BERKELEY CITY COUNCILMEMBER
TERRY TAPLIN
DISTRICT 2

CONSENT CALENDAR
October 11th, 2022

To: Honorable Mayor and Members of the City Council

From: Councilmember Terry Taplin, Councilmember Kate Harrison, and Councilmember Rigel Robinson

Subject: Regulation of Autonomous Vehicles

RECOMMENDATION

Refer to the City Attorney the assessment of the legal abilities and opportunities for the City Council to regulate the operation, sale, and testing of autonomous vehicles (AVs) within the City of Berkeley and report to the Facilities, Infrastructure, Transportation, Environment and Sustainability Committee (FITES) on all findings.

POLICY COMMITTEE RECOMMENDATION

On July 20, 2022, the Facilities, Infrastructure, Transportation, Environment & Sustainability Policy Committee took the following action: M/S/C (Robinson/Harrison) to approve the item with a positive recommendation.

CURRENT SITUATION AND ITS EFFECTS

Autonomous vehicles, better known as driverless cars, are an emerging technology with such potential to transform our transportation system that it inspires great optimism as well as an equal amount of trepidation. Advocates and opponents of the technology agree that the full automation of personal automobiles will have enormous ripple effects throughout our society, impacting the job market, public safety, energy consumption, and our every understanding of how we design our cities and transportation systems. Those pursuing AV technology view removing the variable of human error from personal vehicle transportation as the solution to congestion, fuel efficiency, and traffic accidents themselves. Proponents of AVs also see driverless cars as a valuable resource for persons with disabilities who cannot currently drive personal vehicles, expanding the mobility options for millions.[1] Others are more suspicious of driverless cars.

Some studies suggest any gains made by AVs in reducing congestion and traffic accidents could very well be neutralized by an induced demand for this exciting new transportation method.[2] Furthermore, the introduction of truly autonomous vehicles into

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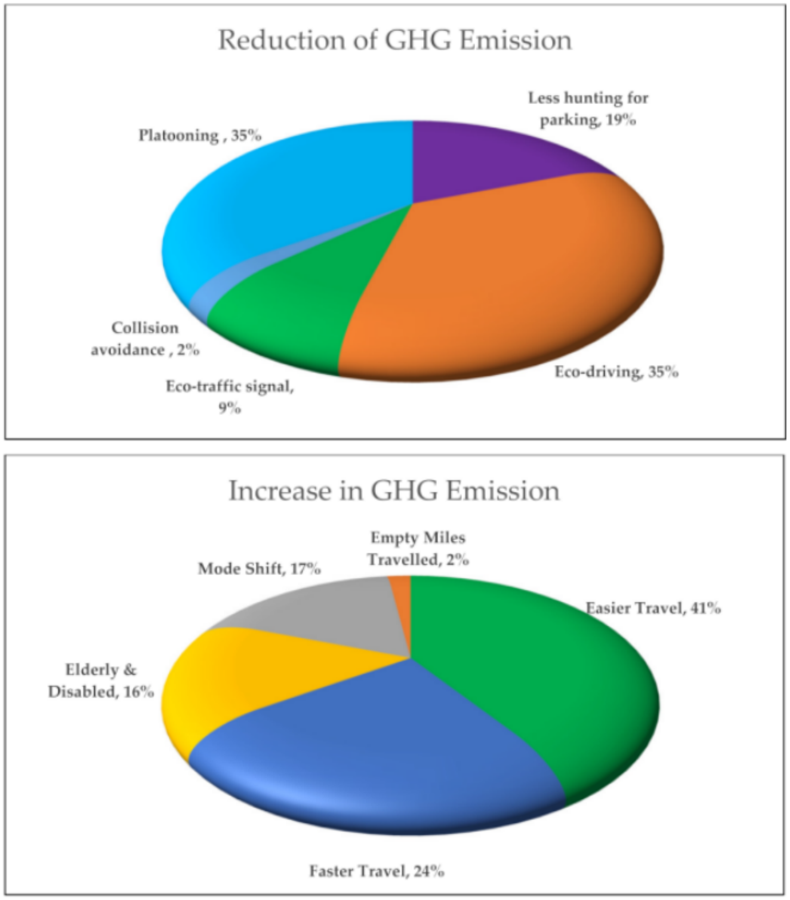
[1] Faisal, Asif, et al. "Understanding autonomous vehicles." *Journal of transport and land use* 12.1 (2019): 45-72.

[2] Medina-Tapia, Marcos, and Francesc Robusté. "Implementation of connected and autonomous vehicles in cities could have neutral effects on the total travel time costs: modeling and analysis for a circular city." *Sustainability* 11.2 (2019): 482.

the market at a time when environmental and street safety advocates are pushing for a decline in all kinds of personal vehicle mode-shares could undo decades of work to reduce car dependency. Of particular concern to the City of Berkeley will be the impact that AVs have on greenhouse gas emissions. On one hand, reduced driving time searching for parking, the potential for autonomous driving to be more fuel-efficient, reduced congestion, and disruptions to the decision-making systems that encourage the unnecessary growth in size of modern personal vehicles could very well reduce emissions. On the other hand, easier and faster travel and the widening of accessibility that fully autonomous vehicles will bring may boost car mode-share beyond levels consistent with our climate needs.[3] While difficult to know for certain, “it is quite possible that AVs could be more energy-efficient, thereby reducing the GHG by functional unit-basis as per-passenger-mile (ppm); however, the overall gain related to transportation GHG emissions could be swamped by a surge in increased vehicle miles traveled (VMT)”[4]. Whether driverless cars revolutionize transportation for better or worse, policymakers must be prepared for an influx of these new vehicles.



Potential impacts of autonomous vehicles on greenhouse gas emissions.[5]

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[3] Massar, Moneim, et al. "Impacts of autonomous vehicles on greenhouse gas emissions—positive or negative?." *International Journal of Environmental Research and Public Health* 18.11 (2021): 5567.

[4] Massar, Moneim, et al.

[5] Massar, Moneim, et al.

According to recent data provided by the California Department of Motor Vehicles, 2021 was a record-setting year for miles driven by test-autonomous vehicles (AVs) in California.[6] Despite the sudden growth in AVs on public roads in recent years, municipal governments have limited control over the regulation of AV testing and little access to basic information on the testing itself. This will pose a growing concern to local policymakers in the coming years as AV testing continues to spread. In California, AV testing oversight belongs to the DMV and the California Public Utilities Commission. This concentration of regulatory power at the state level makes it difficult to even determine the number of AV tests that have been conducted on Berkeley's streets, particularly because the DMV and CPUC do not require that AV companies report the whereabouts of their vehicles.[7] In order for the City to plan for the introduction of AVs onto public roads, use what limited regulatory abilities may be available, and lobby the state government to expand its oversight power, the Berkeley City Council must be made aware of all legal options for setting both AV testing rules and rules for functional AVs in a future where testing is complete and AVs are commercially available.

Beyond the testing of AVs that is expected to continue for many years, Berkeley must be prepared for a scenario where AVs are widely sold and threaten many of the City's transportation and climate goals. For the sake of safer streets and a reduction of fossil fuel emissions, the City of Berkeley is pursuing a growth in non-car transportation mode shares in its transportation, infrastructure, and planning policies. This pursuit may easily be threatened by the sudden availability of self-driving cars. The option for drivers to choose a vehicle that offers the present day convenience of an automobile with an added reduction in the actual requirement to drive the vehicle carries the possibility of undoing any progress made if no preemptive regulatory policies are made. While it will be many years before self-driving cars are available or even common on Berkeley's streets, the City must proceed with transportation planning that is cautious with AVs and committed to a future where cars are not the largest mode-share.

RATIONALE FOR RECOMMENDATION

It is important for the City of Berkeley to have a clear understanding of its exact responsibilities when it comes to autonomous vehicles and where state and federal bodies hold most power. With that knowledge, the City Council can lobby the state government and federal agencies both for more power over the regulation of driverless cars as well as for specific policies that Council determines should be enacted but lacks the power to do alone.

FISCAL IMPACTS

Staff time for the referral response.

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[6] https://techcrunch.com/2022/02/10/fewer-autonomous-vehicle-companies-in-california-drive-millions-more-miles-in-testing/

[7] https://www.sfexaminer.com/findings/how-san-francisco-became-an-autonomous-vehicle-test-course/

ENVIRONMENTAL IMPACTS

Reducing the use of automobiles on Berkeley’s streets is a critical task for the reduction of the City’s fossil fuel emissions, an immense share of which come from private vehicle emissions.[8]

CONTACT

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ATTACHMENTS

1. Understanding Autonomous Vehicles
2. Impacts of Autonomous Vehicles on Greenhouse Gas Emissions—Positive or Negative?

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[8] https://berkeleyca.gov/sites/default/files/2022-01/Berkeley-Climate-Action-Plan.pdf

JTLU

Understanding autonomous vehicles

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JTLU

Understanding autonomous vehicles: A systematic literature review on capability, impact, planning and policy

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Abstract: Advancement in automated driving technology has created opportunities for smart urban mobility. Automated vehicles are now a popular topic with the rise of the smart city agenda. However, legislators, urban administrators, policymakers, and planners are unprepared to deal with the possible disruption of autonomous vehicles, which potentially could replace conventional transport. There is a lack of knowledge on how the new capabilities will disrupt and which policy strategies are needed to address such disruption. This paper aims to determine where we are, where we are headed, what the likely impacts of a wider uptake could be, and what needs to be done to generate desired smart urban mobility outcomes. The methodology includes a systematic review of the existing evidence base to understand capability, impact, planning, and policy issues associated with autonomous vehicles. The review reveals the trajectories of technological development, disruptive effects caused by such development, strategies to address the disruptions, and possible gaps in the literature. The paper develops a framework outlining the inter-links among driving forces, uptake factors, impacts and possible interventions. It concludes by advocating the necessity of preparing our cities for autonomous vehicles, although a wider uptake may take quite some time.

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1 Introduction

The convergence of technology and the city is seen as a possible remedy to overcome the challenges of urbanization such as climate change, congestion, and greenhouse gas (GHG) emissions (Yigitcanlar, 2016). Transport, as an integral part of the city, is responsible for about a quarter to one-third of GHG emissions (Kamruzzaman, Hine, & Yigicanlar, 2015; Arbolino, Carlucci, Cira, Loppolo, & Yigicanlar, 2017; Yigitcanlar, Foth, & Kamruzzaman, 2018). Technology in the name of smart urban mobility is

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becoming a key concept of the contemporary urban policy agenda to address the undesirable effects of transport (Creutzig et al., 2015; Perveen, Yigicanlar, Kamruzzaman, & Hayes, 2017; Perveen, Kamruzzaman, & Yigicanlar, 2017, 2018; Yigitcanlar & Kamruzzaman, 2018b).

As originally conceived within the smart cities agenda (Yigitcanlar, 2015; Lara, Costa Furlani, & Yiticanlaar, 2016; Trindade et al., 2017; Chang, Sabatini-Marques, da Costa, Selig, & Yigicanlar, 2018; Yigitcanlar et al., 2018a), the smart urban mobility concept is characterized by an integration of sustainable and smart vehicular technologies, and cooperative intelligent transport systems (ITS) through cloud-servers and big-data-based vehicular networks (Kim, Moom, & Suh, 2015). In other words, smart urban mobility is conceptualized as urban traffic services combined with smart technologies (Chun & Lee, 2015). Undoubtedly one of the most advanced applications that utilizes numerous ITS tools as a part of the smart urban transport system is autonomous vehicle (AV)—a.k.a. automated car, self-driving car or driverless car (Spyropoulou, Penttinen, Karlaftis, Vaa, & Golias, 2008; Chong et al., 2013; Olaverri-Monreal, 2016).

The basic concept of road vehicle automation refers to the replacement of some or all of the human labor of driving by electronic and/or mechanical devices (Shladover, 2018). Origins of the automated driving technology can be traced back to the early 20th century. At that time, the technology was concentrated on autonomous speed, break, lane control, and other basic cruise control aspects (Shladover, Su, & Lu, 2012; Anderson et al., 2014; Arnaout & Arnaout, 2014; Pendleton et al., 2017). However, only during the last decade or so, incubating conditions of the Digital and 4th Industrial Revolutions gave birth to rapid technological advancements in the field; resulting in numerous prototype AVs being trailed on the roads (Christie, Koymans, Chanard, Lasgouttes, & Kaufmann, 2016).

Many research articles have been published in the academic literature describing the technological advancement of AVs (Denaro, Zmud, Shladover, Smith, & Lappin, 2014). However, academic literature outlining the AV induced disruptions (both positive and negative) in cities and how policies are being introduced to promote or address various disruptive effects is fairly limited (Bagloee, Tavana, Asadi, & Oliver, 2016; Gruel & Stanford, 2016; Truong, De Gruyter, Currie, & Delbosc, 2017), despite a recent prediction suggests that by 2045, AVs would account for up to half of all road travel (Bansal & Kockelman, 2017; Litman, 2017). Even more so, there is no study, to our knowledge, in the academic literature that critically scrutinizes the state of AVs from a combined perspective focusing on its capability, impact and existing/potential policy interventions to reduce/foster the disruptive effects.

Against this backdrop, this paper aims to determine where we are at, where we are headed to, what the likely impacts of wider AV uptake could be, and what needs to be done for AVs to generate desired smart urban mobility outcomes—with a particular focus on the capability, impact and policy. In order to achieve this aim, the study undertakes a systematic review of the literature on AVs published in peer-reviewed journals. The review concentrates on the following research objectives: (a) Highlighting the main findings and contributions of the reviewed literature; (b) Mapping out the relationships among the capability, impact, planning interventions, and pre-deployment policy to accommodate AVs as well as to reduce the undesirable effects of AVs; (c) Determining the gaps in the literature and pointing out directions for prospective research. A key outcome of this research is the development of an AV driving forces, uptake factors, impacts and interventions framework.

2 Autonomous vehicles in a nutshell

2.1 Historical background

Vehicle automation was originally envisioned as early as in 1918 (Pendleton et al., 2017), and the first concept of automated vehicle was exhibited by General Motors in 1939 (Shladover, 2018). The initial phase of research and development (R&D) was jointly initiated by General Motors and Radio Corporation of America Sarnoff Laboratory in the 1950s (Shladover, 2018). From 1964 to 2003, several other R&D programs were operational in the US, Europe, and Japan under individual and joint initiatives of different government institutes and academia to develop automated bus and truck platoons, super-smart vehicle systems, and video image processing of driving scene recognition (Shladover, 2018). AV research was accelerated through the Defense Advanced Research Projects Agency's (DARPA) Grand Challenges Program in the US in 2004. The challenges resulted in AVs capable of traversing dessert terrain in 2005, and in 2007. Researchers also managed to place AVs on urban roads through the DARPA's Urban Challenge Program (Pendleton et al., 2017; Shladover, 2018). Since then, R&D continued at a fast pace in both academia and industrial settings.

Volvo, for instance, started its journey to autonomous driving in 2006, introduced its full autonomous test vehicle in 2017, and has plans to bring its unsupervised AV to the market by 2021. Tech giant Google started its journey towards full AVs in 2009, and by 2017 Google's AV fleet, WAYMO, has completed three million miles driving within four US states. In 2014, TESLA announced that its car will be capable of self-driving about 90% of the time. Today, all TESLA models are equipped with self-driving capability. By 2020, Audi, BMW, Mercedes-Benz and Nissan are expecting to have their AVs in the market.

Bloomberg (2017) provides an inventory of how cities around the globe are preparing for the transition to a world with AVs. According to this study, 36 cities were hosting AV tests, or have committed to doing so in the near future; where 18 other cities are undertaking long-range surveys of the regulatory, planning, and governance issues associated with AVs, but have not yet started piloting. The inventory considers of those piloting cities that were partnering on tests of a variety of AV products, including retrofitted autos and brand-new vehicles like conveyors (small, cart-sized AVs that travel on sidewalks). Testbed locations are generally isolated places from the rest of the city, such as technology parks, college campuses, urban renewal districts, highways, and former international mega-event sites. Therefore, as stated by Bloomberg (2017), while these trials are happening, they are not yet tackling the full challenges of navigating through complex urban environments. Table 1 lists the cities that are piloting (hosting AV tests or have committed to doing so in the near future) or preparing (undertaking long-range surveys of the regulatory, planning, and governance issues raised by AVs, but have not yet started piloting) themselves for an AV uptake.

Table 1. List of cities testing or in preparation for AVs (Bloomberg, 2017)

Piloting cities	Piloting cities (continued)	Preparing cities
Adelaide, AU	Melbourne, AU	Auckland, NZ
Amsterdam, NL	Oslo, NO	Buenos Aires, AR
Austin, US	Paris, FR	Cambridge, US
Boston, US	Pittsburgh, US	Columbus, US
Bristol, UK	Reno, US	Denver, US
Chandler, US	Rotterdam, NL	Dublin, US
Chiba City, JP	San Antonio, US	Los Angeles, US
Detroit, US	San Francisco, US	Montréal, CA
Dubai, UAE	San Jose, US	Nashville, US
Edmonton, CA	Seongnam, KR	Orlando, US
Eindhoven, NL	Singapore	Palo Alto, US
Gothenburg, SE	Toronto, CA	Portland, US
Haarlem, NL	Wageningen, NL	Rionegro, CO
Helsinki, FI	Washington, DC, US	Sacramento, US
Las Vegas, US	West Midlands, UK	Santa Monica, US
London, UK	Wuhan, CN	Seattle, US
Lyon, FR	Wuhu, CN	São Paulo, BR
Milton Keynes, UK	Zhuzhou, CN	Tel Aviv, IL

2.2 Autonomous technology

In line with the automation concept, a taxonomy of 4-level of vehicle automation was developed by the National Highway Traffic Safety Administration (NHTSA) in 2013 (Wadud, MaKenzie, & Leiby, 2016), and a 5-level automation was introduced by the Society of Automotive Engineers International (SAE) in 2014—later on updated in 2016 (Coppola & Morisio, 2016; SAE, 2016a, 2016b; Snyder, 2016; Milakis, van Arem, & van Wee, 2017). In 2016, NHTSA adopted SAE's taxonomy and automation levels (NHTSA, 2016). SAE's taxonomy and automation levels have become an industry standard, and also frequently referred in the academic literature (Rubin, 2016; Scheltes & de Almeida Correia, 2017; Walker & Marchau, 2017; Shladover, 2018). Table 2 describes the operational functions included in automated driving system (ADS), and the role of human driver at each level of vehicle automation.

Table 2. Taxonomy of road vehicle automation derived from SAE (2016a)

Level of automation	Automated driving system		Human driver	
	Operational function	Capability	Operational function	Capability
Level 1 (most functions are controlled by driver)	Control: lateral and longitudinal	In some driving modes	Localisation Perception Planning Management	In all driving modes
Level 2 (at least one driver assistance system is automated)	Control: lateral and longitudinal	In some driving modes	Localisation Perception Planning Management	In all driving modes
Level 3 (driver is able to shift safety-critical functions to vehicle)	Control: lateral and longitudinal Localisation Perception Planning	In some driving modes	Management	In all driving modes
Level 4 (fully-autonomous, but not in every driving scenario)	Control: lateral and longitudinal Localisation Perception Planning Management	In some driving modes	n/a	n/a
Level 5 (fully-autonomous, vehicle's performance is equal that of human driver in every driving scenario)	Control: lateral and longitudinal Localisation Perception Planning Management	In all driving modes	n/a	n/a

In theory, an automated vehicle system can only be termed as an "autonomous" system, when all the dynamic driving tasks, at all driving environment, can be performed by the vehicle's automated system. According to the Federal Automated Vehicles Policy of the US Department of Transportation, a vehicle is denoted as AV if it has levels 3-5 automated systems (DoT, 2016). However, these levels of autonomy are not strictly maintained in the literature and any level of autonomy is referred to as autonomous (Shladover, 2018). Throughout this paper, the term AV will refer to the levels 3-5 automated systems only.

Driving requires a variety of functions, including localization, perception, planning, control, and management (Coppola & Morisio, 2016). Information acquisition is a prerequisite to localization, and perception. If all of these functions, including information acquisition, are available in a vehicle, it could definitely be termed as an AV. If any AV has to communicate with other infrastructures to collect information, or to negotiate its maneuvers, it is termed as connected autonomous vehicle (CAV) (Shladover, 2018), and when any manually driven vehicle, whether manual or automated, has to communicate with other infrastructures to collect information, or to negotiate its maneuvers, it is termed as connected vehicle (CV) (Hendrickson, Biehler, & Mashayekh, 2014; Coppola & Morisio, 2016). Therefore, CV technology is complimentary or has synergistic effect on the implementation of AV to some extent (Shladover, 2018), though connectivity is not a mandatory feature of AVs (Hendrickson et al., 2014).

2.3 Perceived benefits

AVs are expected to be operational both as private and as commercial vehicle (Heinrichs, 2016; Collingwood, 2017; Wadud, 2017). One of the perceived advantages and flexibility of autonomous private car over the conventional private car is that it can simultaneously be used among all members in a family. Commercial AVs could be operated as taxi, bus, and freight services. AV taxis can provide service as a combination of conventional car-sharing and taxi services, which is referred to as shared AV (SAV) or driverless taxi (Fagnant & Kockelman, 2014; Krueger, Rashidi, & Rose, 2016).

Perception prevails that driverless taxi is likely to complement/supplement traditional public transit service, and it can potentially replace the private car and conventional taxis because SAVs are expected to be relatively inexpensive and facilitating opportunity for multitasking during a ride (Malokin, Circella, & Mokhtarian, 2015; Krueger et al., 2016; Milakis, Snelder, van Arem, Homem, & van Wee, 2017). In spite of having cooperation within the fleet, conventional taxi drivers seek to maximize individual profit, overruling minimum wait time and less passenger kilometers travelled (PKT), as identified by the fleet cooperation (Boesch, Ciari, & Axhausen, 2016).

Some transport network companies (TNC), such as Uber and Lyft, have been trying to develop a model similar to SAVs in their operations. However, in this model, human drivers are still responsible for routing, relocation, operation times, and many other decision-making factors. On the contrary, 100% central control system of SAV can overcome the limitations of conventional taxi services. Thus, SAV can ensure more system-optimal and overall profit-maximizing network with a higher service level and lower empty travel cost with respect to conventional taxi services, and TNCs (Fagnant, Kockelman, & Bansal, 2015). With a comprehensive ICT integration, SAV could facilitate dynamic ridesharing (DRS). Hence, SAV can either provide service with DRS or without DRS facility (Krueger et al., 2016).

The barriers to traditional ridesharing service could be overcome through the introduction of DRS (Krueger et al., 2016) or driverless taxi (Martinez & Viegas, 2017). The concept of "mobility-as-a-service" (MaaS) can also be accommodated with the introduction of SAV and DRS. Commercial operations like taxi, bus and freight service can benefit from automation through the postponement of driver costs (Wadud, 2017). Deployment of autonomous private car or taxi may reduce parking demand at urban core locations, repurposing those spaces for the use of other economic activity and in turn, it may act to increase urban density in central business district (CBD) locations (Bagloee et al., 2016; Levine, Segev, & Thode, 2017).

In contrast, reliability, comfort, and reduced perceived value of time may encourage long commute distances, contributing to urban sprawl and influencing real-estate values in ex-urban areas (Heinrichs, 2016; Rubin, 2016; Snyder, 2016). Integration of platooning features in freight and bus services, with the help of autonomous and cooperative technology, can play a vital role in increasing road capacity. These are few prominent and divergent examples of AV, considering its diversity in use.

The technological advancement and potential benefits of AVs, as discussed above, are linked together (Heinrichs, 2016). How are these benefits likely to be translated in the form and structure of urban systems? This research compiles evidence from published literature to address this question.

3 Methodology

This research applies a systematic review of the literature to achieve the research aim and objectives. A systematic literature review follows an explicit protocol for higher data reliability and for shaping the diversity of knowledge in a specific research field (Rowley & Slack, 2004; Brereton, Kitchenham, Budgen, Turner, & Khalil, 2007; Bask & Rajahonka, 2017). It aims at abating bias through comprehensive literature searches and delivers an evaluation trajectory for the reviewer verdicts, procedures and inferences (Burgess, Singh, & Koroglu, 2006; Bask & Rajahonka, 2017). The review involves three major activities: (a) Planning; (b) Realization or review; (c) Reporting and presentation (Tranfield, Denyer, & Smart, 2003; Bask & Rajahonka, 2017; Oliveira et al., 2017).

The above three activities were undertaken according to the methodological principles recommended by Oliveira, Márcio de Almeida et al. (2016) and Oliveria, Albergaria De Mello Bandeira et al. (2017): (a) Planning activity consists of identifying the need for revision (why), purpose of the review (what), and developing the protocol of the review (how, when and where); (b) Review activity including identification, selection, and inclusion of papers, evaluation of the selected papers, extraction of data and information, and synthesis of data; (c) Reporting and presentation includes preparing reports, and presenting results.

Firstly, a research plan involving the research aim and objectives, keywords, and a set of inclusion and exclusion criteria was developed. Research objectives were framed, to explore links among various aspects of AVs and thus to recognize promising areas for future research. As the keyword, we decided to use "autonomous vehicle" OR "automated vehicle" OR "driverless car" OR "self-driving car". To focus on the research objectives, we identified the inclusion criteria—peer-reviewed research articles in English language. An online search was conducted using a university library search engine that connects to 393 different databases including ScienceDirect, Scopus, Web of Science, Wiley online library, directory of open access journals (DOAJ), and so on. Edited or authored books, articles published in other languages, grey literature such as government or industry reports and non-academic research, and editorial papers were not included in the review. The search included only peer-reviewed and full text journal articles available online—procedia papers are considered as journal articles, due to relatively limited numbers of journal articles published on the topic.

Secondly, the search was conducted in January 2018 for journal articles published between January 2000 and January 2018. The review focused on the post-2000 articles due to limited studies focused on AVs prior to this date—particularly on the impact, planning and policy issues. Several thematic searches were specified through a combination of multiple keywords. The keywords used in all thematic searches were divided into two parts: The first part (specified by first parentheses) was directed to the title of the articles, and the second part was directed to the abstract. The resultant search items were initially checked by reading the abstract and then by reading the full-text in order to verify their scope against the research objectives.

The first thematic search was conducted using the search tag of ("autonomous vehicle" OR "automated vehicle" OR "driverless car" OR "self-driving car") AND ("control" OR "management" OR "localization" OR "lane change" OR "maneuver" OR "platooning" OR "merging" OR "crash avoidance" OR "cruise control" OR "navigation" OR "car-sharing" OR "multitasking" OR "valet parking" OR "capabilities" OR "features") to identify studies that focus on the AV capabilities. The search resulted in 616 papers, which were reduced to 49 articles after checking the abstract and further reduced to 16 articles after reading the full-text.

The next thematic search was conducted using the search tag of ("autonomous vehicle" OR "automated vehicle" OR "driverless car" OR "self-driving car") AND ("influence" OR "impact" OR "implication" OR "effect" OR "planning") keywords to identify articles that focus on the AV impacts. The search resulted in 154 papers. We have gone through the abstracts of these papers and limited the selection to 51 articles. After reading the full papers to make sure that they actually fit into our scope of interest, the selection was limited to 33 journal articles.

We conducted next search in the database using the search tag of ("autonomous vehicle" OR "automated vehicle" OR "driverless car" OR "self-driving car") AND ("policy" OR "law" OR "legislation" OR "legal") to identify papers that focus on the AV policies. The search resulted in 159 papers in total, which were screened through by reading the abstract (resulted in 29 articles) and full-text (resulted in 12 articles).

In total, 61 journal articles (peer-reviewed and full text available online) fulfilled our selection criteria, and these papers were then read again and reviewed. Following the selection, we categorized the reviewed papers according to subthemes. Then, we extracted data from the reviewed papers in tables, formulated according to the three subthemes (Appendix Tables A-C). Each table contained the following information against each of the selected article: name of authors, year of publication, title of the article, name of the journal, research aim/objectives, theoretical perspective/framework, method, and main findings.

Then, we discussed and linked up the individual findings of each subtheme into one. Some reviewed papers were discarded at this stage that did not match directly with the subthemes. This helped us to understand where we are at, where we are headed to, what the likely impacts of wider AV uptake are, and what needs to be done for AV to generate desired smart urban mobility outcomes.

The final stage of the review process was to write up and present our findings in the format of a literature review paper. In this process, some relevant literature, although not meeting the pre-determined selection criteria, are included as supporting material to better appreciate the background context and discuss the findings—e.g., books, book chapters, government policies, and online reports. With these, the total number of the reviewed and cited references is increased to over 150.

4 Results

4.1 General observations

In reviewing the literature, technological advancement, policy and legislation analysis, transport modelling and simulation, surveys and interviews, scenario analysis, and case study investigations were found to be the main techniques for qualitative and quantitative analyses in the reviewed 61 papers. These studies are assembled under three broad categories, namely: (a) AV capability—containing 16 studies; (b) AV impact and planning interventions—containing 33 papers; (c) AV policy—containing 12 articles. Review efforts found only 1 paper (peer-reviewed journal article) in the area of planning interventions. This indicates that there exists a gap in the literature in the planning area.

Papers in the AV capability category mainly discussed: (a) How AV operates on public roads; (b) What type of AV capabilities are currently available; (c) What sort of hardware and software are responsible for AV operation; (d) Barriers against the uptake of AV technology; (e) What type of benefits are offered by the AV capabilities.

Articles in the AV impact and planning interventions category mainly elaborated: (a) How perceived value of travel time changes; (b) What type of capacity implications might evolve; (c) How AVs will contribute to reduce road traffic accidents; (d) How AVs might increase or decrease congestion and delay; (e) Whether AVs will enhance or reduce GHG emissions; (f) How employment sector will be affected; (g) How public health can be benefited from AV deployment; (h) How SAVs can contribute in changing car ownership model; (i) How urban land use might be affected due to changes in parking demand, changes in travel time, changes in travel distance; (j) How capital investment decision will be affected. (k) What sort of planning interventions might be required to accommodate disruptions or to control disruptions. The impacts typically cover economic, societal, environmental, and political and governance aspects.

Papers in the AV policy category mainly examined: (a) How conflict can be avoided in between national/federal and state governments in formulating laws; (b) What the jurisdiction of national/federal and state governments should be; (c) How governments, industries, scholars, and professionals can negotiate and agree on formulating laws on liability and privacy; (d) Which organization should standardize or certify technology; (e) Which vehicle should get priority on the road; (f) What should be the new pricing mechanism to manage vehicle kilometers travelled (VKT).

The reviewed literature, in all categories, illustrate that research on AV is mainly limited to developed countries such as the US, the Netherlands, the UK, Canada, Australia, Israel, Germany, Italy, Singapore, Russia, Poland. This finding shows parallels with the AV piloting and preparing cities listed in Table 1. The oldest article reviewed in this study dates back to 2012 (Smith, 2012). Although there were other articles published prior to 2012, Smith's (2012) paper was the earliest published article that satisfied the selection criteria of this research. The majority of papers were published in 2016 onwards (84%)—indicating an exponential growth trend of research on this topic.

4.2 Capabilities

According to many, since the invention of the automobile technology about a century ago, the biggest change to personal mobility is happening right now with AVs (Volvo, 2017). In the presence of autonomous driving technology and capabilities, mobility is predicted to be safer, sustainable, and more convenient, as ADS of an AV will replace the human driver for all sort of dynamic driving tasks in some or all roadway and environmental conditions (Shladover, 2018). When AVs attain the capability of replacing human driver, it actually can perform five basic operational functions through its ADS—localization, perception, planning, control, and management (Coppola & Morisio, 2016; Pendleton et al., 2017). In doing so, AVs will possess certain technological features, advantages or capabilities over a conventional or human driven vehicle. These include platooning, fuel efficiency, eco-driving, adaptive cruise control with queue assist, crash avoidance, lane keeping, lane changing, valet parking or park assist pilot, traffic sign and signal identification, cyclist and pedestrian detection, and safe maneuvering at intersections (Anderson et al., 2014).

At a particular time, the predicted benefit offered by individual AV feature will largely depend on the AV price, acceptance, operational mode (private or shared), AV share in the traffic mix, level of automation in the traffic mix, and fuel efficiency (Diakaki, Papageorgiou, Papar]michail, & Nikolos, 2015; Davidson & Spinoulas, 2016; Daziano, Sarrias, & Leard, 2017; Piao et al., 2016; Chen, Gonder, Young, & Wood, 2017). These are seen as the influencing parameters of an AV scenario (Correia, & van Arem, 2016; Davidson & Spinoulas, 2016). AVs, however, might present a future full of nightmares resulting from different combinations within these parameters, especially if there do not exist adequate planning interventions.

A summary of the literature in this area is presented in Appendix Table A and discussed below.

- Platooning: Highly random and fluctuating car-following behaviors of human drivers are one of the main factors to prompt accidents, oscillations, and traffic congestion. This results in low efficiency in traffic flows and severe environmental impact in many urban regions (Hoogendoorn, van Arem, & Hoogendorn, 2014).

  To overcome these issues, Gong, Shen and Du (2016) developed a novel platoon car-following control scheme that modelled an interconnected dynamic platoon system of CAVs and AVs. Their proposed scheme effectively reduces disturbance transmission of speed errors and relative spacing from the leading vehicle to following vehicles along the platoon. This means that this scheme accomplishes the "string stability" of the platoon. In some other studies, it is also shown that the performance of the conventional cooperative adaptive cruise control (CACC) scheme is outperformed by the developed car-following control scheme in the capacity of achieving stable and smoother traffic flows and traffic oscillations reduction (van Arem, van Driel, & Visser, 2006; Gong et al., 2016).

  With the help of multi-platooning of AVs, Fernandes & Nunes (2012) performed another study to address the urban traffic congestion issue. In this study, they conceptualized design of a multi-platoon communicant AVs to travel along a dedicated lane, where AVs can exit from platoons to offline station and merge back into platoons along the main track following novel algorithms. According to the algorithms, inter-platoon leaders' constant spacing are ensured and offline station vehicles are allowed to leave and join the platoon on main track cooperatively. Simulation results of several scenarios confirmed that proposed algorithms guarantee high traffic capacity and vehicle density and reduce traffic congestion. Validation results of these features also proved that the proposed algorithms enable a clear benefit of a platooning system in comparison to bus- and light-rail-based transit systems (Fernandes & Nunes, 2012).

It is observed from the simulation models of Gong et al. (2016) and Fernandes & Nunes (2012), connectivity among the AVs within a platoon is a prerequisite to form a stable platoon string.

- Merging or Mandatory Lane Change: Most freeway congestion results from traffic oscillations (or stop-and-go) near freeway ramps, caused by merging activities (Zhou et al., 2017). Freeway sections near ramps are considered as the bottlenecks of the freeway system. In a merging situation, if different ratios of AVs equipped with longitudinal and lateral detecting technology, and advance cruise control (ACC) are penetrated on freeway with human driven vehicles, cooperative intelligent driver model (CIDM) of AVs could practically improve the freeway performance (Xiao & Gao, 2010; Zhou et al., 2017). The results from an experiment show that with an increased AV penetration on freeways, standard deviation of speed dispersion or oscillation caused by merged-in vehicle could be reduced progressively, i.e., road safety could be improved. It also shows that when the safe time gap is less than 1.0 second, AVs can improve travel efficiency by minimizing travel time (Zhou, Qu, & Jin, 2017).

  Altche, Qian, and de la Fortelle (2017) assumed a nearer plausible traffic scenario, where all vehicles have semi-autonomous features (ACC, automated braking and accelerating, lane keeping assistance), and are driven by human drivers. In such a scenario, a supervised coordination framework can remove the risk of collision or deadlocks with vehicles arriving from sides, either at intersections or roundabouts, or when merging on freeways (Dresner & Stone, 2008; Zohdy & Rakha, 2016). This framework mainly overrides human control inputs when they would become unsafe and create blocked situation in the defined supervisory area at intersections, roundabout, or merging points.

  Xie, Zhang, Gartner, & Arsava (2017) performed an optimization-based ramp control strategy in a CAV and AV environment to evaluate the performance of freeway due to presence of merging vehicle. Results of nine different combination of freeway and ramp vehicle inputs (veh/h) under three ramp control cases demonstrate that "optimal ramp control model" outperforms two other control cases: "gradual speed limit" and "do nothing" with regards to performance measurement indicators—average delay time, vehicle throughput and average speed (Xie et al., 2017). It is observed that all the three types of freeway merging algorithms, mentioned above can improve speed dispersion on freeway, road safety, travel efficiency, congestion level, average delay time, vehicle throughput, and average speed in a merging situation with the help of different level of autonomous features of AVs with or without V2V and V2I connectivity.
- Lane Changing: To progress towards a fully automated highway driving, the riskiest component added to the advanced driver assistance systems (ADAS) of an AV is lane changing maneuver. This maneuver is the riskiest and challenging in the sense that it involves ego vehicle's (vehicle under consideration, i.e., AV in this case) path change in the presence of other moving vehicles all around it as well as it has to consider changes in both the longitudinal and lateral velocity of the ego vehicle (Nilsson, Brannstrom, Coelingh, & Fredriksson, 2017). During the lane change attempt by a human driver, there are possibilities of collision with at least four vehicles—front and rear vehicles in the same lane, and front and following vehicles in the target lane (Bai, Quan, Fu, Gan, & Wang, 2017; Nilsson et

al., 2017). This sort of collisions can be avoided by selecting an inter-vehicle traffic gap and time instance to perform the lane change maneuver by executing a novel lane change maneuver algorithm in a mixed highway traffic environment with both human drivers and AVs with or without V2V and V2I communication (Nilsson et al., 2017), or in an AV only environment through vehicle to vehicle communication among the vehicles (Bai et al., 2017).

The collisions lead to probable consequences of loss of lives and traffic congestion. In addition to that, due to lack of determining a safe inter-vehicle gap and time instance to perform the maneuver, there exists oscillation, travel delay and capacity reduction in traffic flow (Nilsson et al., 2017). Automated lane changes can address about 4-10% of all accidents that are caused by human error (Luo, Xiang, Cao, & Li, 2015). Uncoordinated lane-changing and exiting behaviors by AVs can also considerably interrupt traffic flow by slowing down other vehicles, or even in worse scenario, by inviting accidents (Meissner, Chantem, & Heaslip, 2016; Talebpour & Mahmassani, 2016). Cooperative lane-changing of AV can ensure improvement of traffic stability, homogeneity, and efficiency, and reduction in traffic congestion (Nie et al., 2016).

- Valet Parking: Autonomous or valet parking is an obvious component of driver assistance technologies (Brookhuis, de Waard, & Janssen, 2001; Li & Shao, 2015). Three sequential steps- circumstance recognition, open-loop (when controller does not require verification of system output or modification of command to the system) motion planning and, closed-loop (information flows around a feedback loop) control execution, are responsible for successful autonomous parking (Lee et al., 2009; Li & Shao, 2015). AVs will not be capable of delivering its full benefits without having this feature as every trip has to be started from and end at a parking place. Relevant products have already been made available in the market by many of the original equipment manufacturers such as Tesla, Volvo, Audi, BMW, Ford, Land Rover, Mercedes-Benz, Nissan, and Toyota (Li & Shao, 2015).

  Valet or auto-pilot parking features of AVs are expected to find cheap or free parking spaces after dropping off the passenger. This in turn saves travel time or cost for commuters or passengers because the passengers do not require: (a) Cruising for a parking space; (b) Walking to the vehicle to pick up; (c) Paying for costly parking (Zhang, Guhathakurta, Fang, & Zhang, 2015). Valet parking has also a number of technical advantages over traditional human-driven parking. It is capable of: (a) Avoiding dynamic obstacles; (b) Moving in the narrow passage parking areas; (c) Parking in a narrower space; (d) Ensuring optimization of gear changes; (e) Avoiding crash occurrence; (f) Finding fastest and shortest parking path; (g) Minimizing search time for parking spot (Fagnant & Kockelman, 2015).

The abovementioned significant AV capabilities have the capacity to induce or affect certain transport system variables (TSV) and as a consequence these variables will disrupt environment, investment, health, employment, infrastructure design, and land-use options. Some of the effects may contribute to the society in a better way, while society may be worse off in others. Timely control of TSV through adoption of short-, mid-, and long-term planning and policy options by concerned national, state and local governments can help in materializing wider AV deployment if this is considered appropriate (Coppola & Morisio, 2016).

4.3 Impact and planning interventions

The extent of AVs' impacts to the society largely depends on their share in the total vehicle fleet (Pinjari & Menon, 2013; Litman, 2017) and level of the AV uptake and usage differentiated by—(a) Light use: private or shared (Gruel & Stanford, 2016; Heinrichs, 2016; Dia, & Javanshour, 2017); (b) Heavy use: bus (Smolnicki & Sołtys, 2016) or freight (Wadud, 2017). Impacts begin with a shift in transport demand and supply variables equilibrium (Childress, Nicholos, Charlton, & Coe, 2015; Rubin, 2016), necessitating obvious adjustments in planning with new ideas, and innovations (Zakharenko, 2016).

The impacts, from a system level to societal level may have ripple effect on each other at multiple levels (Milakis, van Arem, & van Wee, 2017).

The probable areas of influence at a transport system level (either on supply side or demand side), include VKT, PKT, vehicle hours travelled (VHT), value of time (VOT), speed, capacity, headway, traffic flow, delay, travel cost, vehicle operating cost (VOC). These will further affect planning parameters in general such as infrastructure design, transport modelling, capital investment, car ownership, land use, employment, energy consumption, traffic safety and public health, environment (Dixit, Chand, & Nair, 2016). Planning authorities at local and state levels have to cope with the expected disruption in certain cases and impose planning and policy measures to control rest of the disruptions.

A summary of the literature in this area is presented in Appendix Table B and discussed below.

- Infrastructure Design: Road infrastructure will require new design criteria as lateral and longitudinal capacity of the roadway might be changed due to lane keeping and platooning respectively. Lane width might be reclaimed due to more accuracy in maintaining lateral alignment (Smith, 2012). To improve network performance and vehicle throughput, AVs might require dedicated road network in certain areas (Chen, He, Yin, & Du, 2017). Considering the impacts on infrastructure design, literature suggests the following planning recommendations (Hendrickson et al., 2014): (a) Pavement marking may require repainting; (b) No changes are expected in the design of clear zone; (c) Radio advisories and ITS message signs may or may not be obsolete depending on the presence of connectivity in automation; (d) Dedicated short range communications (DSRC) locations for traffic signals have to be identified and prioritized in case of automation with connectivity.
- Car Ownership: Flexibility of SAV and its operation would reduce operational and fixed cost and thereby reduce car ownership (Milakis, van Arem, & van Wee, 2017). The results of an agent-based modelling of different SAV scenarios indicate that each SAV can replace around eleven conventional cars (Fagnant & Kockelman, 2014). Due to exclusion of driver's talent and time, driverless taxi or autonomous car sharing program paves the way to be a cheaper travel option and may discourage traditional car ownership (Bagloee et al., 2016). Though this may be highly unlikely, some visions of pooled/shared ownership of AVs suggest that there could be no need to own private motor vehicles at all in the future (Levin & Boyles, 2015)—also see Ma, Zheng, and Wolfson (2015) for a model on real-time city-scale ridesharing. Planners may replace numbers of conventional on-street and off-street parking facilities by ensuring provision of few suburban multistory garages. They may also execute pickup and drop off points for AVs near transport hubs by eliminating existing paid and unpaid parking lots. This will promote tech- and transit-oriented developments (TTOD).
- Employment: Reduction of traffic congestion, travel time savings, and lower transportation costs of goods could be achieved at the expense of individuals, currently employed in building, driving, and maintenance of automobiles (Crayton & Meier, 2017). Spilling effects in labor market might be a reality due to falloffs in certain related jobs, like diver licensing, traffic policing, and insurance sales (Crayton & Meier, 2017). Moreover, a future with fewer vehicles would also lead to fewer jobs in the automotive industry as a whole (Snyder, 2016). In contrast, Gill, Kirk, Godsmark, & Flemming (2015) predicted potential employment gains in three sectors up to 15%—conversion of parking facilities related construction, roads and highways modification, and IT product and services. State or federal governments might declare rehabilitation package, especially for the abundant drivers of taxi, bus and commercial vehicles. Governments might also arrange specific training depending on the eligibility of drivers so that they can find a job in new sectors. Currently employed automobile technicians and mechanics can be trained up for new technology and this will help them to be remain in the same track without losing job. Automobile industries can also support government's novel initiatives with financial contribution.

- Energy Consumption and Emissions: Practically, fuel/energy consumption of any transport mode depends on travel activity performed by that mode and energy intensity (consumption per kilometer) of that particular mode, and emission is the product of energy consumption and fuel carbon content (Wadud et al., 2016). Automation might plausibly reduce road transport energy consumption and GHG emissions by approximately half—or nearly double them depending on automation level, AV features, use type, and policy intervention (Wadud et al., 2016).

  Litman (2017) predicts that a major share of AVs in road transport will contribute to energy conservation by 2040-2060. Chen, He et al. (2017) indicate that vehicle automation may contribute 45% savings on fuel consumption in optimistic scenario and 30% fuel consumption in pessimistic scenario. Another study shows a 37% of energy savings is possible when AVs are used in conjunction with public transport in lieu of personal car (Moorthy, De Kleine, Keoleian, Good, & Lewis, 2017). On the other hand, large share of SAV fleet could improve fuel efficiency by abandoning highspeed and rapid acceleration of car (Milakis, van Arem, & van Wee, 2017). Liu, Kockelman, Boesch, & Ciari (2017) show that introduction of SAV systems can save 22.4% of total distance-based fuel consumption and this savings cannot be negated by extra VKT.

  Large share of SAV fleet could also limit emissions by abandoning highspeed and rapid acceleration of car (Milakis, van Arem, & van Wee, 2017). Possibility of total distance-based (lifecycle and driving cycle) savings of GHG emissions is 16.8-42.7% due to introduction of SAV systems, and this savings cannot be negated by extra VKT due to AV's advancement, eco-technologies, and change in energy source (Liu et al., 2017). Another study in Lisbon city shows that replacement of conventional private car, taxi and bus by self-driving shared taxi and taxi-bus, keeping existing metro service could contribute in reducing carbon emissions (Martinez et al., 2017). It is also estimated that electric driven autonomous taxis could significantly reduce GHG emissions in 2030 with respect to current conventional and hybrid vehicles (Greenblatt & Saxena, 2015). Smith (2012) predicted reduction of emissions per VKT with an overall increase in total emissions.

  It can be summarized that automation related road transport energy consumption and emission figures are still uncertain in their magnitude. This is because energy consumption and emissions are generally not a direct consequence of automation, rather it is affected by changes in vehicle operations, vehicle design, choice of energy, policy intervention, or transportation system design, which are more indirectly facilitated by automation (Wadud et al., 2016). Policymakers probably have to consider VKT based pricing to substitute earlier fuel tax, if energy source is shifted from fossil fuel to electricity. This is a step toward safeguarding government's financial revenue on the eve of electric vehicle. Government can also promote green vehicle operation by allowing less tax on vehicle purchase price and by reducing vehicle registration fee.
- Traffic Safety and Public Health: Until now, no empirical proof is established about the overall safety advantages of AVs (Winkle, 2016). Most of the investigation related to AVs' potential for crash protection was performed considering assumed AV deployment and market penetration scenarios. These assumptions were based on expert estimates, third-party forecasts and relevant database.

  The German In-Depth Accident Study (GIDAS) and NHTSA crash databases show approximately 93% of road crashes happen due to human error, and it has been speculated that this figure might be completely ruled out in case of full automation of vehicles. Even level 0, and level 1 features of AVs have the potential to minimize one third of the traffic accidents (Bagolee et al., 2016). Daimler, manufacturer of Mercedes-Benz, published a forecasting models on vehicle-safety and crash research in 2010, which suggests increased automation can result in a reduction of crashes by 10% by 2020, 50% by 2050, 71% by 2060, and a total reduction by 2070 (Winkle, 2016). A US study projected that conversion of 10% and 90% of US vehicle fleet to AV would respectively act to reduce annual crashes by 0.2 and 4.2 million, and it could respectively save 1,100 and 21,700 human lives annually (Collingwoood, 2017).

Yet, adjustments of driving behavior in relation to levels 1-3 automation features may invite accidents in many cases (Milakis, van Arem, & van Wee, 2017). However, new crash risks may emerge due to automated system failures in certain cases, and road users may favor additional risk-taking behavior assuming the AV system's perceived and actual competencies (Litman, 2017). By assuring road safety through higher level of AVs, ripple effect of accident related tangible and intangible costs like medical costs, legal costs, insurance and administrative costs, emergency service costs, workplace losses, and property damages can be minimized (Bagolee et al., 2016). This will help federal or state governments to reconsider their budgets in the near future.

- Capital Investment: AVs might act to reduce proposed existing road expansion investment as platooning might significantly increase road capacity—as much as five times by one source (Fernandes & Nunes, 2012). That is why, the literature recommends re-evaluating planned road system capacity enhancement projects before making final investment decision. It has also been suggested that ITS and level of service (LOS) investment projects are assessed for compatibility with CAV fleets (Hendrickson et al., 2014).
- Land Use: AVs will either promote urbanization or promote suburbanization. In reality, transport network will tend to flow in between these two scenarios, depending on transport and urban planning policy, prevailing local conditions, and dissemination of different driverless mobility solutions (Smolnicki & Sołtys, 2016).

At the regional level, accessibility improvements through lower generalized cost of transport due to vehicle automation will result in ex-urbanization to remote areas of former inner city, leading to attractive green urban sprawl surrounding metropolitan regions (Bagolee et al., 2016; Crayton et al., 2017; Milakis, van Arem, & van Wee, 2017) with lower house prices (Heinrichs, 2016), and decline in rent outside CBD (Zakharenko, 2016). AVs' favor towards urban sprawl may prove transit service superfluous except for dense urban areas (Meyer, Becker, Bösch, & Axhausen, 2017). Urban sprawl is also subject to availability of land and land-use policies (Yigitcanlar & Kamruzzaman, 2014; Milakis, van Arem, & van Wee, 2017).

At the urban/local level, presence of commuting AVs and SAVs (with or without dynamic ride sharing) may free up daytime downtown on-street and off-street parking spaces (Bagolee et al., 2016; Heinrichs, 2016; Zakharenko, 2016; Milakis, van Arem, & van Wee, 2017). Different spatial distribution of urban parking demand will be evolved against different SAV operation strategies and client's preferences (Zhang et al., 2015). The results of an agent-based model show that the clients adopting SAV system in lieu of conventional private car can eliminate up to 90% of parking demand at a low market penetration rate of 2% (Zhang et al., 2015). On the other hand, SAVs have the potential to tackle the transport related-social exclusion (Duvarci, Yigitcanlar, & MizoKami, 2015; Kamruzzaman, Yigitcanlar, Yang, & Mohamed, 2016; Yigitcanlar, Mohamed, Kamruzzaman, & Piracha, 2018).

Driving robots' capability of valet parking may promote neighborhood parking zones or collective garages in the inner-city districts. The presence of auto-valet garages will allow more vehicles to be parked and creates the possibility of increasing density of urban core areas by repurposing released parking spaces due to less demand for parking in CBD areas (Heinrichs, 2016). The saved off-street parking spaces could be repurposed for infill residential and commercial development, allowing increase in economic activity to contribute to the further CBD density (Bagolee et al., 2016; Milakis, van Arem, & van Wee, 2017), and the saved on-street spaces could be transformed into HOV lanes, bus lanes, cycle lanes, or new public spaces (Milakis, van Arem, & van Wee, 2017).

Possibility of significant increase in road capacity through platooning—as much as five times (Fernandes & Nunes, 2012) could save road spaces that might be reallocated to other travel modes—like buses, cycling and walking. In an ideal condition, where all the vehicles in roads are fully autonomous, highway capacity might increase around 100% (Farmer, 2016).

Regulatory body may think about limiting the projected increased AV traffic. Because in presence of public transit, under certain conditions AVs will connect to the transit without entering CBD (Zakharenko, 2016). Local and state government authorities have to decide whether they will allow or limit urban sprawl. It should be exclusively bounded by city's land-use policy. Moreover, most of the state and local authorities should decide reallocation of city's road space and parking spaces depending on nature of travel pattern and traffic behavior in a new form of traffic mix.

Considering too many aspects of AV impacts, Isaac (2016) recommended generalized medium- to long-term planning activities. Medium- and long-term planning activities include: (a) Updating transport model with new assumptions; (b) Forecasting financial revenues; (c) Designating traffic lanes for simultaneous operation of AV and/or conventional automobile; (d) Updating traffic signs and markings; (e) Reducing lane widths; (f) Adjusting speed limits, traffic signal locations and timing; (g) Eliminating or reducing parking spaces and add more drop off/pick up locations; (h) Reclaiming city center surface parking lots for potential future developments; (i) Reclaiming right-of-way for people and other mode of transport; (j) Doubling use of the suburb on-street parking areas as charging stations; (k) Developing new predictive models for pavement maintenance.

4.4 Pre-deployment policy

Higher level of vehicle automation poses regulatory challenges for the AV manufacturing countries (Nowakowski, Shladover, Chan, & Tan 2015). The uptake of a new technology like AV should be regulated through federal and state governments' pre-deployment policy. Major regulating policies are revolving around testing and deployment, cybersecurity and privacy, liabilities and insurance, ethics, and repair/maintenance and calibration. Proactive actions in this regard may ensure rapid AV uptake in some jurisdictions and reactive or inert actions may delay the whole uptake process in some other jurisdictions. As an example, AV legislation and policies in the US, the Netherlands, the UK and Sweden are paving the way for other countries (Nowakowski et al., 2015, Vellinga, 2017). However, the first fatal crash by a self-driving UBER involving pedestrian in the US proves that more research, development, legislation and planning are needed for a safer and wider AV uptake.

A summary of the literature in this area is presented in Appendix Table C and discussed below.

- Testing and Deployment: Two main aspects in relation to AV operation, to be bounded by regulation, are testing and deployment. These two main challenges are linked with devising regulations in this particular area to ensure safety without hindering innovation, and defining meaningful requirements or standards without having such technical standards for ADS in place (Nowakowski et al., 2015). Another significant concern focuses on how to maintain legal consistency in different jurisdictions to avoid confrontation with AV manufacturers and to encourage innovation (Vellinga, 2017). Around the globe, policymakers are yet to establish such a consistent legal ground for AV design, testing and deployment. Regulating bodies and practiced legal instruments used by these bodies are also different from each other. Some authorities follow "binding regulation," some follow "non-binding regulation," and some other follow "granting exemption" (Vellinga, 2017).

  In the US, technology aspects of vehicle safety are regulated by federal government agency, and other safety aspects related to vehicle registration and driver's training, evaluation, and licensing are the functions of state government (Nowakowski, Shladover, & Chan, 2016; Vellinga, 2017), but in the UK and the Netherlands, federal government agencies regulate all aspects of vehicle safety for testing and deployment (Vellinga, 2017). Currently, the US federal government agency NHTSA and the UK Department of Transport (DoT) is in favor of non-binding test and deployment regulations for AV under the cover of national policy and code of practice respectively. On the contrary, one of the US states, California has binding legislations in place to regulate the testing and deployment of AVs. Against the backdrop of binding and non-binding regulations and policy, Dutch Vehicle Authority (RDW) granted exemptions to AV from certain laws under certain conditions.

NHTSA provides guidance for both manufacturers and states, though these are not mandatory to abide by. Manufactures involved in designing, developing, testing and selling should follow the NHTSA policy and guidance to ensure safe testing and deployment of AVs on public roads, and states should follow the policy to prevent inconsistencies in AV laws and regulations among the states. The main exception of the UK Code of Practice over NHTSA policy is that it also addresses the requirements about the test driver. RDW grants the exemption to AV testing on public roads with test specific conditions once all the functionalities to be tested are passed on test track. Both the "binding regulations" and "exemption under conditions" are legally binding for manufacturers to ensure safety during testing (Vellinga, 2017). Though "exemption under conditions" poses legal uncertainty for manufacturers, it flourishes technical developments. On the other hand, non-binding regulation can guide manufacturers or testing organizations to adjust with continuous changes in regulation with advancement in technology (Maurer, Gerdes, Lenz, & Winner, 2016).

- Privacy and Cybersecurity: AV will essentially be equipped with tracing technology to recognize accident causing factors and consequently to mitigate product liability (Bruin, 2016). At the same time, AV equipped with such technology might have serious impact on information privacy of the persons in side or around such vehicles. Manufacturers should be held responsible if AV fails to comply with laws associated with protection of personal data (Bruin, 2016). Privacy mainly relates to control over autonomy, information, and surveillance when it comes to AV (Glancy, 2012). Personal autonomy is one's ability to make choices independently about oneself. Use of AV inherently affect autonomy by taking over human control in the way people move one place to another (Collingwood, 2017). Personal information privacy can be violated as AV will collect, store, use, own, transfer, or destroy data/information due to improper or non-existent disclosure control (Collingwood, 2017).

As an example, transmission of present location, past travel pattern, and future travel plan could compromise privacy of AV user. Personal information collection through comprehensive legal and illegal AV tracking will affect privacy associated with surveillance. To protect the privacy associated with AV, generated data ownership pattern and limit of onward data transmission and its usage have to be finalized in the upcoming data privacy act of different countries. To protect the different privacy interests, legislators and regulators should have answers of following questions—Why it is collected, what will be the uses of personal data. How long data should be preserved. Who can and cannot have access to it. Glancy (2012) argued that, without suitable legal safeguards for privacy, AV could face challenges of "market resistance" from prospective users who recognize AV as threats to their privacy.

On the other hand, at the advent of increased computerization and networking, AVs are accumulating autonomous capabilities and are inviting cyber-threats as permanent allies (Yagdereli, Gemci, & Aktas, 2015). One of the main cause of ADS failure is cyber-attacks and software and hardware defects. Hence, this system should be equipped with such defensive system that can respond automatically and dynamically to deliberate and inadvertent attacks and defects (Yagdereli et al., 2015). A cybersecurity system should primarily safeguard on-board data storage, data sharing (Lee, 2017). Cybersecurity concerns should be bounded by regulatory action to protect consumer interests and promote future growth against autonomous unmanned system vulnerabilities. Considering rapid growth and interstate nature of AV technology, Lee (2017) emphasizes federal government to take charge of formulating nationwide regulatory framework for communications, privacy, and cybersecurity pertaining to this technology. Within the federal framework, states and industry should conduct experiment and develop self-regulation. In line with formulated regulations AV cybersecurity requirements should be determined and documented in the systems' requirements documents and it should be done before the design of the system (Yagdereli et al., 2015).

- Liability and Insurance: Data obtained through on-board vehicular systems and sensors of ADS can provide sufficient details of an accident to determine many liability decisions with high degree of precision (Dhar, 2016). This will help to identify "at-fault" driver or vehicle and ensure quick processing of insurance payment to victim. This accurate identification of accident related physical factors to environmental factors to human factors would eventually quash delays and litigation costs linked with tort laws and also exclude necessity for no-fault insurance, which is alive at dozens of US states at the moment.

  Though emergence of AV makes fault identification accurate and smoother than before, it also raises a big question: who will be held responsible for the accident: driver (till SAE level 3), owner, operator, or manufacturer. ADS of AVs serve generally a robotic function and raises novel issues in criminal law as robot can malfunction and cause serious harm to people and property. As robotic systems are inappropriate for criminal punishment, humans who produce, program, and deploy robots should be subject to criminal punishment if the robots are intentionally used to cause harm to others (Gless, Silverman, & Weigend, 2016). However, Gless et al. (2016) advocates in favor of limiting the liability of vehicle operators, if they undermine to initiate reasonable measures to control the risk originated from ADS.

  In the US, states are responsible for liability regimes and insurance (Vellinga, 2017). The Californian draft AV Express Terms suggested that the manufacturer should be held responsible in case of collision or accidents caused by AV and that has to be covered by proper insurance. The Dutch law intended to hold the possessor of AV liable for development risks as they cannot invoke the defense that can be called on by the manufacturer (Vellinga, 2017). The UK proposal discussed first party insurance option for the victim but it did not suggest any other substantial changes in liability rules (UK Parliament, 2016). In this case, victim, regardless of liability, can claim from his insurer and later, insurer can recover the amount from the manufacturer—if manufacturer is found liable. Sweden is practicing first party insurance model since 1975 (Schellekens, 2015).

  If the liability of human driver or owner of the car would shift to manufacturer in case of collision, this might slow down the progress of AV development (Vellinga, 2017). In addition to this, insurance companies may become less interested to insure the high risk of AVs. This issue can be addressed by limiting the amount of damages one can claim due to the fault of AV. In parallel government could be a reinsurer to encourage the insurance companies to insure AVs (Vellinga, 2017).

5 Discussion and conclusion

Within the contemporary smart city debate, AVs represent a way to create an ideal city form and developments in the autonomous driving technology have the potential to bring smart mobility to our rapidly urbanizing world; but for others AV is a branding hoax (Yigitcanlar & Lee, 2014; Yigitcanlar & Kamruzzaman, 2018a). Despite a large body of recent literature on AV's, only a limited number of studies have outlined the disruptive effects that AV might bring on city planning and society in general. This paper, through a systematic review of the literature, aimed to determine the current state of research literature on AV technology, the future direction that this technology is leading to, how the changes are likely to affect our day-to-day travel behavior and long-term changes in the structure of our cities, and what would be the likely policy tools for a smooth transitioning of the technology.

As the literature suggests, AVs' major disruptions in our cities will be in urban transport, land use, employment, parking, car ownership, infrastructure design, capital investment decisions, sustainability, mobility, and traffic safety. It is clear from this study that preparing our cities for AVs through progressive planning is critical to achieving the benefits and to address the resulting disruption. On the eve of rising AV demand, local and state governments should be equipped with better policy and planning tools to accommodate AV technology and its impacts. In parallel, timely interventions from international, national/federal and state levels in terms of regulating, standardizing and certifying this technology and approval of appropriate legislative measures to ensure testing, deployment, privacy, security, and liability issues are addressed. These are discussed in the following sub-sections in detail.

5.1 Driving forces, uptake factors, impacts and interventions framework

This paper has investigated the AV phenomenon from the perspectives of AV capability, impact and planning interventions, and pre-deployment policy. Research area covered under this study is only a small part of a broader framework. Based on the findings of the reviewed papers, the study synthesized a broader framework—for AV driving forces, uptake factors, impacts and interventions—illustrated in Figure 1 and discussed below.

Any new innovation demands external thrust or driving forces from social, political, economic, environmental, and technological sectors that might push forward or pull back the key factors responsible for uptake of that very new innovation. With the help of a force matrix, by awarding score against uncertainty and impact of each force, most influential forces behind the key uptake factors can be ranked. Future plausible scenarios of any new technological innovation uptake are the product of multiple combinations of the highly ranked influential driving forces. In the case of AV uptake, relevant driving forces are technological advancements, economic conditions, customer attitudes, environmental conditions, and government policies. Plausible AV scenarios emerged through any two high ranked influential forces might be termed as AVs in boom, in demand, in standby, or in doubt. The prominent uptake factors under any plausible AV scenario that might lead to changes in values of transport system level variables are AV type, AV growth trend, AV automation level, AV fuel type, AV capabilities, and so on.

Each future plausible AV scenario generally owns a set of AV supply parameters that can act as input parameters for transport modelling. Inclusion of these new modelling input parameters in existing transport modelling exercise can signify impact of AV uptake patterns through expected changes in output parameters. From the modelling output one can identify the changes in demand parameters from scenario to scenario at transport system level. The demand parameters value might roam around VKT, individual driving speed, per capita distance travelled, per capita generalized cost, per capita travel item, parking demand, per capita travel cost, and mode share by trips. This will dictate the quantitative and qualitative changes in societal parameters—see societal impact box in Figure 1.

Finally, decision-makers and planners have to counteract with intervening planning and policy initiatives in the necessary disruptive areas so that optimum benefits from AV can be realized for a city. In this case, the framework highlights some of the prospective areas of planning and policy interest. These are congestion pricing, lane width reduction, new modelling assumptions, on-street charging points, reduction in on- and off-street parking spaces, introduction of zonal parking garages, adjusting signal location and timings, adjusting speed limits, and optimizing AV share.

As the paper investigated the AV phenomenon from the perspectives of capability, impact, planning interventions, and pre-deployment policies, it focused on few of the selective parameters from each block of the described framework. In relation to the framework, this paper mainly researched one of the driving forces vigorously—pre-deployment government policy. The reviewed pre-deployment government policies are—testing and deployment, privacy and cybersecurity, and liability and insurance. Out of the mentioned uptake and penetration factors, we elaborated the capabilities of AV. The reviewed areas of capabilities are platooning, merging, lane changing, and valet parking. In the area of AV's societal impacts and counter measure to negotiate those impacts, the paper reviewed infrastructure design, car ownership, employment, energy consumption and emission, traffic safety and public health, capital investment, and land use.

By analyzing our research area, it is understood that pre-deployment government policy and AV capabilities have lot of contributions in assuming or estimating transport model input parameters. On the other hand, changes in model output parameters can be directly or indirectly translated into societal impact or disruptions. This will ultimately lead to short-, medium-, and, long-term planning and policy interventions at the local, regional, and state levels to address various disruptions or the impacts of AVs.

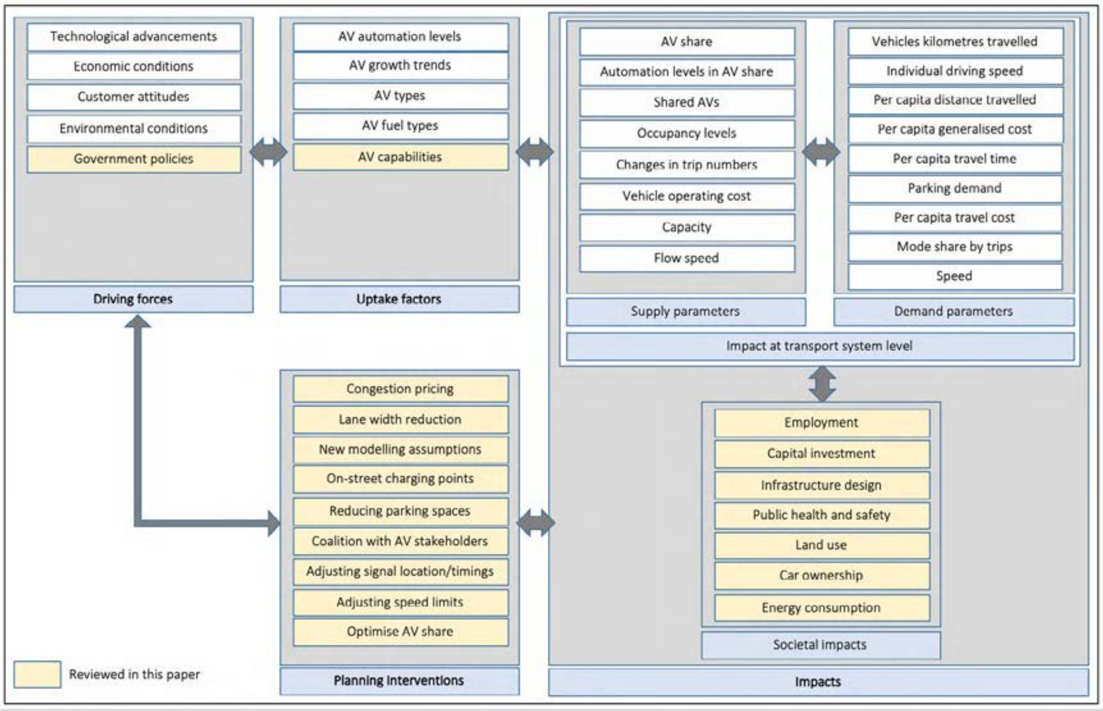

Figure 1. AV driving forces, uptake factors, impacts and interventions framework

5.2 Research implications

The review of the literature suggests that most studies to date are optimistic about the potential benefits that AVs might bring to cities. Rarely have these assumptions been critically examined. In many cases the potential benefits as being advocated are more theory than practice. For example, almost all studies accepted the crash reduction rate (by 90%) with AVs because human error is responsible for most crashes. They assume that when humans are not in charge of driving, crashes would not happen; a rather heroic assumption. These studies do not consider a myriad of issues that can might cause an AV to be involved in a crash such as software failure, factors that are not included within the AVs' artificial intelligence, failure to recognize a new street layout pattern, and so on.

Additionally, frequently claimed benefits of AVs in the literature are that they will reduce congestion through optimum use of road spaces using the platooning technology. These studies rarely consider the scenario that an effective platooning will only work if all AVs are travelling from a defined origin to a defined destination in a dedicated lane. However, trip origins and destinations vary from person to person which implies that AVs will have to frequently change lanes for entry and exit. Moreover, if a non-AV enters into a platoon, the efficiency of platooning will reduce. More importantly, the saved road spaces are likely to be occupied by the induced trips expected to be generated by less mobile people today. Furthermore, the passenger multitasking benefits within AVs may act to increase suburbanization and urban sprawl resulting in additional VKT, and ultimately consume more road space. The prevailing implication that AV's will increase sharing including higher car occupancy also seem weak and should be explored using research on human factors and by investigating AV trial outcomes.

The findings of the review also suggest that effective policy can: (a) Reduce the reliance on traditional vehicles (including AVs); (b) Foster the use of autonomous public transport vehicles (AVPT); (c) Discourage and reduce sprawling development. These are elaborated below:

- In terms of policy to reduce traditional low occupancy private motor vehicle dependency there is a significant supporting literature (Banister, 1997; Newman & Kenworthy, 1999; Yigitcanlar, Fabian, & Coiacetto, 2008; Kamruzzaman, Yigitcanlar, Washington, & Currie, 2014). The policy and planning aspects discussed in the urban and transport planning and urban studies literatures without a specific focus on AVs are also relevant to the AV context (Firnkorn & Müller, 2015; Newman & Kenworthy, 2015). This indicates that there is still a need for further conceptual and empirical explorations for figuring out how to develop and implement AV-related policies and plans to obtain desired outcomes.
- As for the policy to increase the patronage of AVPTs, there is limited research and knowledge. Will the factors (both pull and push) influencing public transport patronage be valid for AVPTs with the widespread deployment of personal AVs or SAVs? The common logic suggests that AVPTs patronage would increase only in the case of convenience of private motor vehicle or private AV is offered. The convenience factors include access to public transport stops (Murray, Davis, Stimson, & Ferreira, 1998; Yigitcanlar, Sipe, Evens, & Pitot, 2007), weather and climatic conditions to access and use public transport (Kashfi, Bunker, & Yigitcanlar, 2015a, 2015b), travel time, cost and in-vehicle conditions (Beirão & Cabral, 2007). Owczarzak and Zak (2015) built a decision model based on the concept of public transportation on demand based on AVs. They find reliability and safety of AVPTs (unlike traditional determinants such as fare, and travel time) will be the key determinants of user acceptance and thus increased patronage (Lamondia, Fagnant, Qu, Barrett, & Kockelman, 2016; Becker & Axhausen, 2017). Similarly, Payre, Cestac, and Delhomme (2014) highlight the importance of acceptance of the technology in its wider roll out. This calls for further empirical investigations both on user confidence and policy formulation aspects of AVPTs.
- In terms of policy to discourage and reduce the sprawling urban development, there is not much research besides some warnings and speculations. For instance, Lari, Douma, and Onyiah (2015) warned us that the decreased travel costs in terms of time and energy (as may be generated by AVs) could result in people living further from urban centers, which would likely to create urban sprawl. The sprawl issue seems to be the biggest challenge for urban policy and planning, hence, there is an urgent need for empirical studies to model the impacts of AVs on our cities, and then develop competent planning policies and actions to address these challenges. Urban policy makers should take this issue seriously.

5.3 Limitations and research directions

The following research limitations should be considered: (a) Exclusion of literature outside the peer-reviewed full text articles available online, might limit the spectrum of the review as a relatively new field AV research has been mostly published in conference proceedings, book chapters, and white papers; (b)

Selection of the search keywords might omit inclusion of some relevant literature; (c) The authors' unconscious bias might have an impact on the execution of the review, and interpretation of the findings; (d) The methodological approach is limited to a manually handled literature review technique; further analytical techniques could have been considered—such as scientometrics, content analysis, cognitive mapping, and concept clustering—to generate a clearer picture of the investigated topic.

As indicated by Yigitcanlar, Currie, and Kamruzzaman. (2017), through the convergence of automation, electrification and ride-sharing technologies, AVs could significantly reshape real estate, urban development and city planning—as the automobile did in the last century. This transformation creates an opportunity for planners to make our cities more citizen-centered by bringing back the human-scale and walkable city practices that motor vehicle domination removed. How well prepared are urban planners, however, to mitigate the disruptive impacts on our cities? Do we yet even understand what these disruptions and their implications are? This review of the literature reveals that presently, urban planning as a profession is largely unprepared for AVs. Urban and transport planners need to be aware, smart and proactive about the potential impacts, particularly in terms of the potential for renewed urban sprawl. A future involving widespread use of AVs presents both land-use opportunities and challenges. Progressive outcomes will require an objective assessment of their complex land-use, economic and community influences on our evolving cities. We, hence, advocate the necessity of preparing our cities for AVs and generating desired smart urban mobility outcomes—through appropriate policies, timely legislations, and accurate planning standards and guidelines—even a wider uptake might take quite some time.

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Appendix

Appendix available as a supplemental file at www.jtlu.org/index.php/jtlu/rt/suppFiles/1405/0.

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Review

Impacts of Autonomous Vehicles on Greenhouse Gas Emissions—Positive or Negative?

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Abstract: The potential effects of autonomous vehicles (AVs) on greenhouse gas (GHG) emissions are uncertain, although numerous studies have been conducted to evaluate the impact. This paper aims to synthesize and review all the literature regarding the topic in a systematic manner to eliminate the bias and provide an overall insight, while incorporating some statistical analysis to provide an interval estimate of these studies. This paper addressed the effect of the positive and negative impacts reported in the literature in two categories of AVs: partial automation and full automation. The positive impacts represented in AVs' possibility to reduce GHG emission can be attributed to some factors, including eco-driving, eco traffic signal, platooning, and less hunting for parking. The increase in vehicle mile travel (VMT) due to (i) modal shift to AVs by captive passengers, including elderly and disabled people and (ii) easier travel compared to other modes will contribute to raising the GHG emissions. The result shows that eco-driving and platooning have the most significant contribution to reducing GHG emissions by 35%. On the other side, easier travel and faster travel significantly contribute to the increase of GHG emissions by 41.24%. Study findings reveal that the positive emission changes may not be realized at a lower AV penetration rate, where the maximum emission reduction might take place within 60–80% of AV penetration into the network.

Keywords: autonomous vehicle; GHG; emission; COVID-19; CLD; energy consumption; VMT

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1. Introduction

According to the United Nations Framework on Climate Change Convention, the transportation sector was responsible for 27% of US greenhouse gas (GHG) emissions in 2010 [1]. GHGs are one of the leading causes of the greenhouse effect worldwide [2]. They serve as artificial heat-trapping agents within the earth's atmosphere. From the perspective of road transportation, fuel sources such as diesel, natural gas, and gasoline produce different GHGs in the form of byproducts. Gaseous emissions resulting from burning these energy sources include methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O), which can last in the planet's atmosphere for several decades, causing continuous global warming [3]. These unregulated GHGs emissions disturb the natural gas cycles governing the planet and pose a significant threat to various flora and fauna types [4]. In European countries, the transport sector was responsible for 30.5% of GHG emissions and 12% contribution of GHG emissions from road transport in 2014 [5]. Another study conducted in China by Liu et al. predicted that the transport sector alone would account for 84.7% GHG emission by the year 2040 [6]. Rising concerns about the negative environmental externalities of road transportation activity and development have urged governments worldwide to assess transportation projects' environmental impacts before implementation. The modern automobile industry trend is to move towards the development of autonomous cars [7]. Multiple considerations are driving this change, including but not limited to improved safety, greater productivity, less fuel consumption and reduced traffic congestion [8,9]. Autonomous vehicles (AVs), also known as driverless or self-driving vehicles, are those vehicles that can operate without driver control the steering, accelerate or brake; the automation ranges from 0: no automation to 5: fully automated [10].

Existing literature on connected and autonomous vehicles mostly addresses their potential impact on the likelihood of traffic safety, travel behavior and congestion, as well as energy use. The effects of partially to fully automated vehicles on traffic performance and greenhouse gas emissions are still obscure. There are many uncertainties prevailing around the actual operation of fully automated vehicles. The Information Handling Services (IHS) Automotive experts reported that it is expected to happen by 2030. HIS estimates also suggest that globally the number of fully automated vehicles (AVs) in operation will be around 21 million in 2035 [11]. Another study reported that connected vehicles would strike the 250 million mark by 2020 [12]; a quarter of a billion cars in operation. A previous study also predicted that fully AVs be offered for auction before 2020 [13]. A projection is that AVs will dominate 20–40% of vehicle market share by 2030; however, it is believed that full-scale transition to AVs is likely to happen in stages over the coming few decades [14].

AVs are mainly equipped with contemporary car technologies, allowing computers to help in various driving operations and reduce human involvement to varying degrees. With rapid advances in communication, autonomous, and car technologies that have far-reaching effects on the transportation sector, it is critical to understand these technologies' role in achieving sustainable urban mobility goals. This involves the safe and smooth operation of people and goods movement in an environmentally friendly manner. The carbon emission rate from each transport mode is significantly influenced by an array of factors, like the type of fuel, vehicle type, and age, etc. Many studies investigated the impacts of the widespread adoption of AV technology [15,16]. The impacts considered air pollutants, including GHG emissions. AVs' introduction may contribute to increased ridesharing, traffic flow smoothing, platooning, efficient driving, efficient routing, eco traffic signal, and less hunting for parking [17–21]. As a result, the energy consumption will be less, contributing to the reduction of GHG emissions. A number of previous studies have investigated the role of AVs in improving transport sustainability by compressing energy use and GHG emissions. For example, one such estimation for the full automation developed by Wadud et al. considering the shared-vehicle scenario was based on the "Strong Responses" [22]. According to this concept, the maximum energy savings through car-sharing, eco-driving, right-sizing, and platooning are wholly neutralized by maximum energy increases from new user groups and higher speeds. In their study, Greenblatt and Shaheen explored the GHG reduction benefits of driverless taxis in the US and claimed that the deployment of each such taxi in the country would cause than 87–94% fewer emissions per vehicle-km trip by the year 2030 [23]. The authors also stated that each deployed driverless taxi in the same year would also cause a 63–82% reduction in GHG emissions than traditional fuel-driven and hybrid electric vehicles. Such reduction would primarily result from variations in three aspects: higher vehicle-km/vehicle/per-year increased fuel efficiency due to re-designed lighter/smaller vehicle sizes, less air friction, and reductions in GHG emissions through electricity consumption. On the other hand, AV may generate increased trips due to faster and more comfortable driving and new trips by captive passengers, such as elderly and disabled individuals [24].

Tomás et al. investigated the GHG implications of three different AV penetration rates (10, 20, and 30%) along an urban freeway corridor in the city of Porto, Portugal [25]. Authors used vehicle-specific power (VSP) and EEA-33 (environmental emergencies member countries) methodologies coupled with the VISSIM traffic model. It was noted that AVs yielded statistically low emission benefits at the corridor level at penetration rates less than 30%. In their study, Stasinopoulos et al. adopted a system dynamics approach and developed a stock and flow model to examine the GHG impacts of vehicle automation in various scenarios [26]. The study reported that emissions benefits of the transition to AVs might be negated by the inefficient use of AVs and induced demand. In another study, Wang et al. compared the fuel-cycle GHG emissions of AVs and vehicle electrification using an activity-based travel demand model for the Hamilton and Greater area [27]. It was concluded that full-scale induction of AVs would result in higher vehicle kilometers traveled, and hence, more GHG emissions are expected (2.5%). On the other hand, vehicle electrification may reduce vehicle emission intensities by approximately 11% and regional GHG emissions by over 5%. Hong and Zimmerman predicted that AVs can reduce GHG emissions by 20% compared to no-AV conditions in the year 2040, even under the worst-case scenario if vehicle automation provoked increased personal use with 85% vehicle fleet electrification [28]. A study conducted by Liu et al. also suggested that high AVs penetration rates in the long-term (by the year 2045) under optimistic scenarios will lead to a net reduction of GHG emissions [29].

This paper develops a landscape of multi-faceted issues related to GHG emissions from AV adoption at different levels by reviewing, synthesizing, analyzing, and comparing contrast research studies. While comparing the GHG emissions from AVs to its counterpart, fossil fuel vehicles (FFV) may have different attribute levels (e.g., gasoline-powered, eclectic, hydrogen-powered), this review study is only limited to the realm that both AVs and FFVs are only operated on fossil fuels. The study provides a causality analysis of GHG emissions from AVs from a holistic point of view. The primary objective of using a causal loop diagram (CLD) in our study is to understand the factors that can critically affect how the adoption of AVs may bring energy and GHG emission benefits to the transportation sector. CLD is used to see how these factors interact and influence the emission benefits of adopting AVs in the transport industry. Another section addressed the dynamics of GHG emissions during a global pandemic, focusing on travel behavior and how the individual vehicle ownership model may change in favor of adopting AVs.

The remainder of this paper is structured as below. Section 2 provides an overview of the study methodology. Section 3 presents a description of the causes of GHG reduction by AVs, while the possible causes of the increase of GHG emission by adopting AVs are discussed in Section 4. Section 5 illustrates the changes in GHG emission at different AV penetration levels. Section 6 covers a discussion of the relationship between energy consumption and GHG emission; two sub-sections of Section 6 shed light on the causal loops of GHG emission from AVs from a system perspective and changed travel behavior during a global pandemic, respectively. Finally, Section 7 summarizes the study findings with concluding remarks.

2. Methodology

The systematic review has a formal protocol describing the strategy proposed for conducting the examination, identifying questions and methods employed to carry out the analysis [30]. The review process used in this study comprises three steps:

1. Planning: Defining the research issue, setting the criteria, identifying the limitation and development of the overall protocol.
2. Execution: Selection of research in database, categorizing useful references and bibliography, abstract of published manuscript.
3. Analysis: Summarizing the selected articles and classifying it to fit the proposed protocol.

Various guidelines could manifest a systematic literature review. One of the popular methods is demonstrated by Kitchenham and Charters, a process that entails a number of tasks, including establishing a review protocol, identifying and selecting primary studies, extracting and synthesizing data, and finally, reporting study findings [31]. This paper focused on a systematic keyword search in the topic section of literature databases from disparate sources and repositories. The articles were searched for based on specific terms such as “autonomous vehicles,”; “self-driving car,” and “driverless car” appeared in the title, keywords, and abstract in the journal database. However, care was taken to single out the articles which were not focused on autonomous driving related to extensive applications, testing, and research in robotics, underwater vehicles, unmanned aerial vehicles, etc. The effects of AV-generated GHG emissions are explicitly investigated to achieve an overall classification to identify current gaps in the scientific literature in the realm of AV-related publications for roads, traffic studies related to commuting. The year of publication timeline and number of citations were taken out of the equation in selecting the articles to maximize the number for consideration. Articles found in different databases were also identified for eliminating duplication. The flowchart presented (Figure 1) illustrates the methodology deployed in this study.

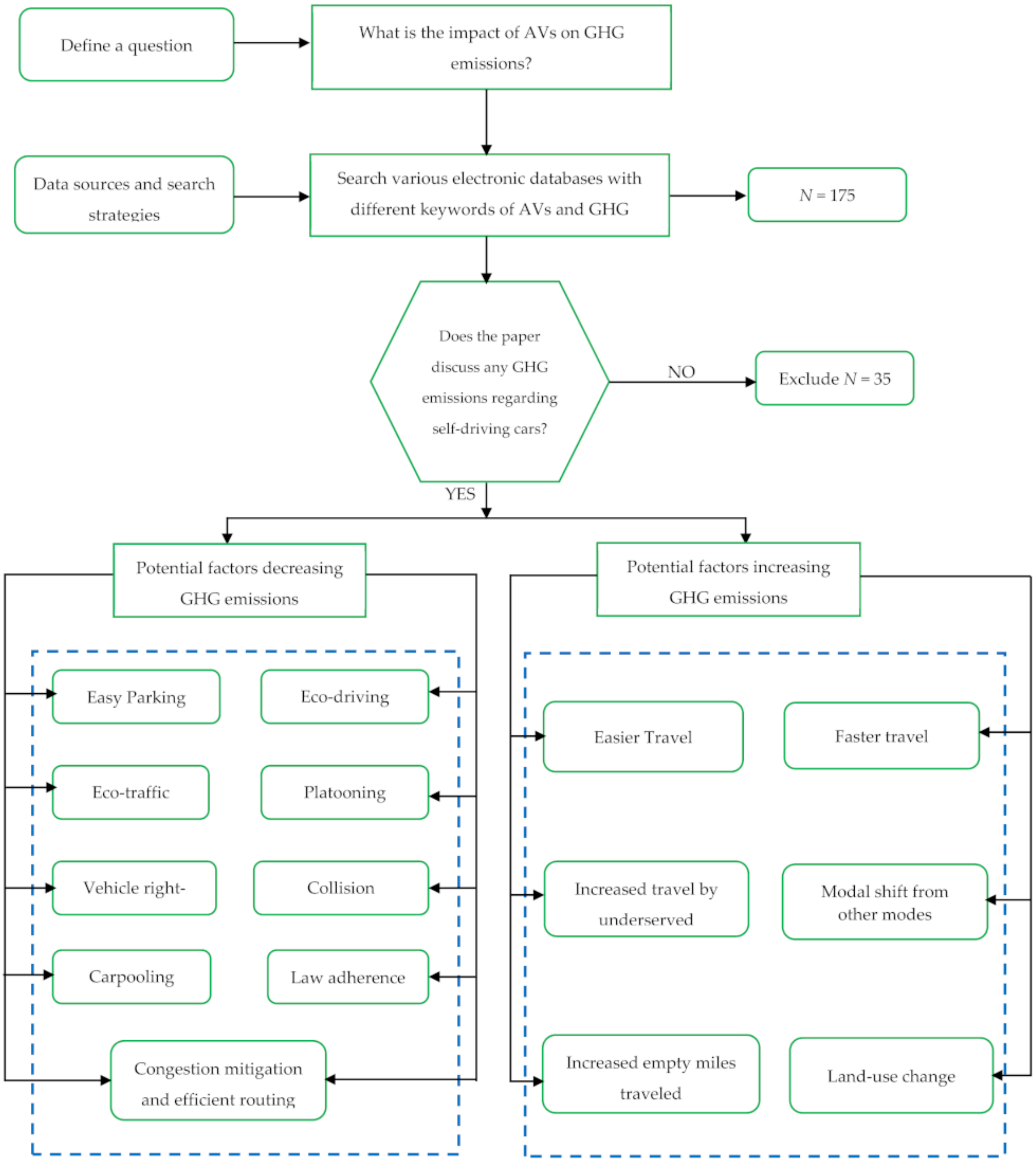

Figure 1. Methodology plan.

3. Causes of Reduction in GHG Emissions

This section provides a brief explanation of potential factors that are expected to reduce lower GHG emissions due to vehicle automation. Two types of vehicle automation strategies are considered, i.e., partial automation and full automation.

3.1. Easy Parking

Guccione and Holland identified that drivers looking for parking are responsible for about one-third of traffic in the city [32]. From the fuel efficiency point of view, a vehicle searching for parking leads to a double threat. Being on the road consumes extra fuel for itself; the additional traffic makes the other vehicle suffer by staying more on-road and ending up using undue fuel. Roadside parking maneuver also has an important share in cities carbon emission system [33]. Shoup added to the literature with an estimation of 2–11% of total emission in a CBD being caused by parking hunt [34]. Easy parking refers to parking spaces' availability through communication technologies that allow vehicles and infrastructure to exchange information, resulting in accurate parking information. In another study, Brown et al. estimated up to 5% of emissions in an average passenger car is attributed to the search for parking. Fully automated vehicles can achieve a 5–11% emission reduction from reduced circulation for parking in the cities [35]. Moriarty and Wang also estimated that parking space could be drastically reduced, and vehicles searching for parking could be cut down by 80% with shared ownership of AVs [10]. During peak traffic hours when congestion is high and off-peak travel periods, when most parking spaces may be occupied, the same reduction may occur. Partially automated vehicles would also minimize emissions due to improved ability to locate available parking spaces correctly; however, the projected savings could be lower, considering the lack of automatic implementation. In general, the easy parking feature of vehicle automation is expected to reduce GHG emissions depending upon various other factors, due to minimum vehicle idling and searching for suitable parking locations.

3.2. Eco-Driving

Eco-driving refers to efficient driving through maximizing speed and acceleration operating profiles. Eco-driving is often referred to as "Hypermiling," and is nothing but a set of driving skills practiced by enthusiastic drivers to push the fuel economy's limit by minimizing braking-acceleration cycles, as braking causes a waste of energy [15,36]. CAV technologies have the ability to leverage and extend such efficient driving benefits by enabling vehicles to incorporate eco-driving automatically. CAVs can coordinate with other vehicles with smarter communication capability to make integrated driving decisions that would optimize overall traffic flow conditions and support the entire driving platoon. Barth and Boriboonsoms deployed a traffic simulation model to determine the emission effects of coordinated eco-driving [15]. The coordinated eco-driving system takes advantage of a virtual traffic management center to monitor vehicles' speed and acceleration characteristics. They simulated a mixed fleet of vehicles on Southern California highways and estimated that carbon dioxide emissions reduction within a range of 10–20% could be achieved by eco-driving on congested highways. However, it has been noted that the reduction of emission starts to disappear as traffic approaches free flow. In a similar study, Barth demonstrated that a coordinated eco-driving system would minimize emissions by 5–10% in heavily congested road traffic [15]. Li and Gao conducted a series of micro-simulation modeling studies to investigate speed synchronization impacts in a connected environment [37]. Their primary objective was to establish an optimal control strategy to optimize fleet-level average fuel economy in a connected vehicle environment. The findings suggested that reducing 10% of GHG emissions could be achieved in such an arrangement.

Two research projects conducted at the Virginia Tech Transportation Institute estimated potential emissions impacts of vehicle-to-vehicle (V2V) communication and coordination [19,38]. The proposed method involved complex optimization models integrating road-characteristics, information of the lead vehicle, vehicle acceleration portfolio, and microscopic fuel consumption models to produce a fuel optimal speed profile for vehicles in the network. Optimal driving cycles may reduce energy consumption by 35–50% under oversaturated conditions if these conditions exist at all in reality [39]. It is well known that frequent stops and accelerations/decelerations operations contribute to significant fuel consumption. The eco-driving attribute of AVs facilitates smooth vehicle navigation through the network, due to smart communication with other vehicles, as well as highway infrastructure, which in turn lowers the GHG emissions.

3.3. Eco Traffic Signal

AVs can communicate with infrastructure on their own, particularly with traffic signals at intersections. This communication offers information to vehicles, which helps them change their driving pattern, thereby minimizing the number of stops at the intersection referred to as the eco traffic signal system. Li and Gao investigated optimal signal control strategies for fuel economy in a connected vehicle environment and showed that gasoline vehicles could achieve 10% emission reduction via such strategies [37]. Rakha et al. estimated potential emission impacts of vehicle-to-vehicle communication and signal coordination, and it turned out to be 8–23% emission savings depending on the vehicles' traveling attributes [19,40].

The potential to reduce fuel consumption and GHG emission at the intersection is very high, as vehicles traveling near intersections at lower speeds tend to consume more fuel [41]. Yelchuru and Waller adopted micro-simulation models to estimate vehicle emissions under connected eco-traffic signal timing and the associated optimal signal timing plans [42]. According to the study, under a fully connected protocol, 2–6% emission reduction can be achieved in an average passenger vehicle. Zimmerman et al. compared traffic patterns before and after a user information system was introduced at different signalized intersections in Phoenix, Arizona [43]. The empirical data reported that the delay was reduced by 6.2%, resulting in a 1.8% emission reduction using vehicle speed profile and energy consumption correlation. As mentioned, signalized intersections in urban areas have the huge potential to reduce GHG emissions at the network level. AVs are equipped with different sophisticated sensors for communication with roadway surroundings that can guide the drivers/vehicles to adjust the driving patterns, minimize stops and speed variance. All these factors will reduce fuel consumption and hence vehicular emissions.

3.4. Collision Avoidance

Human error accounts for more than 90% of accidents [44,45]. Collision avoidance systems in AVs are designed to provide necessary information ahead of time to the vehicle by means of well-designed vehicle mount sensors to avoid collisions. The sensors track nearby vehicles and objects to warn the system of preemptive maneuvers. In addition to the obvious individual advantages of accident avoidance, the system provides collective fuel-saving and environmental benefits by eliminating the chance of traffic congestion that might have arisen at a vehicle crash scene. According to Schrank et al., nationwide, 1.9% of GHG emission by the light duty vehicle (LDV) fleet was produced, due to the traffic congestion created at the accident spot [46]. Najm et al. integrated forward collision warning and adaptive cruise control functions to develop the ACAS for LDV applications [47]. The development of ACAS was based on an operational field test of 10 vehicle fleets driven by 66 drivers among diverse age and gender groups. The ACAS system has the potential to prevent about 10% of all rear-end crashes, which is expected to bring some indirect emission benefits. The collision avoidance attribute of both partial and full automation will reduce the GHG emissions, by preventing and minimizing jams and traffic congestion causing traffic accidents.

3.5. Platooning

The vehicle platooning concept refers to the practice of multiple vehicles trailing closely enough to minimize aerodynamic drag to save energy and reduce vehicle emissions.

Vehicle platooning can be safely and successfully implemented by leveraging automation and connectivity technologies. This strategy is particularly attractive considering that a significant portion of fuel consumption is attributed to confronting aerodynamic resistance while driving. Kasseris estimated that aerodynamic drag accounted for 50–75% of the tractive energy requirements for driving on a highway [48]. The shape of the vehicles in the convoy, distance headway, and order of the vehicles are the variables responsible for drag reduction in platooning. Since platooning advantage is more applicable to the vehicles in the middle of the pack, average fuel saving increases with the number of vehicles in the platoon. For two sedan cars running 1 m apart, the average reduction in drag has been estimated to be 10% [49]. Drag reductions ranging from 20% to 60% have been reported for platoons consisting of mixed vehicle types [50,51]. For a 3-truck platoon of freight trucks, Tsugawa has reported a 10% reduction in energy consumption at 80 km/h, with a 20 m gap between trucks; the reduction could reach up to 15% at 5 m gap [52]. The assumption that 50% tractive energy is used to overcome drag resistance could be combined to the advantage of vehicle platooning, which may yield an overwhelming 22.5–27.5% emission reduction. Zabat et al. also examined the potential of emission reduction in vehicle platooning through experiments done in a series of wind tunnels, along with numeric simulations using a passenger van [53]. They found that the average emission reduction per vehicle ranges from 10% to 30%, depending on the vehicles' space in the platoon, number of vehicles, and other variables. Another study confirmed that when 15 vehicles are driving 6–8 m apart, they may achieve optimum fuel saving in the platoon, however, such a gap is extremely unsafe for conventional human-driven cars, but entirely within the capacities of autonomous vehicles [54]. It may be argued from the present literature that AVs vehicle platooning will lead to lower GHG transport emissions, primarily due to drag reduction and lower speed fluctuations.

3.6. Vehicle Right-Sizing

Automation technologies have the potential to scale down the size of automobiles without compromising safety [22]. A significant improvement in fuel efficiency could be achieved by vehicle downsizing. The LDVs are designed to run on US roads with the least capacity of holding four passengers [22,55]. However, the average occupancy of these LDVs is only 1.67 in 2009 [56]. Once individual trip requirements are fulfilled, vehicle right-sizing can significantly reduce the average energy intensity. The vehicle size appropriation works best when it is coupled with car-sharing or carpooling. A fleet of shared AVs could easily supply the right-sized vehicle to meet passenger demand and discourage over-designed cars from being under-used [57]. MacKenzie et al. tested multiple conflicting influences on vehicle weight in terms of technological changes and functional improvement [58]. They indicated that progress in energy efficiency technology had been counterbalanced by increasing vehicle size and vehicle content. In particular, their study revealed that, for an average 2011 model car in the U.S., the safety-related features accounted for a total of 7.7% of the car's weight, and dislodging them could result in a 5.5% reduction in emission. In general, a reduction of 20% in vehicular weight is attributed to a 20% increase in fuel efficiency [59]. The engine power required and amount of fuel consumed during a trip are proportional to the size of a vehicle. With AVs technologies in practice, manufacturers can scale down the vehicle sizes, leading to substantial energy and GHG emission benefits.

3.7. Congestion Mitigation and Efficient Routing

As intermittent traffic experiences frequent stop-and-go and idling conditions, a car driving through heavy traffic will use more fuel, thus emitting more GHG than uncongested traffic. AVs will have the ability to coordinate with other vehicles and infrastructures (V2V and V2I) at the intersection, to improve the traffic flow and reduce the crash frequency that will result in less energy use and less GHG emission [22]. Bigazzi and Clifton's study indicated that internal combustion engines (ICEs) fail to maintain fuel efficiency in slow-moving traffic at a speed of 30 miles per hour or lower [60]. In contrast, Gas electric hybrid vehicles are less sensitive to speed variations and retain fuel efficiency roughly at 20 mph. Though vehicles with different powertrain respond differently to congestion, an AV essentially powered by electricity has a higher potential of reducing GHS.

V2I technology available in AVs could also reroute cars within the road network in case of an unexpected influx of traffic into the grid network generated from a sports/entertainment event [61]. A fully developed city's infrastructure is capable of receiving data from vehicles, anticipating traffic flows, and route vehicles with preference and faster routes given to emergency responders and school buses most efficiently [62]. Smart vehicle communication characteristics of AVs can give early warnings of traffic incidents and unanticipated traffic ahead. This will allow the vehicles to take optimal routes and smoothly flow through the network, and hence lower GHG emissions are released into the atmosphere.

3.8. Carpooling

The occupancy rate is a key factor for GHG emissions associated with existing car travel. Fewer passengers per vehicle will result in more vehicles running on the road than required, and this will result in emissions increasing by several folds. For instance, only 11% of Americans carpool to work, and a staggering average of 113.6 million people make solo trips to and from work daily [63]. AVs have the potential to emerge as a new paradigm of business model to leverage the benefit of ridesharing, which would bring about a modal shift from individually owned vehicles to shared mobility services. Such changes are expected to reduce transportation GHGs significantly. AVs will also provide the option of carpooling and ridesharing that can lower GHGs emissions by reducing the auto-ownership, and travel through other less convenient transport modes.

3.9. Traffic Law Adherence

Iglinksi and Babiak believe that autonomous vehicles will more strictly adhere to traffic laws as compared to the human driver, due to their integrated onboard programming logic [64]. AVs will be more likely to travel at posted speed limits designed to cater to optimal fuel efficiency, reducing GHGs considerably. Similarly, AVs will also strictly comply with traffic signals and thus reducing the nuisance and congestion created by human traffic. GHG reduction at different levels of vehicle automation reported in the literature are listed in Table 1.

Table 1. Reduction of GHG emission at different levels of vehicle automation.

Study	Level of Automation	Cause of Reduction in GHG	Results	Condition
Stephens (2016) [17]	Partial Automation	Driver profile and Traffic flow calming	0–10% 0–5%	During peak hours During non-peak hours
	Full Automation		10–21% 5–11%	During peak hours During non-peak hours
Barth and Boriboonsomsin (2009) [15]	Full Automation	Eco-driving	10–20% nearly 0%	Congested highway traffic. Free flow
Xia et al. (2013) [65]			5–10%	Under congested city traffic
Li and Gao (2013) [37]			10%	Under congested city traffic
Rakha (2012) [40]			8–23%	Under different speed, congestion level and design characteristics
Yelchuru (2014) [42]	Partial automation	Eco-traffic signal timing V2i/i2v communication	1.8–2%	City driving
	Full Automation		2–6%	City driving
Schrank et al. (2012) [46]	Partial Automation	Collision avoidance	0–0.95%	City driving
Stephens (2016) [17]	Full Automation		0–1.9%	

Table 1. *Cont.*

Study	Level of Automation	Cause of Reduction in GHG	Results	Condition
Stephens (2016) [17]	Partial Automation	Platooning	0–12.5%	During peak hours
Schito (2012) [50]	Full Automation		12.5–25%	During non-peak hours
			22.5–27.5%	During non-peak hours
Zabat et al. (1995) [53]			10% to 30%	During peak hours
			20–25%	During non-peak hours
Wadud et al. (2016) [22]			3% to 25%	During non-peak hours
Wadud et al. (2016) [22]	Full Automation	Vehicle/powertrain resizing	45%–roughly 50%	No condition mentioned
Burns et al. (2013) [66]				
Shoup (2006) [34]	Full Automation	Less Hunting for Parking	2–11%	During city driving
Brown et al. (2014) [35]	Full Automation		5–11%	
Barth (2009) [15]	Partial Automation		2–5%	
Brown et al. (2014) [35]	Full Automation	Increase in Ridesharing	Roughly 12%	During city driving
Stephens (2016) [17]	Partial Automation	Faster travel	0–10%	During peak hours
	Full Automation		10–40%	During non-peak hours
Haan et al. (2007) [67]	Full Automation		20–40%	During non-peak hours
Brown et al. (2014) [35]	Full Automation		0–40%	During non-peak hours
	Partial Automation		0–10%	During non-peak hours
Stephens (2016) [17]	Partial Automation	Easier travel	4–13%	No condition mentioned
Stephens (2016) [17]	Full Automation		30–156%	Living farther
Childress et al. (2015) [68]	Full Automation		3.6–19.6%	Capacity will increase and value of travel time cost will reduce
Gucwa (2014) [69]	Partial Automation		4–8%	Living farther
Brown et al. (2014) [35]	Full Automation		50%	
MacKenzie et al. (2014) [58]	Partial Automation		4–13%	
Stephens (2016) [17]	Full Automation	Increased Travel by Underserved Populations	2–40%	Elderly and disabled would travel as much as drivers without medical conditions
MacKenzie et al. (2014) [58]	Partial Automation	Mode Shift from Walking, Transit and Regional Air	2–10%	No condition mentioned
Harper et al. (2016) [70]	Partial Automation		Up to 12%	
Brown et al. (2014) [35]	Full Automation		Up to 40%	
Fagnant and Kockelman (2014) [71]	Full Automation	Increased empty miles travelled	5% to 11%	On city driving

4. Causes of Increase in GHG Emissions

This section reviews some of the predominant factors that may increase GHG emissions due to vehicle automation. The impact of two-vehicle automation strategies, i.e., partial automation and full automation, will be discussed.

4.1. Easier Travel

Easier travel involves reaching destinations more quickly due to capacity increases and fewer crashes, and lower travel costs. Travel may be faster and more reliable if crashes and congestion are reduced, and travel demand may increase. Capacity would effectively increase by less congestion and fewer crash delays, which could also trigger increased travel. Using activity-based travel model-generated scenarios, Childress et al. analyzed possible changes in travel patterns in the Puget Sound region [68]. These evaluated scenarios were comprised of a 30% increase in roadway capacity, resulting in a 3.6% increase in emissions, and a 35% reduction for the highest-income households in the perceived value of travel time cost. In a different scenario, assuming everyone owned an automated vehicle (no shared one), which resulted in a 30% increase in roadway capacity and 50% less parking costs, along with a 19.6% increase in emissions. People may be more likely to drive in automated vehicles under congested conditions. Easier travel means that more and more people will be attracted to use AVs, especially during traffic congestion situations. Greater demand and increase in road capacity will ultimately lead to increased vehicular emissions.

4.2. Faster Travel

CAVs will be able to navigate and respond more quickly than human drivers with the state-of-the-art communication technology available onboard; it follows that AVs will be able to ride more safely at higher speeds than human drivers. AVs are expected to leverage V2V and V2I networks that communicate charted courses seamlessly to raise the speed limits on freeways [62]. To ensure a safe driving environment that accounts for operator reaction time, vehicle design, and road limitations, speed limits were initially imposed in the US, later changed at the federal level to minimize fuel consumption [32]. Therefore, an increase in fuel consumption is expected for increasing speed limits across the country due to AVs [22]. Considering driver's value of time analysis, Wadud et al. analyzed the possible repercussions of increased highway travel speeds due to automation technologies [22]. A typical car's speed-fuel consumption relationship was used to conclude that GHG emission of the highway could increase by 20–40% [72]. According to Brown et al., the increase in highway fuel use could be as high as 40% or more as a result of faster travel [73]. Brown et al. focused on travelers' time budgets based on Schafer et al.'s observation that different societies display the same willingness to travel [35,74]. They hypothesized that if people could travel faster, they might prefer to live further away from their regular destinations, only to promote urban sprawl. Ultimately, this might trigger a possible increase in emissions by 50%. The onboard vehicle communication and sensing technologies of AVs will require a higher posted speed limit at the network level. It is established that faster travel is accompanied by greater fuel consumption, and hence the rate of GHG emissions.

4.3. Increased Travel by Underserved Populations

Although access to mobility services to the disabled and people at dotage rendered by the AVs seems beneficial for society, it is likely to increase overall VMT. Due to the lack of adequate data on why some population groups travel less than others, it is difficult to forecast future travel patterns of those who are currently underserved. MacKenzie et al. observed from the 2014 National Household Travel Survey data that VMT for adults over 62 years old is much lower than the 42 years old group [58]. Fully automated vehicles could fulfill this travel demand. They estimated that increased travel could raise emissions by 2–10%. Harper et al. assumed that non-drivers would travel as much as drivers in each age group aged between 19–64; drivers with medical conditions are also expected to have similar travel patterns as drivers without medical conditions within each age group [70]. Dividing the sample population into three distinct groups of non-drivers 19 and older, elderly drivers without a medical condition, and drivers 19 and older with a medical condition, it was estimated that the underserved could increase emissions up to 12% by using fully automated vehicles. Examining data from the 2009 NHTS and the 2003 Bureau of Transportation Statistics publication "Freedom to Travel," Brown et al. estimated a 40% increase in GHG emission, If all age segments traveled close to the top decile in each segment [35]. The fact that AVs can be used by non-drivers, people without driving licenses or people with special needs will increase the road user population and hence the daily number of vehicle trips. However, although it may have several positive prospects, GHGs are expected to increase.

4.4. Mode Shift

The theory of travel behavior implies that the preference to use one mode over another is influenced by several variables, including, but not limited to, socio-economic status, age, gas price, urban form, and transportation options availability. Metropolitan Area Planning Council (MAPC) conducted a study in the Boston area, in which researchers found that those who use transit passes daily, or weekly, would replace transportation network companies for transit frequently. Frequent transit users are more likely to be willing to sacrifice the service in favor of a ride-sharing opportunity, even at a large difference in cost or forfeiting the money they already paid to avail the service [75]. A ride in a driver-less, fully autonomous vehicle will likely be cheaper [76,77]. New mobility services, and eventually autonomous vehicles, on the contrary, could increase ridership by solving the first-mile/last-mile problem and serving as a complement to mass transportation, thereby increasing GHG emissions. Shifting a staggering 56.5 billion miles (according to the National Transit Database for 2013) to vehicle-miles constitutes an increase in emissions of 2.0%. If it is assumed to be in city travel only, it accounts for an increase of 3.7% in city emission. Considering the change from air transport, an estimated 79.8 billion passenger miles traveled over domestic flights of less than 500 miles. Shifting all of these passenger-mile to non-shared vehicle-mile AVs in a possible scenario reflects a rise of 2.9% in emissions. However, this condition is projected to increase emissions only on highways. With AVs in operation at relatively lower journey costs than other transport modes, more and more people will be inclined to use AVs, which will also lead to high GHG emissions.

4.5. Increased Empty Miles Traveled

AVs have not been extensively studied for potential changes in vehicle travel without a passenger. A vehicle owner could send his driverless AV to pick up family members or send nearby locations beforehand to minimize wait time. An agent-based model of self-driving vehicles moving in a square grid representing an imperial city was used by Fagnant and Kockelman to investigate the travel patterns of users of a shared fleet of self-driving vehicles [71]. With some predefined available data from 2009 NHTS, they examined scenarios with varying trip generation rates, level of network congestion, neighborhood size and vehicle relocation strategies. Finally, the study concluded that almost 11 conventional vehicles could be replaced by a self-driving vehicle with an increase of 5–11% in emission for vehicle repositioning. Vehicle idling while waiting for the passengers' pick up from their destinations is the main source of increased vehicle miles traveled and resulting emissions.

4.6. Land Use Change

Since individuals are liberated from the pressure of being behind the wheel and can use the time for work or recreation instead, there is a likelihood that they can accept longer commutes. For example, Cervero and Murakami observed data from 370 urbanized areas in the U.S. They deployed structural equation modeling to determine the relationship of population density with VMT per capita and found that an increase in population density leads to a decrease in per capita VMT [78]. When it comes to urban form, they pointed out a vital issue: traditionally, societies have been more reluctant to relocate residential roads or emphasize keeping the roads in the first place when built [79]. These findings indicate that if the introduction of AVs increases the pressure of growth in suburban areas, an increase in GHG emissions could result as people are concentrated in areas that facilitate more auto travel. Access of AVs to remote and sub-urban areas will encourage the public to opt for longer commutes and frequent travel, which will ultimately cause increased vehicular emissions at the network level.

5. Change in GHG Emissions at Different AV Penetration Levels

This section investigates changes in emissions at different AV penetration levels using integrated traffic microsimulation and emission models. With better operating efficiency and improved powertrain technology, AVs are expected to yield overall emission benefits.

Stogios et al. designed a study to evaluate the potential impacts that AVs could offer under varying scenarios [80]. Under interrupted and uninterrupted traffic flow conditions, high and low traffic conditions were evaluated. This study integrated the use of VISSIM microscopic software with the MOVES emission model to assess vehicular emissions. Eight inbuilt car-following and two lane-changing parameters present within the VISSIM model are investigated, representing AV driving behavior. The high traffic volume is reflected by an increase of 50% increase of the demand, while low traffic volume is produced by reducing the demand by 50%. A set of simulations is completed in the VISSIM model with 10%, 30%, 50%, 70%, and 90% of AVs penetration rate to investigate the changes in emission from the base condition. The study revealed that headway time has the highest impact on emissions and average delay than other parameters. Maximum headway time representing a cautious driving behavior resulted in a 31% increase in overall emissions, while a shorter headway time resembling aggressive driving behavior reduces the emission by 10%. The growing penetration of AVs into the network within high-traffic conditions results in minor incremental changes in emission factors and the number of stops per vehicle. In contrast, aggressive AVs reduce the average number of stops and emissions with increased market penetration. The AV penetration rate results, however, are not as evident under low traffic conditions. That is to conclude from the study that AVs will offer the maximum benefits under congested traffic conditions.

Olia et al. deployed the PARAMICS microsimulation framework integrated with CMEM emission model to measure the vehicle emission at different market penetration of connected autonomous vehicles [81]. The CMEM model is capable of continuously estimating gas emissions and fuel consumption at the microscopic level. The emission and fuel consumption in the CMEM model vary based on vehicle type, age, fuel system, and emission control technology. The vehicles in this model were divided into three categories, unfamiliar non-connected, familiar non-connected and CVs to produce emission factors for CO_2, CO, NOx and HC. The results showed that with a gradual increase of CVs market penetration, the emission factors decreased. The maximum emission benefit could be realized at 50% CV penetration, where the GHG emission is reduced by 30% from the base condition.

Another study by Conlon and Lin attempted to quantify the changes in CO_2 emission as the AVs are gradually penetrated into a congested urban road network [82]. SUMO traffic microsimulation and Newton-based greenhouse gas model (NGM) emission model were integrated to estimate the emission for different AV penetration, ranging from 0% to 100% into the network with an interval of 10%. At an AV penetration rate lower than 30%, the total CO_2 emission had increased from the baseline of 0% AVs. The increase of total emission is explained by the difficulty in the interaction between human-driven vehicles (HDVs) and AVs. As the AVs penetration rate gradually increased, the study network started to realize the benefit of AVs in traffic operation, travel speed, and emission reduction. However, the emission reduction remained plateaued between a wide range of 40% to 90% AV penetration. Finally, at full AV penetration with no heterogeneity, the network was found to yield a maximum reduction of CO_2 emission of 4.08% from the base condition. The changes in emission at different AV penetration levels from different studies could be compared for better understanding (Figure 2). Existing literature in this regard suggests that noticeable emission benefits of AVs at the network level can be achieved at penetration rates ranging between 30% and 50%.

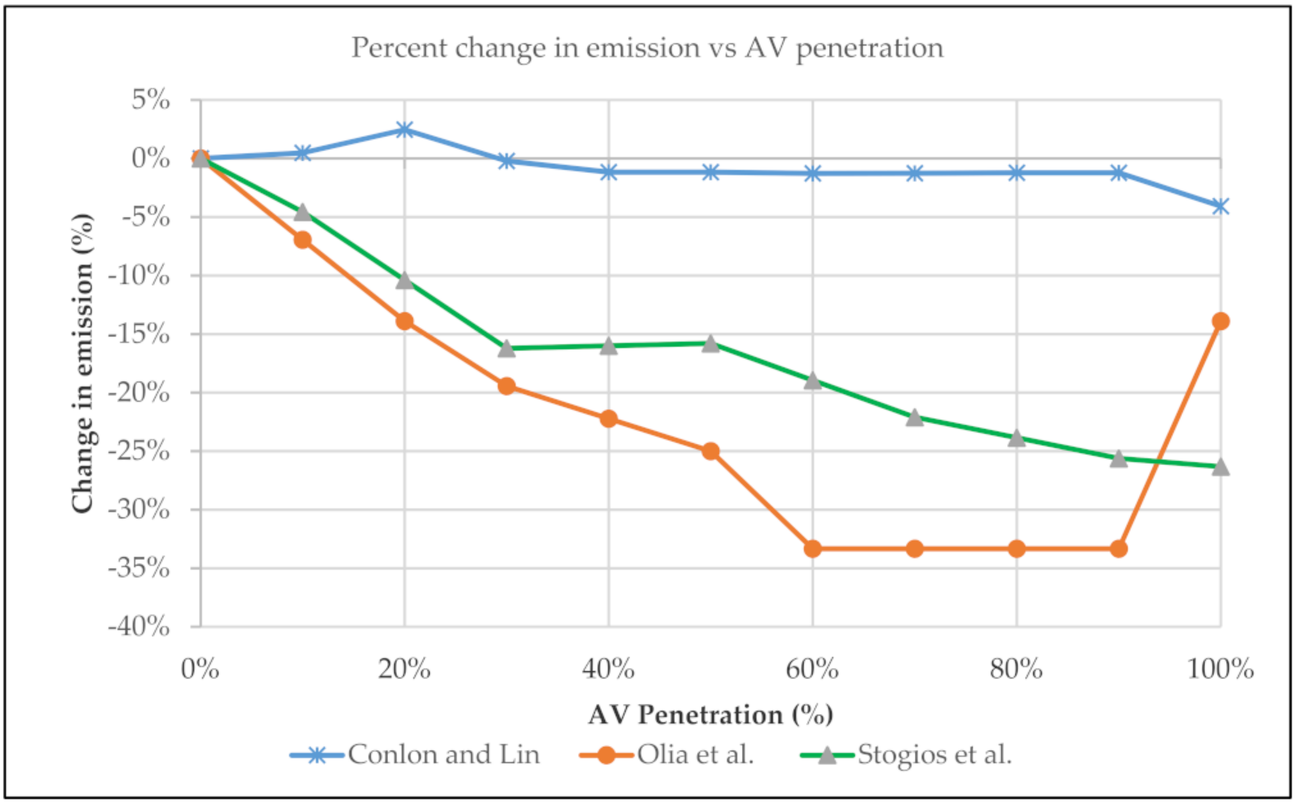

Figure 2. Emission changes by AV penetration [80–82].

6. Energy Consumption and GHG Emission

In recent years, the transportation sector has become the top GHG emitter surpassing electricity generation in the U.S. It accounted for approximately 28.5% of total atmospheric emissions in the country and continued to be the rapidly growing emissions source of any energy-related sector [83,84]. The global share of GHG from transportation is estimated to be around 24% of all emissions [85]. Passenger cars are accountable for 75% and 60% of transportation emissions worldwide and in the U.S., respectively [84,85]. The emergence of AVs can bring numerous energy and emission benefits, due to homogeneous traffic flows, lower highway congestion, lighter and smart vehicles shaped to minimize air resistance, minimum vehicle idling, the need for less powerful engines, etc. This would further enhance fuel efficiency and reduce emissions.

Similarly, shorter time spent searching for nearby parking and reduced needs for construction, operation, and maintenance of parking infrastructures could also bring various environmental benefits. Furthermore, the prospects that AVs serving passengers' demand for performing various activities will be larger than traditional vehicles cannot be excluded. Under such circumstances, larger vehicle sizes may somehow limit fuel efficiency gains. However, shared AVs may be programmed to continuously drive rather than looking for parking in the city's downtown until the next call for a ride, thus generating more emissions. This issue may be partially mitigated by programming the AVs to drive themselves outside of the downtown of an urban area where parking is free or relatively cheaper. However, this extra travel will lead to more energy consumption, creating more traffic congestion and subsequently producing more vehicular emissions.

In the literature, numerous studies have discussed the prospects of fuel energy saving through vehicle automation. For example, Wu et al. reported that the deployment of a fuel economy optimization system could offer the automated systems or human drivers with essential guidance about optimal deceleration/acceleration profiles, taking into account vehicle current speed and acceleration, as well as other information such as headway spacing, signs, and traffic lights [86]. The authors conducted a driving simulator experiment in an urban setting through a network of signalized intersections and noted a nearly 31% reduction in fuel consumption for drivers using the system. Likewise, Khondaker and Kattan reported that a variable speed limit control algorithm resulted in approximately 16% fuel savings compared to an uncontrolled scenario [87]. The proposed control system integrated real-time intelligence about individual driver behavior (like the level of compliance with the established speed limits, acceleration/deceleration) in the situation of 100% connected vehicles (CVs) environment. However, fuel savings were only marginal at a penetration rate of CVs below 50%. In their study, Li et al. demonstrated that under automated car-following scenarios, the application of a pulse-and-gliding (PnG) controller could offer up to 20% savings in fuel compared to a conventional linear-quadratic (LQ)-based controller [88]. Other field tests and simulation studies have also shown that various types of adaptive cruise controller (ACC) and cooperative adaptive cruise controller (CACC) vehicle control algorithms could significantly reduce fuel energy consumption [89–92].

Zohdy and Rakha designed a controller equipped with CACC that can guide the optimum course of vehicles in the context of the urban road intersections network [93]. The study compared the fuel consumption for their system with various intersection geometries, and noted that on average, 11%, 45%, and 33% fuel saving were obtained compared to conventional intersection control approaches of a roundabout all-way-stop and traffic signal, respectively. In their studies, Kamalanathsharma, and Rakha; Asadi and Vahidi, and Ala et al. reported that the CACC that uses vehicles to infrastructure (V2I) communication to optimize vehicle trajectories in the vicinity could lead to a reduction in a fuel energy saving of about 47%, 30%, and 19%, respectively [94–96]. A recent study conducted by Manzie et al. also reported that a road-vehicle environment where vehicles can exchange traffic flow information via inter-vehicle communication and sensors could achieve about 15–25% savings in fuel consumptions [97]. They further stated that this number could reach as high as 33%, depending on the amount and quality of traffic information that they can process and exchange.

Similarly, in another study, Wang et al. observed that a higher penetration rate of intelligent vehicles equipped with a longitudinal vehicle controller was associated with lower NO_x emissions in a congested platoon [98]. Bose and Ioannou reported that a fleet containing only 10% ACC-equipped vehicles could lower NO_x emissions by 1.5% CO and CO_2 emissions by up to 60% [99]. Choi and Bae examined the CO_2 emissions profiles for manual and CVs under lane changing operations [100]. The study found that CVs can lead to 7.1% less CO_2 emission, while lane change can maneuver faster to a slower lane. Likewise, lane change operations for CVs from a slower to a faster lane were associated with around 11.8% CO_2 emissions benefits. Fagnant and Kockelman conducted a larger-scale agent-based study. They replicated a mid-sized city scenario where nearly 3.5% of the total trips on a given day are undertaken by shared AVs [71].

These researchers observed that autonomous vehicles could have a significant positive effect on reducing various pollutants (i.e., SO_2, CO, NOx, volatile organic compounds (VOC), PM10, and GHG). VOCs and CO emissions were reduced the most, mainly due to the lower frequency of the vehicle's cold start. Effects on the particulate matter with a diameter less than 10 mm (PM10) and GHG were comparatively insignificant due to the need for additional trips that shared vehicles have to make to pick up and drop off passengers from different locations. However, it is worth mentioning that this simulation study was limited by the assumptions that automated vehicles in the fleet are not essentially powered by electricity, hybrid-electric, or running on alternative fuel and passengers would not make trips more frequently. The long-term effect of automated vehicle-related emission reduction could realize a very optimistic level, as indicated in a study by Greenblatt and Saxena that estimated the emission of shared electric autonomous taxis. The study found that the GHG reduction per vehicle per mile in 2030 could be 87–94% less than the emissions of gasoline-based internal combustion vehicles in 2014 and 63–82% less compared to hybrid-electric vehicle emissions in 2030 [101].

Brown et al. also predicted considerable energy-saving up to 91% per automated vehicle in 2030 in a framework that accounted for the highest impact of energy-saving factors (e.g., efficient travel, electrification and optimized vehicle weight) and increased energy use (e.g., increased travel distance by dependent traveler) [35]. However, the factors and to what extent they will offer emission benefit in the future remains an open question. As a result, the trade-off between energy savings and increased energy use from automated vehicles might fluctuate substantially.

Few studies have also argued that the benefit in emission reduction by AVs could be fully offset by increased travel, due to lower costs involved in travelling. A study by Taiebat et al. used microeconomic modeling and applied econometric techniques to analyze the travel and energy impacts of CAVs with respect to the price of fuel and travel time [102]. While increased fuel economy in CAVs reduces the amount of energy required per mile traveled, it also decreases the cost of travel, encouraging additional travel and leading to an energy "rebound effect." The elasticities of VMT demand with respect to fuel and time costs were estimated using the developed microeconomic model under income and time constraints. The forecasted travel demand for a typical household was estimated to increase by 2–47%. Numerous plausible scenarios involving changes in fuel economy and time costs resulted in an overall increase in energy consumption. In higher-income quantiles, backfire is more likely as the reduction in time cost is less appreciated in this class, only to offset the energy savings from CAVs. On average, a 38% reduction in time costs completely offsets a 20% increase in fuel economy provided by CAVs. Numerous researchers have also pointed out that the higher penetration of automated vehicles may actually increase the vehicle fleet number and contribute to the rise of GHGs in the environment [103]. The burgeoning number of automated on-demand mobility or ride-hailing services may lead to an enlargement of the number of vehicles in the fleet, increased VMTs and road congestion, and thereby increased fuel consumption and GHG emissions.

Synthesizing the result of all the previous studies, some charts could be developed to better understand and visualize the results of the level of GHG decrease or increase. The first graph (Figure 3) shows the factors that will increase emissions, while others are for the factors that will reduce the emission (Figure 4). In the last chart, Figure 5 demonstrates the result ranges for all research studies.

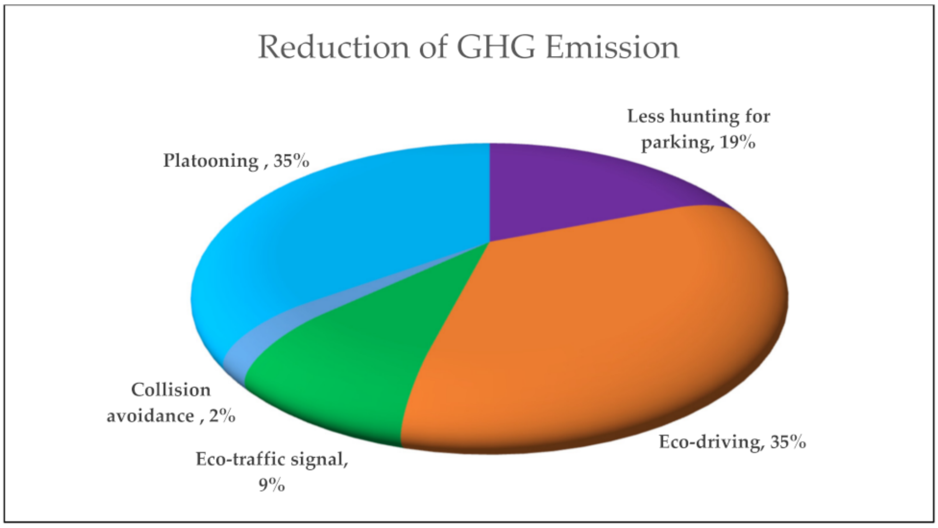

Figure 3. Average contribution of the causes on GHG emission reduction.

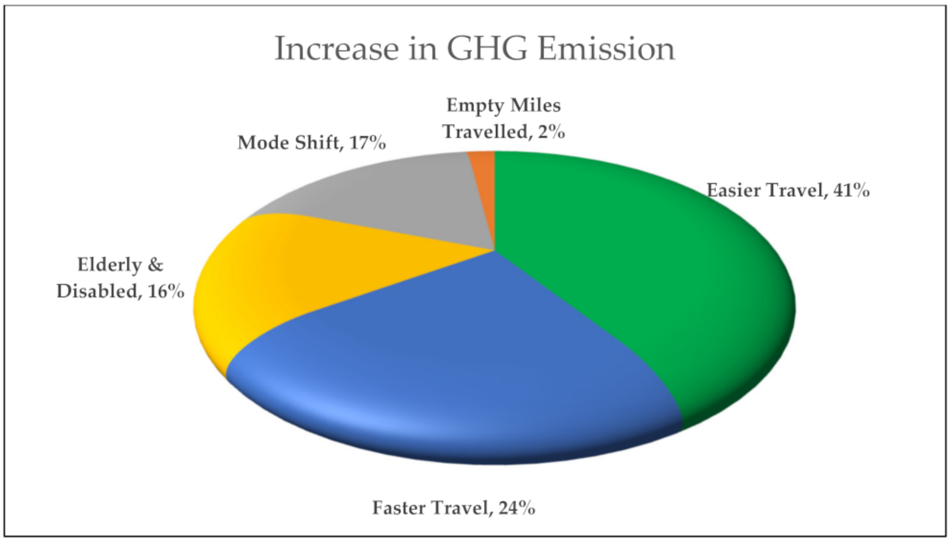

Figure 4. Average contribution of the causes on GHG emission increase.

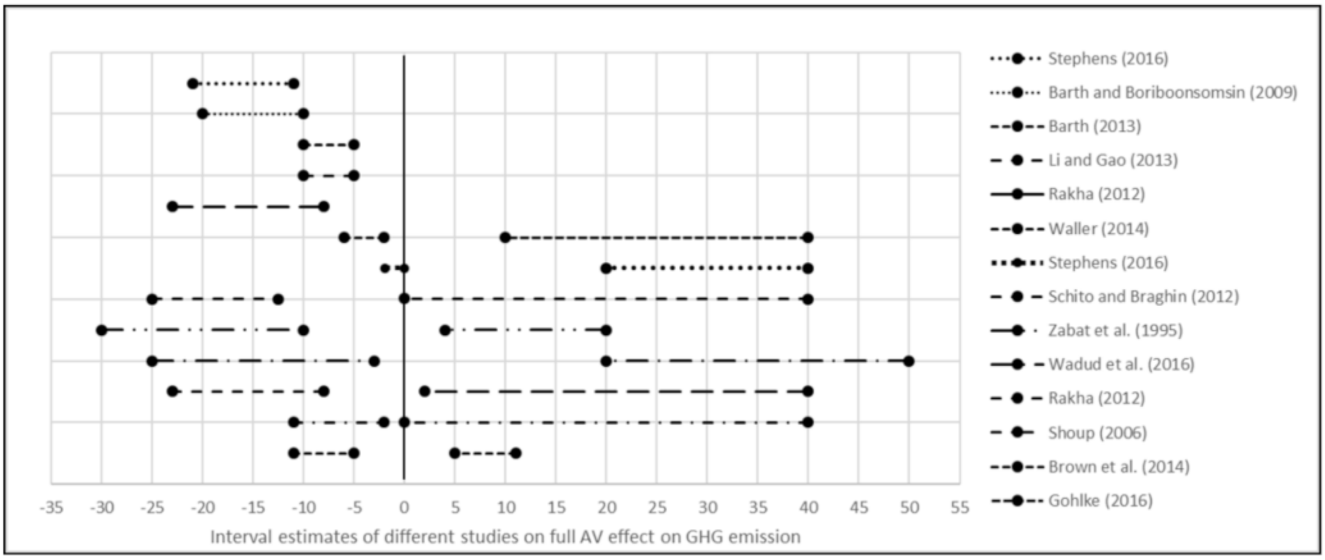

Figure 5. Interval estimates of different studies on full AV effects on GHG emission.

6.1. Causal Loop Diagram (CLD) of the AV's Effect on GHG Emission

In transport studies, system dynamics have been applied, as the feedback and connections provided by these models are useful for defining interactions of variables within the transport system. Shepherd provided a review of the different system dynamics modeling approaches used in transport systems [104]. In his study, he mentioned that the causal loop diagram (CLD) is the primary technique used to analyze the qualitative relationships between various aspects of the system within system dynamics modeling. CLD is a helpful tool to explore possible sources of dissent to strategies, synergies, and repercussions within the system. Such prospects will then help identify potential problem statements that can be addressed by quantitative modeling. A CLD illustrates how important variables of the system interrelate with each other by using text, arrows and symbols. Arrow running from the "cause" to the "effect" with a polarity represents the interaction between two variables, known as a causal connection. A positive polarity indicates that deviations in the "causal" variable would result in deviations in the "effect" variable in the same direction, assuming all other influences remain constant in the system. Similarly, a negative arrow shows that changes in one variable cause the other to change in the opposite direction, given that all other conditions are fixed.

The feedback loops created by the causal relationship are termed as balancing (B) or reinforcing (R) based on the polarity sign, which represents positive or negative feedbacks, respectively within the system [105].

A CLD is developed based on the literature to depict the interactions of different root causes and variables with the GHG emissions from AVs (Figure 6). The CLD starts with the gradual penetration or increased market share of AVs within the transportation system. This system dynamic model assumes that both the non-AVs and AVs use fossil fuel for power generation. Since the AVs are fuel-efficient, there is a substantial chance that the demand for AVs increases, with all its benefits in terms of traffic safety, operation, and management. However, since the AVs are expected to offer several benefits to the transport system, the introductory retail price of it might be some fold higher than the conventional non-AVs. A higher retail price of AV will impart a negative effect on AV's market share.

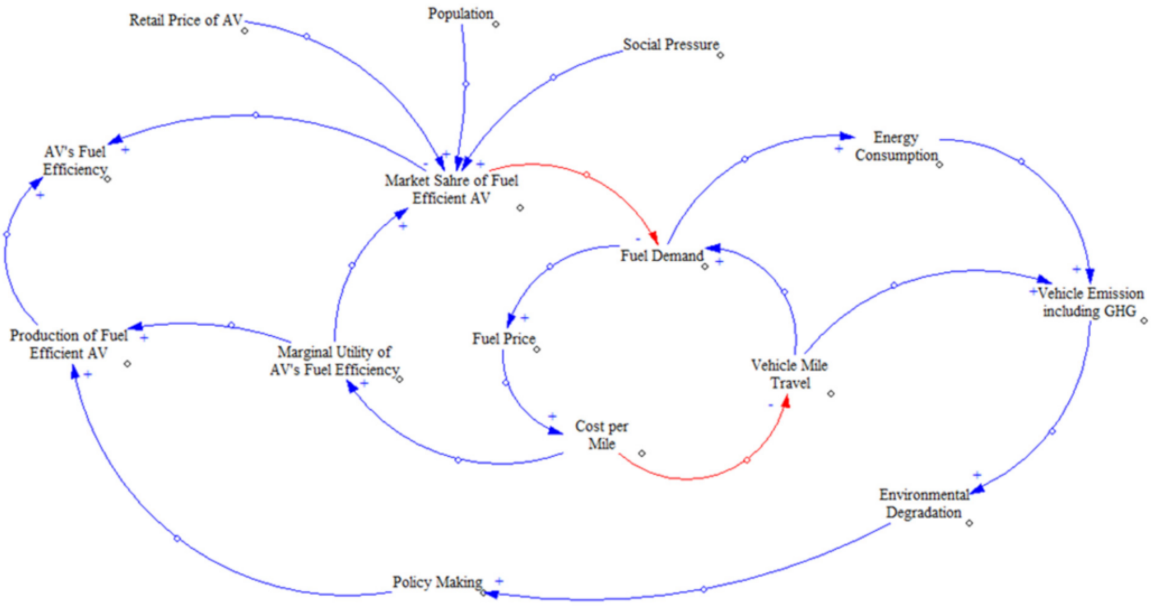

Figure 6. Causal Loop Diagram of the influence of fuel-efficient AVs on GHG emissions (inspired by [106,107]).

Nevertheless, the increase in population and social pressure to purchase AVs will positively affect the AV's penetration rate to the market. In this context, it is predicted that the number of cars in the city will increase as the population increases, causing road congestion as well. Congestion reduces the efficiency of automobile engines, contributing to increased fuel consumption and leading to higher rates of pollution [107]. An increased market share of fuel-efficient AVs will reduce the fuel demand as a whole. The reduced fuel demand initiates a balancing loop; a shortfall of demand will push the fuel price to increase and increase travel cost per mile, only to be balanced by less miles traveled. The price of gasoline is a wiggle that can play either in favor or against AVs. As observed today, gasoline prices have not prevented the ownership and use of fossil fuel vehicles (FFV) in general, but if prices go up, FFV use could fall as people move to more affordable choices, given the limited nature of petrol resources. However, an increase in the cost/miles travel will observe fuel-efficient AVs' marginal utility as people will enjoy the added benefit by buying an additional AV unit.

A reinforcing loop will also generate fuel demand. In the event of increased demand, energy consumption will also escalate, giving rise to vehicle emission or GHG emission. Implementing pollution reduction policies that cause environmental degradation should be balanced in this loop, though there is a delay in this cycle that prevents it from performing as planned. The mounting pressure on policy regulation to control the environmental degradation will possibly deter the growing AV production. More capital is expected to be invested within the automobile industry to make the AVs more fuel-efficient.

6.2. AVs Potential Impact on Reducing GHG Emission during a Global Pandemic

On 30 January 2020, the World Health Organization (WHO) announced the respiratory coronavirus disease outbreak 2019 (COVID-19) and subsequently, on 13 March, declared a global pandemic. While government policies in most countries reduced mobility, travel also declined in response to the number of local cases in the respective country. This shows how people adapted their travel behavior depending on the level of information available on the outbreak. Not only did people restrict their travel, but destinations were often avoided that had more infected cases. The automotive and transport industries are closely observing how consumer behavior changes will impact AV technologies in key aspects of the economy and daily life, given that numerous changes have been imposed upon people's daily lives due to the global COVID-19 pandemic.

COVID-19 is overhauling the consumer's perceptions towards public transit in ways that are likely to support AV technology in the longer run. As the pandemic has spread across the world, people have generally remained home, either by choice or by local directives. Hence, transit ridership has declined substantially, barring essential and emergency support workers. Major cities like New York, Washington, D.C., and San Francisco of the US have seen the ridership plummeted by a staggering 70–90% in August 2020 compared to the same time in the previous year [108]. While the decrease in ridership is attributed to home-based work, the closure of educational institutes, and local travel bans, consumers have become more interested in personal motor vehicle ownership than ever before. While the potential car customer might be putting new purchases on hold, McKinsey's recent survey reported that "20 percent of people in the United States who do not possess a vehicle under their name, now considering buying one" [108]. This group mainly includes people who live in cities and rely on public transportation for mobility. While the customer demands for new and used cars may have temporarily postponed adopting AV systems in the consumer sector, the COVID-19 pandemic per se warranted the important role of AV in day-to-day business and, most importantly, to deal with the risks posed by COVID-19.

Over the past decade, the automotive industry has had to adapt to changing attitudes to mobility, with global car ownership predicted to peak in 2034 before beginning its decline. However, with many still reluctant to use public transport due to the risk of infection, the prospect of owning a car may seem more inviting in the context of the unprecedented COVID-19 pandemic. This change in attitudes towards mobility is already evident in the adoption of micro-mobility solutions, while some have predicted that autonomous vehicles, capable of driving with some to no human input, may see an acceleration in terms of development, deployment and public interest. With industrial activity forced to slow down, flight and car journeys decreasing, greenhouse gas emissions around the world have plummeted. Consumers will get used to these changes, which is likely to see an increase in the adoption of autonomous vehicles in the future. These new vehicles are meant to be fuel-efficient, affordable, clean and green and a natural feature in smart cities and interactive communities—and will forever change the future of mobility. One of the key barriers to autonomous vehicle rollout is public perception, with a 2018 survey by OpenText revealing that 52% of consumers would not buy a driverless car. However, the COVID-19 pandemic may have contributed to changing attitudes. When weighing up the risk of COVID-19 infection presented by public transport or shared mobility, it is possible that the public will look more favorably on driverless cars. The current pandemic has had a significant impact on transport demand and mode, with a shift away from shared mobility, and in particular public transport, because of worries over public health.

7. Conclusions

Net effects of vehicle automation on emissions across a variety of illustrative examples show that automation could theoretically reduce GHG emissions and energy usage plausibly by almost half—or double-fold—depending on the implications that would come to the fore [22]. It is believed that reductions in GHG emissions through AVs' adoption will be negated to an unascertained extent, mainly due to increased car travel, facilitated by other factors such as lower perceived travel time and costs per km/trip, probable loss of public transport patronage, and possible increases in car ownership. Thus, it is quite possible that AVs could be more energy-efficient, thereby reducing the GHG by functional unit-basis as per-passenger-mile (ppm); however, the overall gain related to transportation GHG emissions could be swamped by a surge in increased vehicle miles traveled (VMT).

The effect of AV adoption on consumer travel patterns could be more pronounced from environmental aspects rather than technical attributes. While it is challenging to accurately estimate the behavioral fronts to AV adoption, a more tangible consideration of the relationship between different AV adoption models and anticipated travel behavior is vital for estimating AVs' environmental impacts. It may be argued from the discussion presented herein that if AVs are deployed within less approbatory areas or if the road transportation sector is continued to be dominated by privately owned vehicles, it is likely that AVs may escalate the transport-related GHG emissions. Hence, adoption tendencies like vehicle ownership models are also expected to largely influence whether AVs will decrease or increase the overall VMT as well as the subsequent GHG emissions. Few studies have indicated that the positive emission changes may not be realized at lower AV penetration rate, where the maximum emission reduction might take place within the 60–80% AV penetration rate.

Impacts of autonomous vehicles on GHG emission are highly dependent on continuous technological development and evolution, market reaction, and regulatory actions, making it challenging to confidently predict the overall benefits expected to deliver by AVs to the transportation systems in terms of GHG emission. With long-term land-use adjustments, the role of policy, welfare and equity yet to be explored and the potential effects of AVs remain unknown; it is unlikely that we can anticipate long-term effects on GHG emission with certainty. Moreover, the overwhelming COVID-19 global pandemic has also posed challenges to some of the well-perceived mode choice models, which may force the policymaker to adopt suitable mobility alternatives that ensure public health and safety. Therefore, it is of paramount importance to develop appropriate methodologies, tools, and techniques to better understand the impact of GHG emissions for AV adoption at different levels by harnessing an appropriate system approach.

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