte & Ratti, 2018; Gelauff et al., 2019; Heinrichs, 2016; Hiramatsu, 2022; Kyung-Hwan et al., 2015; Moore et al., 2020). Interestingly none of the modelling studies considered the potential contribution to density caused by the replacement of parking by other land uses, and only two considered home relocation caused by lower disutility of time, and lower transportation costs (Gelauff et al., 2019; Hiramatsu, 2022).

3.3. Destination accessibility

All quantitative impacts of AVs on destination accessibility are presented in Table 4. Overall, studies found that the expected increases in travel utility caused by AVs will

Table 3. Quantitative impacts of AVs on residential and employment densities.

AV Type	Location	Impact	Residential Density		
			Description	Major Assumptions	Source
SAV	Suburbs	−3%	Change in population density in major suburban/rural areas in scenarios with large level-5 SAV penetration (PT-1).	Feedback effects of automation on road capacity, congestion and travel times are considered.	Gelauff et al. (2019)
SAV	Suburbs	0% to 0.4%	Population change range in outer suburban areas (zone D, E, F and G) due to the introduction of SAVs.	Virtual city model; the urban and transportation systems follow the economic equilibrium theory; lower value of time for AV riders since users can work and do leisure activities during the trip.	Hiramatsu (2022)
SAV	CBD	127%	Change in the population density.	40% of travel demand served by SAVs. Road capacity and value of time changes follow a meta-regression model including SAV penetration rate, road type and SAV automation level.	Zhong et al. (2020)
SAV	CBD	3%	Change in population density in four largest cities in scenario with large level-5 SAV penetration (PT-2).	Feedback effects of automation on road capacity, congestion and travel times are considered.	Gelauff et al. (2019)
SAV	CBD	0.8%	Increase in population in CBD area (zone A) due to the introduction of SAVs.	Virtual city model; the urban and transportation systems follow the economic equilibrium theory; lower value of time for AV riders since users can work and do leisure activities during the trip.	Hiramatsu (2022)
PAV	Suburbs	−0.5%	Change in the population density of suburbs outside the Randstad zone in scenario with large level-5 PAV penetration (CAR-2).	Feedback effects of automation on road capacity, congestion and travel times are considered.	Gelauff et al. (2019)
PAV	Suburbs	−1.3% to 0%	Population change range in scenarios 2 and 3 with PAV in the periphery (zone 3).	Different variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand (scenario 3 only). Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV	Suburbs	−19.3% to 2%	Population change range in outer suburban areas (zone D, E, F and G) due to the introduction of PAVs.	Virtual city model; the urban and transportation systems follow the economic equilibrium theory; lower value of time for AV riders since users can work and do leisure activities during the trip.	Hiramatsu (2022)
PAV	CBD	0%	Population change range in scenarios 2 and 3 with PAV in the CBD (zone 1).	Different variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand (scenario 3 only). Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)

(Continued)

Table 3. Continued.

AV Type	Location	Impact	Residential Density		
			Description	Major Assumptions	Source
PAV	CBD	−1%	Change in the population density in the four largest cities in scenario with large level-5 PAV penetration (CAR-2).	Feedback effects of automation on road capacity, congestion and travel times are considered.	Gelauff et al. (2019)
PAV + SAV	Suburbs	0%	Population change range in the periphery (zone 3).	Scenario 4 with variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand derived from accessibility changes.	Cordera et al. (2021)
PAV + SAV	Suburbs	−21.4% to 19.4%	Population change range in outer suburban areas (zone D, E, F and G) due to the introduction of PAVs and SAVs.	Virtual city model; the urban and transportation systems follow the economic equilibrium theory; lower value of time for AV riders since users can work and do leisure activities during the trip.	Hiramatsu (2022)
PAV + SAV	CBD	0%	Population change range in the CBD (zone 1).	Scenario 4 with variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand derived from accessibility changes.	Cordera et al. (2021)
PAV + SAV	CBD	34.3%	Increase in population in CBD area (zone A) due to the introduction of PAVs and SAVs.	Virtual city model; the urban and transportation systems follow the economic equilibrium theory; lower value of time for AV riders since users can work and do leisure activities during the trip.	Hiramatsu (2022)
Employment Density					
SAV	CBD	104%	Job density increase in the city centre.	40% of travel demand served by SAVs. Road capacity and value of time changes follow a meta-regression model including SAV penetration rate, road type and SAV automation level.	Zhong et al. (2020)
PAV	Suburbs	−0.7% to −0.1%	Change range in the number of jobs in suburbs (zone 3).	Scenarios 2 and 3 with different variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand (scenario 3 only). Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV	CBD	0.2% to 1.6%	Change range in the number of jobs in the city centre (zone 1).	Scenarios 2 and 3 with different variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand (scenario 3 only). Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)

(Continued)

Table 3. Continued.

AV Type	Location	Impact	Residential Density		Source
			Description	Major Assumptions	
PAV + SAV	CBD	-0.8%	Change in the number of jobs in the city centre (zone 1).	Scenario 4 with increases in road capacity (80% in interurban roads and 40% in urban roads) and induced demand. Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV + SAV	Suburbs	0.6%	Change range in the number of jobs in suburbs (zone 3).	Major assumptions: scenario 4 with increases in road capacity (80% in interurban roads and 40% in urban roads) and induced demand. Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)

primarily benefit suburban and exurban areas by enhancing job accessibility, this may consequently drive urban sprawl in cities (Childress et al., 2015; Cohen & Cavoli, 2018; Gruel & Stanford, 2016; Meyer et al., 2017; Nadafianshamabadi et al., 2021; Wellik & Kockelman, 2020). An empirical study in Dallas, Texas, USA, found that up to 68% more urban sprawl is projected due to increases in accessibility in suburbs (Moore et al., 2020). This effect tends to be more significant for low-income residents (Ahmed et al., 2020; Kim et al., 2020; Nahmias-Biran et al., 2020; Zhou et al., 2021) and suburbs surrounding highways (Cordera et al., 2021). Some studies also reported increases in accessibility in city centres and surrounding neighbourhoods (Dianin et al., 2021; Kang & Kim, 2019). For scenarios with PAV and SAV operating together, accessibility increase was the dominant result citywide.

Regarding CBD accessibility impacts, relationships varied by AV modes. For PAV only, accessibility was found to increase between 17 and 187% (Cordera et al., 2021). For SAVs only, accessibility changes varied from -4 to 21% (Zhong et al., 2020). For scenarios with PAVs and SAVs together, negative accessibility variations were found in two different studies owing to factors, such as increases in average journey times and higher empty-cruising travel demand (Cordera et al., 2021) and lower consumer surplus (Nahmias-Biran et al., 2020).

Accessibility variation in suburbs were found to be primarily positive for PAVs (Cordera et al., 2021) and divergent for SAVs (Zhong et al., 2020). For the mixed AV mode scenarios, accessibility significantly decreased in the periphery (Cordera et al., 2021). Moreover, Zhou et al. (2021) found that SAVs can increase overall accessibility in Singapore solely if private vehicles can coexist. These results indicate that PAVs tend to benefit suburban accessibility more than SAVs. Therefore, if PAVs become dominant in suburbs, a significant accessibility increase is expected; consequently, further urban sprawl may occur. However, experts have claimed that induced travel demand may offset these potential long-term accessibility gains by increasing congestion, and, consequently, travel time (Milakis et al., 2018).

Table 4. Quantitative impacts of AVs on destination accessibility.

Destination Accessibility					
AV Type	Location	Impact	Description	Major Assumptions	Source
SAV	CBD	−4% to 21%	Job accessibility change range in scenario with road congestion pricing for TAZs within the toll ring area.	40% SAV penetration rate; road capacity and value of time changes follow a meta-regression model including SAV penetration rate, road type and SAV automation level.	Zhong et al. (2020)
SAV	Suburbs	−31% to 33%	Job accessibility change range in scenario with road congestion pricing for TAZs outside the toll ring area.	40% SAV penetration rate; road capacity and value of time changes follow a meta-regression model including SAV penetration rate, road type and SAV automation level.	Zhong et al. (2020)
SAV	Citywide	−4.17 min	Change in average accessibility in daily average travel time savings.	Pricing is 75% of conventional taxis for single rides and 70% of single-ride services price for shared rides.	Zhou et al. (2021)
PAV	CBD	17.4% to 187.1%	Accessibility change range in the CBD (zone 1)	Scenarios 2 and 3 with different variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand (scenario 3 only). Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV	Suburbs	−1.2% to 37.6%	Accessibility change range in the periphery (zone 3).	Scenarios 2 and 3 with different variations in road capacity (80% in interurban roads and 40% in urban roads) and induced demand (scenario 3 only). Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV	Citywide	0% (1) and 10% (2)	Accessibility change averaged by population size in scenario 2. (1) conservative and (2) optimistic road capacity increases	Increase in road capacity from 80% (1) to 270% (2) for extra-urban areas, and 40% for urban roads; increase in travel demand by new users is 16%.	Meyer et al. (2017)
PAV + SAV	CBD	SG\$ −0.7	Median accessibility change represented by consumer surplus in Singapore dollar.	SAV cost is 33% of current mobility on-demand services.	Nahmias-Biran et al. (2020)
PAV + SAV	CBD	−58.3% to −71.1%	Accessibility change range in the CBD (zone 3).	Scenario 4 with variations of road capacity (80% in interurban roads and 40% in urban roads) and induced demand. Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)

(Continued)

Table 4. Continued.

AV Type	Location	Impact	Destination Accessibility		
			Description	Major Assumptions	Source
PAV + SAV	Suburbs	−73% to −77.8%	Accessibility change range in the periphery (zone 3).	Scenario 4 with increases in road capacity (80% in interurban roads and 40% in urban roads) and induced demand. Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV + SAV	Citywide	5.20 min	Change in average accessibility in daily time savings.	Pricing is 75% of conventional taxis for single rides and 70% of single-ride services price for shared rides.	Zhou et al. (2021)
PAV + SAV	Citywide	1.4% (1) and 10.3% (2)	Accessibility change averaged by population size in scenario 3. (1) conservative and (2) optimistic road capacity increases.	Increase in road capacity from 80% to 270% for extra-urban areas, and 40% for urban roads; increase in travel demand by new users is 16%. No ride-sharing.	Meyer et al. (2017)
PAV + SAV	Citywide	SG\$ 1.08	Accessibility change range represented by consumer surplus in Singapore dollar.	SAV cost is 33% of current mobility on-demand services.	Nahmias-Biran et al. (2020)
PAV + SAV	Citywide	23.2% to 36.3%	Accessibility change range in four different scenarios considering different PAV and SAV penetration levels.	PAV ownership from 10% to 50%; SAV fleet size from 2% to 10% of total vehicle fleet; VoT from 10% to 60% of the current.	Luo et al. (2019)
PAV + SAV	Citywide	\$6.6 to \$9.20	Employment economic accessibility change range (i.e. consumer surplus variation) for four different classes of workers.	SAV travel cost is \$0.30/mile; maximum SAV trip length is 10 miles for transit integration; no parking costs for SAVs; 5-minute pickup waiting time.	Ahmed et al. (2020)
PAV + SAV	Citywide	8.5% (1) and 8.9% (2)	Accessibility increases for low income (1) and high-income (2) residents..	Scenario with 30% increase in road capacity, −35% reduction in travel time perception and −50% parking costs	Childress et al. (2015)

3.4. Distance to CBD

Distance to CBD is an important measure to comprehend how sprawled and connected to downtown a city is (Carroll et al., 2021). An increasing distance from home to CBD normally means more urban sprawl. The quantitative impacts of AVs on distance to CBD are presented in Table 5. Most studies found positive correlations between AV availability and willingness to relocate home further from city centres (Bansal & Kockelman, 2018; Guan et al., 2021; Nodjomian & Kockelman, 2019). These findings support the aforementioned AV impacts on urban density leading to denser urban cores and more sprawled suburbs. As a consequence of this trend, population density in the middle suburbs may be significantly reduced.

Table 5. Quantitative impacts of AVs on distance to central business district.

Distance to CBD					
AV Type	Location	Impact	Description	Major Assumptions	Source
SAV	Citywide	−3.6% to 13.8%.	Household median distances to CBD change range.	Scenarios with travel cost of \$0.15/mile, different age groups and kids.	Zhang and Guhathakurta (2021)
SAV	Citywide	−4.2%	Change in the city radius (i.e. from 9.6–9.2 miles).	100% SAV adoption by commuters; virtual monocentric city model; economic equilibrium model is assumed; no parking is available.	Larson and Zhao (2020)
PAV	Citywide	14%	Change in the average commute distance.	The commute cost is assumed as 50% of the fixed vehicle ownership cost.	Zakharenko (2016)
PAV	Citywide	11.5%	Change in the city radius (i.e. from 9.6–10.7 miles).	100% PAV adoption by commuters; virtual monocentric city model; economic equilibrium model is assumed.	Larson and Zhao (2020)
PAV + SAV	Citywide	8% (3) –7% (5)	Changes in the average commute time to CBD.	Scenario 3 considers 40% lower value of time. Scenario 5 considers parking demand reduction and no VoT change.	Llorca et al. (2022)
PAV + SAV	Citywide	1.3%	Change in average commute distance to CBD.	Scenario with +100% road capacity, −20% VoT, and −100% intersection delay.	Nadafianshahamabadi et al. (2021)
PAV + SAV	Citywide	5.0%	Increase in the average trip distance.	Scenario 4 with PAVs and SAVs and increases in road capacity (80% in interurban roads and 40% in urban roads) and induced demand. Induced demand is derived from the improvements in accessibility.	Cordera et al. (2021)
PAV + SAV	Citywide	74% (1) 14%(2) 12%(3)	Home relocation reported in a stated-preference survey.	Scenario with AV level 4 technology available. (1) Stay at the same location. (2) Move closer to the CBD. (3) Move further from the CBD.	Bansal et al. (2016)
PAV + SAV	Citywide	82%(1) 7% (2) 11%(3)	Home relocation reported in a stated-preference survey.	Scenario with AV level 4 technology available. (1) Stay at the same location. (2) Move closer to the CBD. (3) Move further from the CBD.	Bansal and Kockelman (2018)
PAV + SAV	Citywide	30% (USA) 42% (China)	Home relocation reported in a stated-preference survey.	Percentage of respondents who reported willingness to move further from the city if AVs level-4 become available.	Guan et al. (2021)

Similar to the empirical studies, modelling results (Table 5) also showed that distance to the CBD would overall increase after the implementation of AV systems. Like trip distance, Llorca et al. (2022) predicted an increase of about 8% in the average commute time to the CBD. These increases in both commute distance and time to the CBD are driven primarily by the assumption of potential reductions in the disutility of travel time that AVs may allow, which may encourage residents to live further away from work and travel longer distances. Also, Liu et al. (2021) found that higher automation levels may lead to an increase in average travel time if the highway capacity is less elastic than the value of travel time for on-demand AVs. However, potential improvements in road capacity and traffic flow may contribute to counterbalance these effects. For instance, Szimba and Hartmann (2020) found that AV automation levels 4 and 5 may, respectively, reduce average commute time by 20 and 27%. Lastly, Larson and Zhao (2020) estimated a reduction of 4.2% in the city radius if SAVs become dominant and no parking lots are available.

3.5. Urban design

Urban design features, such as sidewalks, cycle lanes, car lanes, block sizes and street network density might be significantly reshaped due to the introduction of AVs. AVs will impact rights-of-way, travel lanes and intersections (Fraedrich et al., 2019; Riggs et al., 2020).

Experts suggest that AVs may overall increase safety for pedestrians and cyclists in the long-term (Botello et al., 2019). Nevertheless, lane segregation by mode, and multi-level crossing with AVs and non-motorised modes may be necessary to ensure safety and appropriate AV traffic flow (Botello et al., 2019). Segregated street platform spaces for SAV drop-off and pick-up lanes, autonomous delivery services and curbside parking may also be necessary (Fayyaz et al., 2022). Survey results show that the possibility of AV lane segregation seems to be the most important factor to encourage AV adoption (Carrese et al., 2019). However, AV-only lanes may also hinder walkability (Botello et al., 2019). For instance, a modelling study in Vienna, Austria, found that the implementation of PAVs and SAVs may negatively impact street compatibility with pedestrians and cyclists at city centres due to increases in traffic volume (Soteropoulos et al., 2021). Nevertheless, compatibility improvements were found in suburban areas, especially for SAVs with stop-based services rather than door-to-door (Soteropoulos et al., 2021).

The implementation of AVs may positively affect road capacity due to platooning technology (Heinrichs, 2016). Potential growth in ride-share adoption using SAV systems may also contribute to enhancing road capacity. For instance, according to Liu et al. (2022), a single SAV has the potential to substitute 3.8 private human-driven vehicles if ride-sharing is available in conjunction with a car-sharing service. On the other hand, road capacity may also be negatively affected by AVs. For instance, Miller and Kang (2019) argue that AVs may reduce road capacity as operators will feel more comfortable without the burden of driving, which it may contribute to reducing the value of travel time and generate more traffic. Furthermore, potential increases in vehicle ownership and VMT due to lower costs of vehicle acquisition, maintenance and insurance as well as lower disutility of time, remote parking and trip generation from people unable to drive may offset potential road capacity gains due to AVs (Chapin et al., 2016; Emberger & Pfaffenbichler, 2020).

3.6. Diversity of land uses

AVs may also significantly affect land use mix. For instance, the potential decrease of parking demand in the city may transform current parking spaces into commercial, residential and mixed-use hubs (Hawkins & Nurul Habib, 2018). Furthermore, the introduction of AVs tends to attract more commercial land use to suburbs due to accessibility gains. According to Bridgelall and Stubbing (2021), the average trip rate for commercial land use might triple by 2050, and commercial land use may shift towards lower density suburbs. According to Kumakoshi et al. (2021), commercial land use area may increase by 35% owing to parking reductions after the introduction of SAVs. On the other hand, a simulation study in Seoul, found that commercial land use area may significantly decrease in a scenario with fully autonomous SAVs, whereas industrial and residential land use areas tend to largely increase (Kang & Kim, 2019).

Researchers have suggested that AVs may firstly be adopted in single-use zones rather than mixed-use areas (Nodjomian & Kockelman, 2019). This is due to the potential reduction in the disutility of travel, and higher accessibility, especially for those who currently need to commute long distances by human-driven vehicles. It has also been suggested that some land uses will become obsolete due to the adoption of AVs while some new uses will be created. For instance, it will be necessary to implement local depots for the cleaning, maintenance, charging and repairs of SAVs in service (Heinrichs, 2016). Charging stations may function as mobile office locations, gas station and private garages will be replaced by other uses (e.g. shops, schools, etc.) (Yigitcanlar et al., 2019), and car-park area will be significantly reduced (Zhang & Guhathakurta, 2017).

4. Conceptual framework

The findings presented in the previous sections are presented in this section in the form of a conceptual framework using causal loop diagrams. This framework presents the researcher's own perceptions about the scope and structure of a problem based on research findings (Adelman, 1997). It also facilitates comprehension of the current state of knowledge and by highlighting omissions in published literature as identified gaps yet to be researched. The framework also allows an assessment of several mechanisms that will drive changes in the built environment.

4.1. Central business district

The impacts of AVs on the CBD built environment are illustrated in CLDs for PAV (Figure 2 (a)), SAV (Figure 2(b)) and mixed-AV mode scenarios (Figure 2(c)). SAV is expected to reduce parking, making space available for other uses notably commercial and residential. An increase in commercial land would generate more employment in the CBD, and, consequently, employment density would increase. Similarly, an increase in residential land is likely to increase residential density. Existing SAV impacts on accessibility in the CBD are conflicting, and more studies are needed to comprehend this relationship. If accessibility increases, commercial land use and job density tend to increase. Finally, higher employment density may require higher street network density (i.e. total street area divided by the total area of the suburb) to address the rise in travel demand by commuting vehicles.

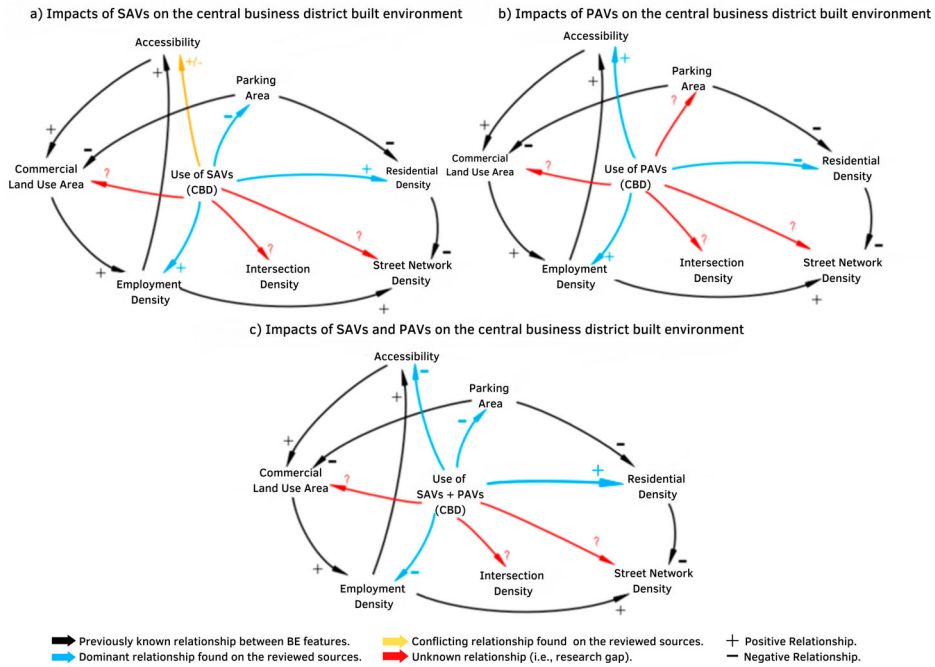


Figure 2. Built Environment Impacts for Central Business Districts. SAVs, PAVs, SAVs + PAVs.

On the other hand, more residential density in city centres may allow more transit use, walking and cycling to work, what may eventually counterbalance the demand on the street network. Overall, the effects of SAV on street networks and intersection densities are not known yet.

The relationship between the use of PAVs and residential density in city centres is negative, and it may eventually increase demand on the street networks due to more commuting trips. Furthermore, PAV tends to provide more accessibility in the CBD, which will eventually lead to more commercial land uses and employment density. The direct effect of PAVs on CBD parking is still unknown. However, it can be implied that PAVs may reduce demand for parking in the CBD if empty-cruising is possible. If parking demand reduces, there will be vacant land to develop more dwellings and commercial land use.

When SAV and PAV are combined (Figure 2(c)), decreases in parking demand, accessibility and employment density were found, whereas other effects are still unknown. Less accessibility means less opportunities to access commercial land use, what may explain the reduction in employment density when both modes are operating together in the CBD.

4.2. Suburbs

The impacts of AVs on the suburban built environment are illustrated in the CLDs for PAV (Figure 3(a)), SAV (Figure 3(b)) and mixed-AV mode (Figure 3(c)). SAVs may likely reduce parking area in suburbs and subsequently free up spaces to develop other land uses. However, results for SAV impacts on residential density in suburbs are divergent. It is also not clear yet how accessibility will be impacted by SAVs on suburban areas.

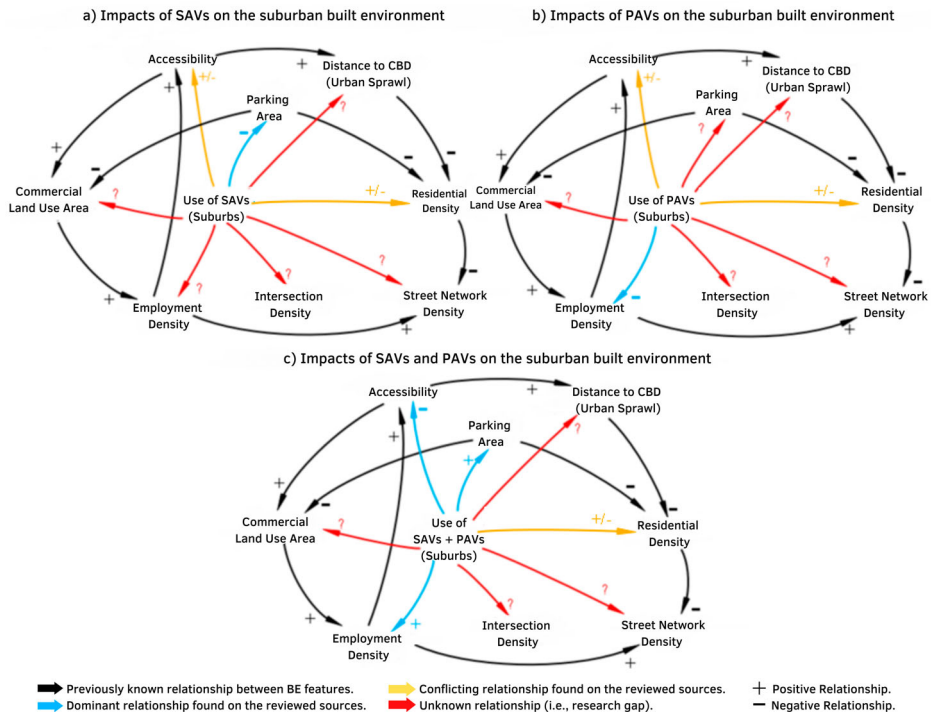


Figure 3. Built Environment Impacts for Suburbs. SAVs, PAVs, SAVs + PAVs.

The results for the relationship between PAV and residential density are also divergent. However, it is known that PAVs tend to reduce suburban employment density. This may subsequently act to reduce street network density. Results for accessibility are conflicting, and the impacts on other variables are still unknown limiting the assessment of other indirect effects. For mixed-AV modes, Figure 3(c) shows that parking area and employment density are likely to increase, whereas accessibility tends to decrease. More parking and less accessibility mean less likely to develop commercial land use area, which will eventually reduce employment density and street network density.

4.3. Citywide

Most studies used citywide scenarios in order to assess the broader impacts of SAV (Figure 4(a)), PAV (Figure 4(b)) and mixed-AV mode scenarios (Figure 4(c)). Overall, the use of SAVs may likely decrease parking area in cities. Hence, there may be more vacant lands to increase residential and commercial land use densities, and eventually free up street spaces. Accessibility tends to decrease with SAVs across the city; this would drive more urban sprawl. Nevertheless, there were conflicting findings on the direct impacts of SAVs on the average distance to CBD, indicating that urban sprawl may not be a dominant trend for SAVs on cities.

Figure 4(b) shows that urban sprawl will likely be the dominant trend with PAVs across the city due to improved accessibility level. This trend is confirmed by the positive direct relationship between the use of PAVs and distance to CBD. More urban sprawl will eventually lead to

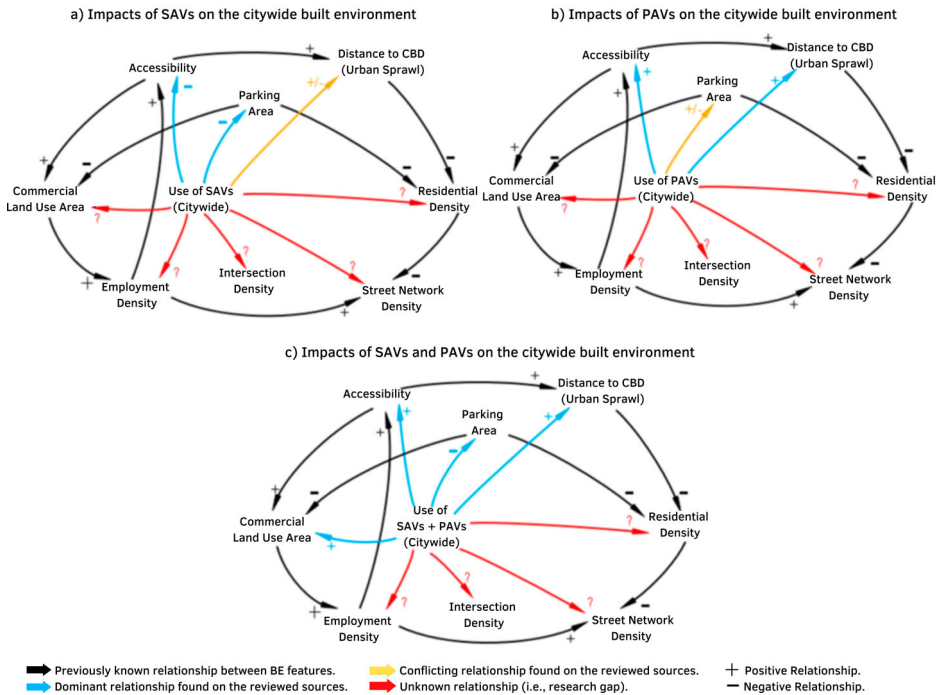


Figure 4. Citywide Built Environment Impacts. SAVs, PAVs, SAVs + PAVs.

lower residential density, and more street network density. On the other hand, the effects on parking are not clear yet, and may depend on the scenario settings (e.g. induced demand, car ownership, possibility of empty-cruising, off-street car-park layouts).

Figure 4(c) indicates four dominant relationships in case of mixed AV scenarios across the city. Whereas accessibility, distance to CBD and commercial land use area will likely increase, parking area tends to decline citywide. Increases in the average home distance to the CBD leads to a lower residential density. However, the elimination of parking may induce more housing development. More accessibility and less parking also favour more commercial developments; this will eventually increase employment density citywide, and induce street network expansion.

4.4. Research gaps and directions for future research

Several research gaps were found in this review. These are unknown quantitative relationships between AVs and the built environment and are highlighted in the causal loop diagrams using red arrows and question marks. Overall, no quantitative result was found for AV impacts on intersection density and street network density. In city centres and suburbs, it is also unknown how AVs will quantitatively impact commercial land use areas. There are speculative studies that forecast the replacement of vacant parking land by commercial land use in suburbs and city centres, but these impacts have not been quantified yet. Furthermore, no quantitative result was found for PAV impacts on parking areas in city centres and suburbs. Also, it is unknown how average commute distances between suburbs and CBD will be affected by SAV, PAV and mixed-AV mode

scenarios. Other research gaps include SAV impacts on employment density in suburbs, mixed-AV mode impacts on residential density in suburbs and AV impacts on residential density citywide. Thus, future research is needed to fill these gaps in knowledge.

Results were considered divergent when the findings are conflicting to each other in assessing the impacts of a particular type of AVs on a specific built environment attribute. For example, SAV impacts on accessibility in the CBD were reported to be both positive and negative depending on scenario assumptions in Zhong et al. (2020). Likewise, divergent accessibility results were found for SAVs (Zhong et al., 2020) and PAVs (Cordera et al., 2021) in suburbs for different scenarios. Citywide, divergent results were found for SAV impacts on distance to CBD, and PAV impacts on parking. Therefore, more studies are needed on these relationships to draw a precise conclusion.

5. Discussion

5.1. How to manage AV impacts on parking?

5.1.1. Replacement of vacant parking land

AVs are expected to significantly reduce the demand for parking, especially if SAV becomes the dominant mode (Kumakoshi et al., 2021; Zhang & Guhathakurta, 2017). This potential reduction of parking demand may allow the replacement of obsolete parking land by other land uses. Zoning policies should be updated to introduce these potential changes. For instance, minimum parking requirements for businesses in city centres may be replaced by minimum drop-off and pick-up areas, and charging spot requirements. Furthermore, car-park design standards should be adapted to allow layouts with less aisles, multiple rows of stacked vehicles and robotic valet.

Moreover, zoning policies should also consider to encourage the replacement of future vacant parking lands by affordable housing to accommodate the potential population relocation from middle suburbs to city centres and outer suburbs. On the other hand, potential vacant housing land in middle suburbs may need to be replaced by AV car-parks and charging stations.

In order to guide policy-makers and researchers in the public parking renewal process in the AV era, Xia et al. (2021) proposed a research framework based on four key issues: “how much to renew (i.e. demand forecast analysis), when to renew (i.e. update time series evaluation), what to renew (i.e. function replacement decision), and how to update (i.e. design empirical research)”. The findings presented in this study highlight the need to include a fifth component in this framework, “where to renew”, given that the demand for parking varies between different parts in a city.

While a number of urban redevelopment options emerge from AV induced parking reduction it should also be stressed that there is a potential danger caused by empty parking lots that are not redeveloped. They could induce a degree of “obsolescence” and potential economic decline if not redeveloped for new uses. Policy makers need to be aware of these risks and be ready to implement new uses promptly.

5.1.2. Empty-cruising and congestion pricing

Empty-cruising may lead to higher parking demand in suburbs and act to increase traffic congestion (Millard-Ball, 2019; Silva et al., 2022; Zhang & Wang, 2020). Millard-Ball (2019)

estimated that empty-cruising costs are 90% cheaper than hourly parking costs in dense areas, which may encourage AVs to search for free parking in suburban areas. Moreover, if free parking slots are not available and their prices exceed cruising costs, PAVs may choose to not park, and continuously circulate until their owners request a new ride (Millard-Ball, 2019). In this scenario, PAVs would likely choose to circulate at low speeds to minimise travel costs, and, therefore, more congestion might occur. Millard-Ball (2019) suggests that congestion pricing should be introduced to mitigate these issues. Likewise, experts have emphasised the need to implement access restrictions for both empty and single-occupant AVs in city centres to mitigate congestion and parking demand (Nogues et al., 2020). However, Zakharenko (2016) suggested that congestion pricing should be applied solely to commute trips. The author argues that congestion pricing for empty-cruising of AVs would force empty AVs to park in downtown areas, which would offset potential parking demand reductions and welfare gains in CBD areas (Zakharenko, 2016).

5.1.3. Empty-cruising, equity and traffic

If demand for suburban parking spaces increases, transportation and land use equity issues may emerge in suburbs, such as the inefficient use of valuable land parcels and increasing traffic congestion (Zhang & Wang, 2020). In addition, if SAVs go mainstream, new curbside pick-up and drop-off spots will be needed (Stead & Vaddadi, 2019; Zhang & Wang, 2020). These new spots may eventually replace some of the existing on-street parking and transit stops (Fayyaz et al., 2022; Gonzalez-Gonzalez et al., 2019). Fayyaz et al. (2022) estimate that an average of 1.4 curbside parking spots will be required to serve every 100 trips at peak hours, and should be located every 30 m. In addition, empty-cruising SAVs may increase VMT and congestion (Winter et al., 2021). However, these issues may be mitigated with appropriate SAV parking management strategies, such as the implementation of restricted dedicated SAV systems throughout the network, and parking relocation algorithms (Winter et al., 2021). For example, Overtoom et al. (2020) found that the adoption of SAV drop-off-and-ride facilities nearby transit stations is an effective measure to reduce traffic delays and congestion nearby transit stations for a SAV penetration rate of at least 25%.

5.1.4. Empty-cruising and waiting time

Another important issue related to PAV is the potential elimination of walking from parking spots to the final activity location, since drop-off may occur closer to destinations (Bahk et al., 2022). However, this will also introduce pick-up waiting times for PAV owners similar to ride-sourcing services, especially at CBD destinations. This may occur because PAVs tend to find cheaper parking, which are usually available outside high-density areas, and this may lead to higher travel times, and, consequently, longer pick-up waiting times (Bahk et al., 2022). Although PAV owners will be able to track the exact locations of their vehicles in real-time, for journeys with a short stay at destinations as well as for urgent and unplanned trips, the proximity of the vehicle to the owner tends to play a more critical role, and therefore the willingness-to-wait tends to be lower. Therefore, a very complex set of trade-offs among willingness-to-pay, willingness-to-wait and willingness-to-walk will be critical to determine PAV adoption, future demand for parking spaces and regulating policies (Bahk et al., 2022).

5.1.5. Park-and-ride

Demand for car-parks nearby transit stations tend to decrease since AVs may replace park-and-ride with drop-off-and-ride (Overtoom et al., 2020; Zhang & Wang, 2020). Hence, AVs may operate as a feeder system for public transportation, which may mitigate first-mile and last-mile transit accessibility issues compared to human-driven cars (Ahmed et al., 2020). Policy-makers should consider to update zoning policies to plan the replacement of future obsolete park-and-ride land by other land uses, such as affordable housing, green areas and businesses.

5.2. How to mitigate AV effects on urban sprawl?

Density benefits in city centres seem to depend very much on economic conditions. The positive density effects in city centres found in this research depend very much on the conversion of land from parking to residential and commercial land uses. This should normally be driven by urban economics as land prices in CBD's are often higher than other zones. However, an economic downturn would be an unfortunate timing for CBD parking removal as this land might become derelict affecting long term CBD economic performance.

A great challenge ahead is to find the right balance in allowing the penetration of PAVs and SAVs to reduce urban sprawl. Overall, SAVs seem to be more beneficial than PAVs in this regard. However, their penetration level in low-density suburbs will likely rely on their operation model and costs. In a free market, SAVs may be more feasible in high-density areas, whereas people who live in suburban areas with a lack of employment opportunities seem to have a higher willingness-to-pay for PAVs (Nodjoman & Kockelman, 2019). Thus, public policies will be needed to subsidise SAV penetration in suburban areas to prevent urban sprawl. For instance, city governments can partner with SAV operators to connect SAVs to mass transit as a feeder system to solve first/last mile issues. This could be done through an integrated Mobility as a Service platform. Furthermore, congestion pricing for commuting PAVs, and transit-oriented mixed-use developments in suburban areas may also shift demand from PAV towards SAVs.

5.3 How to adapt cities to accommodate AVs?

5.3.1 Street design

Planners and policy-makers should consider revising current street design guidelines to account for AV impacts. Less street space for cars may be possible due to traffic efficiency gains caused by platooning technology (Yigitcanlar et al., 2019). Feasible road lane width requirements may be reduced from the current 3.0m-3.5 m to 2.45m-2.75 m (Fayyaz et al., 2022; Lee et al., 2022). Furthermore, other road geometric design features, such as vehicle stopping and passing sight distances, and lateral clearance on horizontal curves may be significantly reduced (Othman, 2021). These potential reductions in urban spaces for cars may permit wider sidewalks (Riggs et al., 2020), and more flexible use of road infrastructure, such as pedestrian-only zones or public transport lanes at specific times of the day (Stead & Vaddadi, 2019).

5.3.2. Crossings, pavement and utilities

Intersections, traffic signage and signalisation may also be significantly impacted by AV wireless and real-time information technology (Chapin et al., 2016). If AV level 5 goes mainstream, intersections will no longer require traffic stop signs (Fraedrich et al., 2019), and safety barriers (Stead & Vaddadi, 2019). Less traffic signage will also free up space on sidewalks that could be replaced, for instance, by urban amenities. However, traffic flow issues with non-motorised modes at intersections with no traffic lights may require the construction of either overhead or underpass pedestrian and cyclist infrastructure (Heinrichs, 2016), which will eventually lead to potentially unfundable infrastructure costs.

Furthermore, the costs of replacing or moving utility infrastructures may be prohibitively high, particularly on a city network wide scale (Fayyaz et al., 2022). For instance, Othman (2021) points out that current bridge design standards are not safe to allow autonomous truck platoons. Besides, pavement deterioration may be intensified due to the elimination of the wheel wander by AV lane keeping systems (Othman, 2021). Consequently, existing overhead structures and pavements may need to be rebuilt or strengthened to allow autonomous vehicles; a significant additional cost to cities.

A potential alternative to diminish the need for pedestrian crossing structures is to limit AV traffic flow to arterial streets and freeways. Consequently, solely non-motorised and public transit modes would be allowed on local and collector streets forming pedestrian-friendly superblocks. A superblock policy of this kind has been initially implemented in Barcelona, Spain, in 2019, providing more walkability and significant health benefits (Mueller et al., 2020). For instance, Lee et al. (2022) proposed a patchwork urban design concept in Seoul, South Korea, where several superblocks are designated solely for AVs and non-motorised modes. This concept also proposes that the AV-only superblocks will be connected by major roads with segregated lanes for human-driven lanes, AVs and public transportation. Furthermore, some minor roads may solely allow human-driven vehicles and non-motorised modes. Likewise, a study in Melbourne, Australia, proposed urban design guidelines for AV implementation in suburban and urban areas, including AV-only lanes, drop-off and pick-up spots nearby transit hubs, replacement of parking spaces by charging stations and bike lanes, and an intelligent transportation system in major crossings to provide real-time information for AVs regarding pedestrians and cyclists (Manivasakan et al., 2021). These design guidelines presented positive impacts on safety, accessibility and traffic efficiency.

5.3.3. Intersection density

Intersection density is another critical built environment feature related to urban design. The higher the intersection density, the higher the walkability levels (Ewing & Cervero, 2010; Frank et al., 2010). Studies have found that high intersection density favour SAV adoption (Nodjomian & Kockelman, 2019; Wang & Zhang, 2021). Nevertheless, no quantitative research has been found regarding the potential impacts of AVs on intersection density. It is critical, for example, to investigate how intersection density will affect AVs and other modes in scenarios with no traffic lights at intersections. A growing need for grade separated pedestrian crossing infrastructure may lead policy-makers to increase

the distance between pedestrian crossings in highways. As a result, it may eventually reduce intersection density, and, consequently, walkability may be negatively affected.

6. Conclusion

Sporadic knowledge is being generated about the long-term effects of autonomous vehicles (AVs) on the built environment across the world. This study is a first attempt to synthesise this knowledge. This paper aims to conceptualise why these effects occur and how. As such, the study presented nine causal loop diagrams explaining the chain of AV effects on the built environment, their directions and magnitudes (where available), based on three types of AVs (private, shared and both), and three different geographical contexts (CBD, suburb and citywide).

The findings of this paper present both opportunities and challenges for cities to improve sustainability in the long-run. While the effects of SAVs on the built environment seem more positive, PAVs would negatively affect the sustainability of cities. For example, SAVs may likely contribute to increasing residential and employment densities in the CBD. An increasing residential/employment density has been identified to have a significant positive effect on the society (e.g. crime, social interaction and trust) (Twinam, 2017), environment (e.g. less greenhouse gas emissions, water and land conservation) (Norman et al., 2006), economy (e.g. more sales, jobs, innovation, productivity) (Steiner, 1994) and public health (e.g. less obesity and cardiorespiratory diseases) (Sallis et al., 2016). In contrast, PAVs may likely contribute to intensifying urban sprawl in suburban and rural areas.

The causal loop diagrams provide an opportunity to derive effective policy measures both to capitalise the benefits and address the challenges of AVs. It would help to understand the flow on effects of such policies. They can be developed at the upper level to address/promote a range of consequences downstream or at the lower level to address/promote specific consequences. For example, allowing empty cruising for PAVs at the upper level would free up parking space for the CBD, which would subsequently encourage residential and commercial development. Furthermore, the development of the causal loop diagrams also helps us to identify the many unknowns in the literature concerning the long-term effects of AVs on the built environment. Although an attempt is made to fill-in the diagrams based on related literature, there remain gaps. For instance, future research is needed to comprehend AV impacts on urban design features, such as intersection density, intersection weaving (i.e. removal of traffic lights), street network density, and pedestrian, cycling and transit rights-of-ways. Furthermore, research is needed to comprehend how infrastructure utilities, pavement and urban amenities will be affected by AVs. Other research gaps are the impacts of AVs on land use mix, and SAV feasibility to tackle first/last mile issues.

A limitation of this review is the speculative nature of most of the reviewed sources due to a lack of large-scale empirical data from AVs in operation. Furthermore, most quantitative studies used different assumptions, models and indicators, making direct comparison problematic. In addition, this systematic scoping review did not consider the impacts of flying autonomous taxis and autonomous mass transit systems (e.g. autonomous bus, train and tram) on the built environment. Also, this review solely considered results for AVs with high levels of automation (i.e. levels 4 and 5) in the long-term. Some relevant

AV features discussed in this review, such as driverless ride-sourcing, empty-cruising and driverless self-parking are only suitable for levels 4 and 5. Nevertheless, future studies may attempt to address this limitation by investigating potential distinctive effects on the built environment for level 3, and, separately for levels 4 and 5. Lastly, the vast majority of the literature is concentrated in North America, Asia, Europe and Oceania (see appendix); therefore, the results of this systematic scoping review may not be adequate for cities in other geographic contexts.

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Appendix – Literature review source description

Source	Method	Built Environment Indicator	Context	Source	Method	Built Environment Indicator	Context
Ahmed et al. (2020)	Modelling	Accessibility	USA	Liu et al. (2021)	Modelling	Commute time and residential density	General
Azevedo et al. (2020)	Modelling	Parking	General	Llorca et al. (2022)	Modelling	Household Relocation	Germany
Bahk et al. (2022)	Modelling	Parking	General	Luo et al. (2019)	Modelling	Accessibility and Household Relocation	Japan
Bansal and Kockelman (2018)	Survey and statistical analysis	Household Relocation	USA	Manivasakan et al. (2021)	Design Guidelines and Framework	Urban Design	Australia
Bansal et al. (2016)	Survey and statistical analysis	Household Relocation	USA	Meyer et al. (2017)	Modelling	Accessibility	Switzerland
Bin-Nun and Binamira, (2020)	Survey and Framework	Household Relocation	USA	Milakis et al. (2018)	Interviews with experts	Accessibility and Household Relocation	General
Bischoff et al. (2019)	Modelling	Parking	Germany	Milakis et al. (2017)	Literature Review	Several	General
Botello et al. (2019)	Interviews with experts	Urban Design	USA	Millard-Ball (2019)	Modelling	Parking	USA
Bridgelall and Stubbing (2021)	Modelling	Commercial Land Use	Canada	Moore et al. (2020)	Modelling	Household and Workplace Relocations	USA
Carrese et al. (2019)	Survey and modelling	Household Relocation	Italy	Nadafianshamabadi et al. (2021)	Modelling	Road capacity and Land Use Relocation	USA
Cohen and Cavoli (2018)	Literature Review	Accessibility	General	Nahmias-Biran et al. (2020)	Modelling	Accessibility and Household Relocation	Singapore
Chapin et al. (2016)	Literature Review and Forecasting	Several	USA	Narayanan et al. (2020)	Literature Review	Several	General
Childress et al. (2015)	Modelling	Accessibility	USA	Nodjomian and Kockelman (2019)	Survey	Several	USA
Cordera et al. (2021)	Modelling	Accessibility and Land Use Relocation	Spain	Nogues et al. (2020)	Backcasting and interviews	Several	General
Dianin et al. (2021)	Literature Review and Framework	Accessibility and Land Use Relocation	General	Nourinejad et al. (2018)	Modelling	Parking	General
Duarte and Ratti (2018)	Literature Review	Several	General	Okeke (2020)	Modelling	Parking	England
	Modelling	Road capacity and Parking	Austria	Othman (2021)	Literature Review	Urban Design and Parking	General

(Continued)

Continued.

Source	Method	Built Environment Indicator	Context	Source	Method	Built Environment Indicator	Context
Emberger and Pfaffenbichler (2020)							
Faisal et al. (2019)	Literature Review	Several	General	Overtoom et al. (2020)	Modelling	Parking and Road Capacity	Netherlands
Fagnant and Kockelman (2014)	Modelling	Road Capacity	USA	Rafael et al. (2022)	Modelling	Urban Design	Portugal
Fayyaz et al. (2022)	Literature Review	Urban Design	General	Riggs et al. (2020)	Design Guidelines and Framework	Urban Design	General
Fox (2016)	Literature Review	Urban Density	General	Shatu and Kamruzzaman (2022)	Literature Review and Framework	Urban Design	General
Fraedrich et al. (2019)	Literature review, survey and interviews	Several	Germany	Silva et al. (2021)	Survey and scenario building	Parking and Urban Design	Hungary
Gelauff et al. (2019)	Modelling	Household Relocation	Netherlands	Silva et al. (2022)	Literature Review	Urban Design	General
Golbabaee et al. (2021)	Literature Review	Several	General	Simons et al. (2018)	Literature review	Parking	USA
Gonzalez-Gonzalez et al. (2019)	Backcasting	Several	General	Soteropoulos et al. (2021)	Literature Review and Modelling	Urban Design	Austria
Guan et al. (2021)	Survey and statistical analysis	Household Relocation	China and USA	Stead and Vaddadi (2019)	Literature Review	Several	General
Gruel and Stanford (2016)	Literature Review and Forecasting	Several	General	Szimba and Hartmann (2020)	Modelling	Commute time, distance to CBD and urban sprawl	Germany
Hawkins and Nurul Habib (2018).	Literature Review	Several	General	Thakur et al. (2016)	Modelling	Household Relocation	Australia
Heinrichs (2016)	Literature Review and Forecasting	Several	General	Wang and Zhang (2021)	Modelling	Several	USA
Hiramatsu (2022)	Modelling	Household relocation	Japan	Wellik and Kockelman (2020)	Modelling	Land Use Relocation	USA
Kang et al. (2022)	Modelling	Parking	USA	Winter et al. (2021)	Modelling	Parking	Netherlands
Kang and Kim (2019)	Modelling	Diversity of Land Uses	South Korea	Xia et al. (2021)	Literature review and proposal	Urban Design	General
Kondor et al. (2019)	Modelling	Parking	Singapore	Yigitcanlar et al. (2019)	Literature Review	Several	General
Kong et al. (2018)	Modelling	Parking	General	Zakharenko (2016)	Modelling	Parking and Household Relocation	General
Kim et al. (2020)	Empirical and Modelling	Household relocation	USA	Zhang and Guhathakurta (2017)	Modelling	Parking	USA
	Modelling	Parking	Japan	Zhang et al. (2018)	Modelling	Road Capacity	USA

Kumakoshi et al. (2021)							
Kyung-Hwan et al. (2015)	Modelling	Road capacity and Land Use Relocation	South Korea	Zhang et al. (2015)	Modelling	Parking	USA
Larson and Zhao (2020)	Modelling	Distance to CBD and Urban Sprawl	USA	Zhang and Wang (2020)	Modelling	Parking	USA
Lee et al. (2022)	Design Guidelines	Urban Design	South Korea	Zhang and Guhathakurta (2021)	Modelling	Household Relocation	USA
Legacy et al. (2018)	Literature Review and Forecasting	Several	General	Zhou et al. (2021)	Modelling	Accessibility and Household Relocation	Singapore
Liu et al. (2022)	Modelling	Road capacity and Parking	China	Zhong et al. (2020)	Modelling	Accessibility	China