



## Multidimension Analysis of Autonomous Vehicles: The Future of Mobility

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### Abstract

The level of investment in AVs technology has been increasing over the years as both researchers and developers are cooperating with the objective of developing AVs and understanding their behaviors and implications. Despite the enthusiastic speculation about AVs, little is known about the implications of AVs on our lives and the intertwined relationships between the implications. Thus, the main objective of this paper is to reveal the benefits and risks of AVs and sketch out the main trends in this area in order to provide some directions and recommendations for the future. This study focuses on analyzing the impact of AVs on the required fleet size, vehicle utilization, cost of mobility, public transit service, public behavior, transportation network, land use, economy, environment, society, and public health. Furthermore, the paper analyzes the intertwined relationship between the implications of AVs. Additionally, the paper sheds light on the potential benefits and challenges of the deployment of AVs in developing countries. The analysis shows that while AVs offer multiple benefits, they also pose new risks. The degree to which AVs can affect our plant mainly depends on regulatory actions, as the broader implications of AVs are mainly dependent on how the technology will be adopted, which can be controlled by regulatory actions.

**Keywords:** Autonomous Vehicles; Economy; Environment; Public Health; Society; Transportation Network.

### 1. Introduction

The idea of vehicle automation has always been a source of interest to researchers in the history of transportation. One of the early attempts in the way for vehicle automation was the vehicle-to-vehicle communication system that was first proposed and discussed in 1920 [1]. This was followed by the invention of the electromagnetic guidance system that is used for vehicle guidance in 1930. In the 70s, the main focus was devoted to the idea of smart highways that were based on the magnets added to the vehicles [2]. 1980 was a turning point in the transportation engineering field the first autonomous vehicle was invested as a result of the partnership between Mercedes-Benz and the Bundeswehr University in Munich [3]. This invention opened the way towards thinking of other aspects and dimensions of AVs, such as the legislation adoption, the ethical issues, and the social impacts. Additionally, this invention has motivated a large number of companies to invest in autonomous vehicle technology [4]. In general, there are six levels of automation as defined by the National Highway and Transportation Safety Administration, starting from level 0, which refers to human-driven vehicles or no automation at all, to level 5, which refers to fully self-driving vehicles. In between, levels 1 to 4 refer to partial automation as follows: Level 1 refers to the automation of one control function, such as the lane-keeping assistance system, Level 2 refers to the automation of two control functions, Level 3 means that the vehicle is able to perform most of the driving tasks but human override is still required, and Level 4 refers to full automation but the driver is able to override the automation actions [5, 6].

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The level of investment in AVs technology has been increasing over the years as both researchers and developers are cooperating together with the objective of developing AVs and understanding their behaviors and implications [7]. Google was one of the early investors in AVs technology in 2009. The Google self-driving vehicle program was announced and targeted for 2020 as the testing year for AVs [8]. This was followed by the Uber-Volvo cooperation program that focuses on the development of AVs by 2020 [9]. Similarly, in 2014, Apple announced their own automation program, called "Project Titan," that focuses on the development of AVs by 2023 [10]. Additionally, new startup companies have been launched with the objective of developing AVs or providing some of the automation services. Zoox is a startup company that was launched in 2014 with the objective of developing AVs. The company's market value has steadily increased over the years, and in 2018, the value of Zoox reached 3.2 billion dollars [11]. In parallel, cities all over the world started testing AVs, and many cities allowed the deployment of AVs on their roads [12, 13]. The main objectives of these pilot programs are to understand the behavior of AVs and test the public's attitude towards this new technology. Despite the enthusiastic speculation about AVs, little is known about the implications of AVs on the environment and society. Thus, the main objective of this paper is to reveal the benefits and risks of AVs and sketch out the main trends in this area in order to provide some directions and recommendations for the future.

The paper is structured as follows: Section 2 presents the methodology used in this study, while section 3 shows the main motivation and objectives of this study. Section 4 analyzes the impact of AVs on the different aspects investigated in this study. Section 5 discusses the main benefits and challenges of the deployment of AVs in developing countries. Finally, section 6 summarizes the main outcomes of this study and provides some recommendations for future research.

## 2. Research Methodology

This paper focuses on reviewing papers that focus on studying the implications of AVs on the transportation network, public behavior, land use, environment, society, and public health. The methodology followed consists of five main tasks. The first task in the planning tasks and it focuses on identifying the keywords that should be used to find the paper and identifying the databases and search engines that will be used to find the papers. The keywords used were: "Implications of automated vehicles", "autonomous vehicles", "self-driving cars", "road capacity and automated vehicles", "autonomous vehicles and society", "autonomous vehicles and economy", "autonomous vehicles simulation", "agent-based autonomous vehicles", "autonomous mobility", and "shared autonomous vehicles". Additionally, the databases and search engines used were: "Scopus", "Web of Science", "ScienceDirect", "Springer", "IEEE Xplore", and "TRID". The second task in the methodology was the search tasks and in this task the keywords identified during the planning stage were used to search for papers in the databases and search engines identified. The third process is identifying the inclusion criteria and this task focuses on setting the criteria that should be followed in order to review the papers found during the search process. In this study, only papers and reports in English from 2010 onwards were included. The fourth task is the screening process, and this task focuses on screening the papers and during this process the abstract, keywords, and conclusion were revised in order to make sure that the paper address one of the topics studied in this paper. Finally, the fifth task that focuses on reporting, analyzing, and presenting the review results was carried out to reveal the implication of AVs. Figure 1 summarizes the methodology process followed in this study.

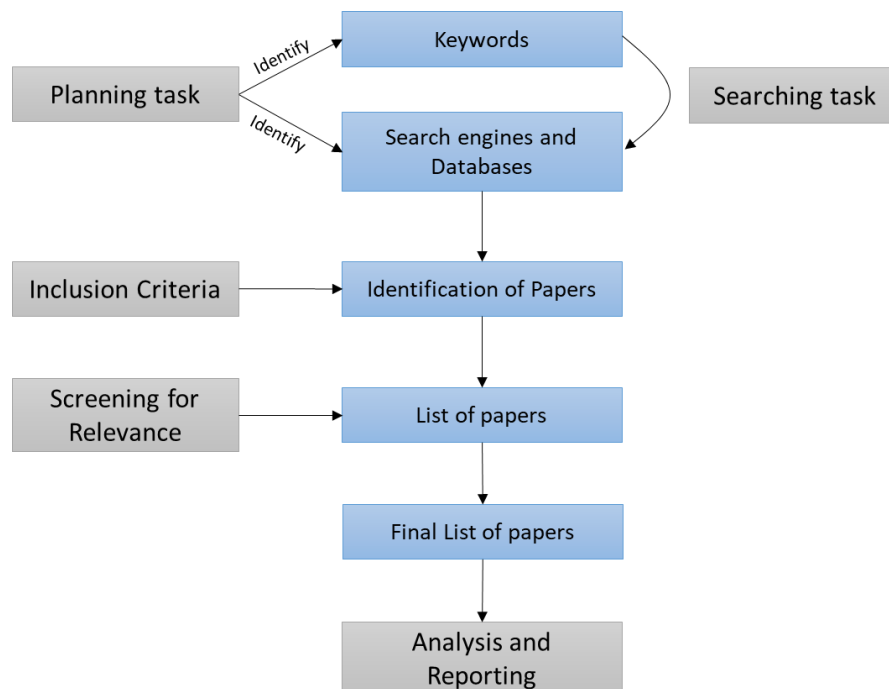


Figure 1. Research methodology followed in this study

### 3. Motivation and Research Objectives

Over the last few years, a large number of researchers devoted their focus to understanding and studying AV in different fields, and studying the implications of AVs is not an exception. A large number of simulation studies that focus on quantifying the implications of AVs can be found in the literature; however, a holistic view of all these studies is still missing. Although some review papers that focus on understanding the implications of AVs can be found in the literature as summarized in Table 1, those papers focus on analyzing the implications of AVs on one branch or aspect and ignore the impact on the remaining aspects, which might be misleading. The main reason that causes this issue is that there are intertwined relationships between the implications of AVs across different branches (see Figure 18), which necessitate the need for a holistic review that considers analyzing AVs across different branches. As a result, this paper focuses on providing a comprehensive review that holistically studies the implications of AVs across different branches and reveals the intertwined relationships between these different branches. Specifically, this paper focuses on studying the implications of AVs on the transportation network, public behavior, land use, environment, economy, society, public health, and the benefits of deploying AVs in developing countries. This comprehensive review offers the ability to understand the implications of AVs on new areas, that were not explored before, such as: the implications of AVs on public transit service and the possible competition between AVs and public transit, the potential benefits of AVs in developing countries, and the associated challenges, and the benefits of AVs in pandemics and the impact of the current pandemic (COVID-19) on the public attitude towards AVs technology. Additionally, the paper summarizes the key benefits and risks of AVs and reveals the intertwined relationships between the implications of AVs.

**Table 1. Selected AVs review papers and their scope**

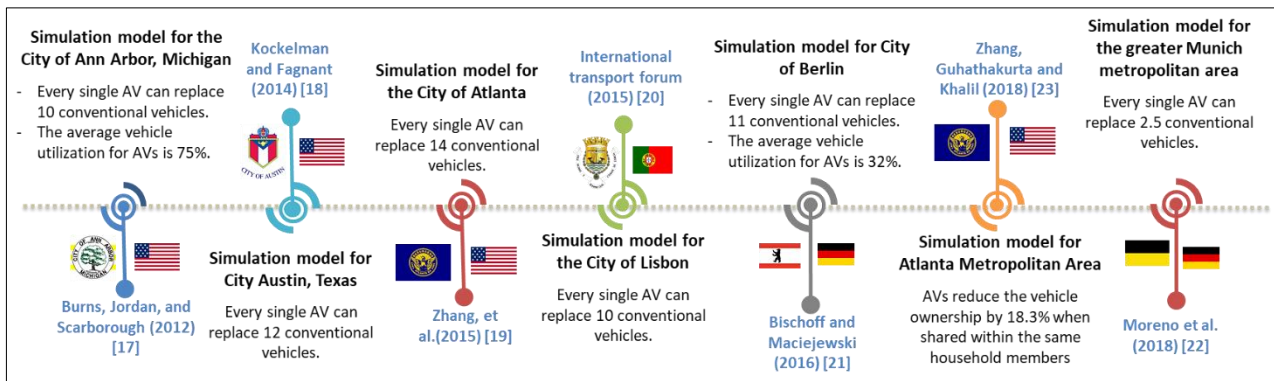
Study	Scope
Narayanan et al. (2020) [104]	Implications of shared AVs on multiple branches
Kopelias et al. (2019) [105]	Environmental impact of AVs
Spence et al. (2020) [106]	Implications of AVs on the public behaviour
Sohrabi et al. (2020) [107]	Implication of AVs on the Public Health
Hao and Yamamoto (2018) [108]	Implications of shared AVs on the public behaviour
Gandia et al. (2019) [109]	Scientometric and bibliometric review of AVs
Peng et al. (2020) [110]	Scientometric and bibliometric review of AVs
Faisal et al. (2019) [111]	Implications of AVs on the landscape
Rojas-Rueda et al. (2020) [60]	Implications of AVs on the public health
Sun et al. (2017) [112]	Implications of AVs on the travel behaviour and the current business models

In general, it is commonly known that the human factor contributes to a large portion of the accidents, and it is estimated that around 90% of the accidents occur as a result of the human error [14, 15]. Thus, as AVs can eliminate the human behavior from the driving task, it is expected that AVs can significantly improve traffic safety. However, the implications of AVs on the environment, society, land use, and public health are yet to be studied. As a result, the next sections will go into the detailed implications of AVs and the expected outcomes from the deployment of AVs.

## 4. Implications of AVs

### 4.1. Impact on the Required Fleet Size to Serve the Demand

The deployment of AVs will be associated with many changes. One of the major impacts of AVs is the impact of AVs on the required fleet size to serve the demand and the associated changes in the vehicle utilization. In general, it is expected that AVs can reduce the required fleet size to serve the same demand and this reduction will be associated with an increase in the vehicle utilization. Figure 2 summarizes the results of previous simulation models that show the impact of AVs on the required fleet size. The figure shows the methodology, simulation area, and results of these studies in an ascending order. The simulation studies show that AVs can replace more than 10 conventional vehicles when used as a shared mode as shown in the first five studies [17-21] in the Figure 2. This reduction in the fleet size will be associated with a significant increase in the vehicle utilization from 5% [16] to up to 75 [17]. However, the adoption of AVs as a private mode shows much lower impact on the fleet size as shown in Moreno, Michalski, et al. (2018) [22] study who built their simulation model based on the results of a stated preference survey that shows that 24% of the respondents are willing to share their trips in AVs. Similarly, the study by Zhang et al. (2018) [23] shows a minor impact on the fleet size as the simulation model used in this study was based on the assumption that AVs will only be shared between the same household members.

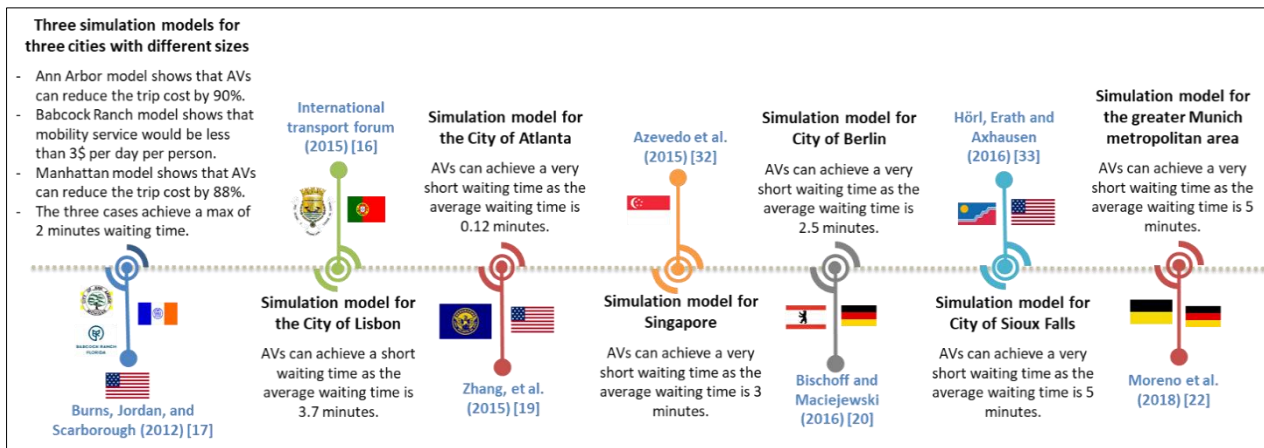


**Figure 2. Summary of the simulation studies showing the changes in the required fleet sizes to serve the demand**

As a result, it can be concluded that AVs have the potential to reduce the fleet size and this reduction mainly depends on the mode of the adoption of AVs. However, the major benefits can be achieved when shared AVs are used as the case of shared AVs will be associated with lower fleet size and higher vehicle utilization, which is beneficial to the society as it allows for the adoption of newer and greener technologies. Regulatory action is the major factor that can affect the impact of AVs on the vehicle ownership. For example, cities might take actions that allow only shared AVs to operate on the streets. Currently, multiple cities around the world allowed for testing autonomous shuttles only on their streets such as: Texas, Wageningen, Helsinki, Paris, Shenzhen, Sion and Edmonton in the USA, Netherlands, Finland, France, China, Switzerland, and Canada. The deployment of AVs as a shared mode of transportation achieves the maximum desirable benefits of autonomous vehicles. A real-life example for the potential impacts of AVs on the fleet size is the Singaporean scenario. In general, Singapore is considered the leading city in the adoption of AVs. The city allowed for the testing and deployment of different modes (buses and cars) of AVs since 2015 that more than 10 companies are testing and operating their vehicles on the streets of Singapore. In 2018, the vehicle ownership has reduced by 15% (in three years) as a result of the adoption of this new technology [24].

#### 4.2. Impact on Trip Costs, Waiting Time, and Possible Competition with Public Transit

As shown above, AVs have the potential to serve the same population with much lower fleet size. Thus, the implications of AVs on the trip costs and passenger waiting times should be analyzed. In general, passenger waiting time is a critical factor that affects the passengers' satisfaction of the service provided as people perceive their waiting time much longer than the in-vehicle travel time [25]. Multiple studies in the literature focus on understanding how people perceive their waiting time in the form of waiting time to in-vehicle time ratios. Starting with one of the early studies by Horowitz (1981) [26] who found that this ratio is 1.9 which means that 1 minute waiting is equivalent to 1.9 minutes of in-vehicle time. Then, in 2004, Wardman (2004) [27] found that this ratio can go up to 2.5. This was followed by Abrantes and Wardman (2011) study that shows that this ratio is 1.4 [28]. Thus, it can be concluded that the waiting time is a critical factor that has a significant influence on the commuters' satisfaction and on their selection of the traveling mode. Currently, it is estimated that the average waiting time in the USA and Canada is 40 minutes [29, 30] and 20 minutes [31] consecutively. Thus, any reduction in this waiting time will attract the commuters especially if this reduction is associated with a reduction in the average trip cost. Multiple studies in the literature investigate and quantify the average trip cost and waiting time for shared AVs in different cities across the world as summarized in Figure 3. The figure clearly shows that AVs have the potential to provide a low waiting time with low trip costs across the different simulation studies conducted in different cities. This reduction in the trip cost besides with the reduction in the waiting time is significantly lower than the trip cost and waiting time of public transit service across different countries as summarized in Table 2. The table shows the average trip costs and waiting times of both AVs and public transit, and the savings achieved with the deployment of AVs. Thus, it is expected that AVs can attract the commuters of public transit and in this case AVs will be a strong competitor to public transit service. As a result, it is expected that public transit might incur significant losses in the era of AVs and in the extreme case AVs might fully replace public transit and public transit agencies must be aware of the upcoming disruption.



**Figure 3. Summary of the simulation studies showing the expected trip cost and travel times of shared AVs**

**Table 2. Comparison between the expected waiting time and trip costs for AVs and the actual trips costs and travel time of public transit across different cities**

Study	City	AVs		Transit		Savings	
		Waiting time (min)	Cost (\$)	Waiting time (min)	Cost (\$)	Waiting time (min)	Cost (\$)
Burns et al. (2012) [17]	Ann Arbor	2	2\$ per day	40 [29, 30]	3\$ per trip [116]	38	4\$ (assuming two daily trips per person)
	Babcock Ranch	1	0.8	-	-	-	-
	Manhattan	1	1	13 [117]	2.75 [119]	12	1.75
International transport forum (2015) [16]	Lisbon	3.7	-	14 [118]	3.6 [119]	10.3	-
Zhang et al. (2015) [19]	City of Atlanta	0.12	-	40 [29, 30]	-	39.88	-
Azevedo et al. (2015) [32]	Singapore	3	-	8 [118]	-	5	-
Bischoff and Maciejewski (2016) [20]	Berlin	2.5	-	10 [118]	5.8 [119]	7.5	-
Hörl et al. (2016) [33]	City of Sioux Falls	5	-	40 [29, 30]	-	35	-
Moreno et al. (2018) [22]	The greater Munich metropolitan area	5	-	9 [118]	5.8 [119]	4	-

#### 4.3. Associated Changes in the Public Behavior

One of the main benefits that is frequently mentioned in the literature is the ability of the commuters of doing productive activities during tier trips and thus the trip time cannot be considered as an economic loss anymore [34]. While AVs can reduce the operating fleet size (which might reduce traffic congestion) as summarized in section 4.1, AVs might motivate people to make additional trips and travel further which worsens traffic conditions [35-37]. As a result, it is expected that AVs will increase the VKT, emissions [36], and energy consumption in the form of fuel for diesel engine vehicles [38]. As a result, multiple studies in the literature focus on quantifying the impact of AVs on the VKT, and these studies are summarized in Figure 4. The studies clearly show that AVs have the potential to increase the VKT; however, this increase changes significantly across the studies because every study has a unique operating strategy. Thus, it can be concluded that AVs will increase the VKT, but this increase mainly depends on the operating strategy adopted in the future. Additionally, it must be mentioned that all studies analyzed in this study and summarized in Figure 4 show that AVs will increase the VKT as a result of the adopted operating strategy and these studies do not take into consideration the expected induced demand or the expected increase in the trip length. This increase in the VKT besides with the expected increase in the VKT as a result of attracting transit users [37] (as mentioned in section 4.2) are expected to worsen the traffic conditions, significantly increase the VKT (even more than the increases shown in previous studies in Figure 4), emissions, and energy consumption. Thus, AVs might not be able to solve the congestion problem. In the contrast, AVs might worsen traffic conditions [39], increase the VKT, emissions, energy, and in turn destroy the environment. In this case, regulator action plays a major role to restrict these negative impacts of AVs on the environment by controlling the changes in the public behavior in the era of AVs. For example, AVs might be allowed only to support public transit service as a first mile-last mile solution.

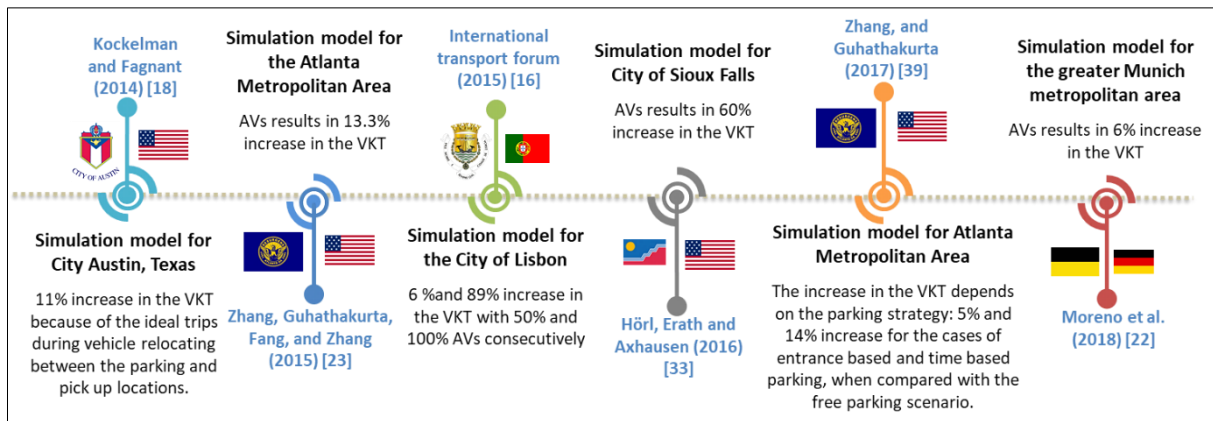


Figure 4. Summary of the simulation studies showing the expected changes in the VKT

#### 4.4. Implications of AVs on Capacities of Roads and Intersections

One of the main benefits of AVs is the high level of communication between the vehicles that makes it possible for the vehicle to travel in platoons with small a separating distance between the vehicles (distance ahead). This communication allows the vehicles to travel closer to each other or, in other words, AVs reduce the required lane width [40, 41] and increase the capacity of the transportation network. Figure 5 summarizes the results of previous studies that simulated AVs and shows the impact of AVs on both the intersection and road capacity. It can be clearly stated that AVs have the potential to significantly increase the transportation network. However, the main issue is that this capacity increase cannot be achieved until a high level of AVs penetration is achieved [37] because the human factor will always be the dominant factor that controls the traffic flow operations for safety reasons.

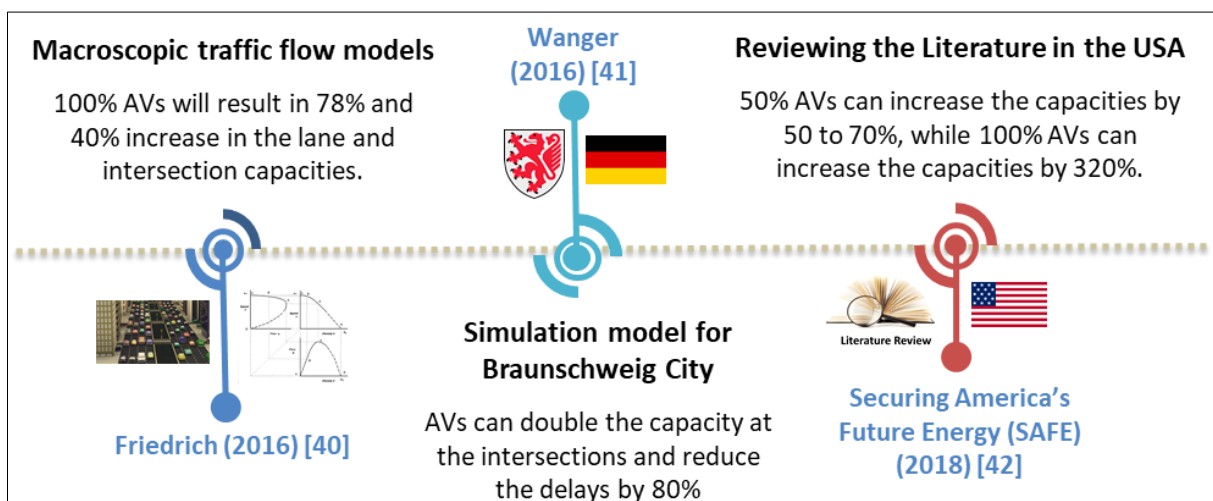


Figure 5. Summary of the results of previous studies analyzing the impact of AVs on the capacities of roads and intersections

#### 4.5. Impact on the Parking Demand and Parking Lots

It is expected that the influence of AVs will go beyond just changing the streets and can be extended into changing the neighborhoods, and the structure of cities. For example, AVs have the potential to significantly reduce the parking demand to serve the same population as summarized in Figure 6. Previous studies in the literature show that AVs will be associated with 80% to 90% reduction in the parking demand regardless of the location of deployment of AVs as shown in multiple cities in the USA, and in Lisbon, Portugal. This reduction in the parking demand can be translated into a dramatic reduction in the required parking spaces that free up new spaces for new development, which will be highly beneficial especially in CBD areas. It is estimated that utilizing the freed-up parking lots for other developments will increase the value of the land use. For example, the value of land use can increase by 5% when the parking lots are used in the real estate industry [38]. Similarly, it is expected that AVs will not rely on on-street parking as the vehicles will travel to the nearest parking lot after the completion of the trip, which in turn increases the available capacity in the streets for the running traffic. Moreover, the reduction in the parking demand will be associated with changes in the design of houses as the end house parking area will not be required and can be utilized for other activities. Additionally, it is expected that AVs will change the guidelines for the required dimensions for every parking space for every vehicle.

In general, the required parking dimension will be reduced and increase the capacity of parking lots by 20% or more. Additionally, AVs will change the current parking strategy as vehicles will be able to block each other. The blocking strategy besides with the reduction in the parking dimensions means that AVs can significantly increase the capacities of parking lots to 2.5 of the capacity in the case of traditional vehicles [42, 43]. Additionally, the reduction in the parking demand will develop a more environmentally friendly transportation system as this can reduce the congestion and energy consumed in the process of searching for a parking lot [37, 44].

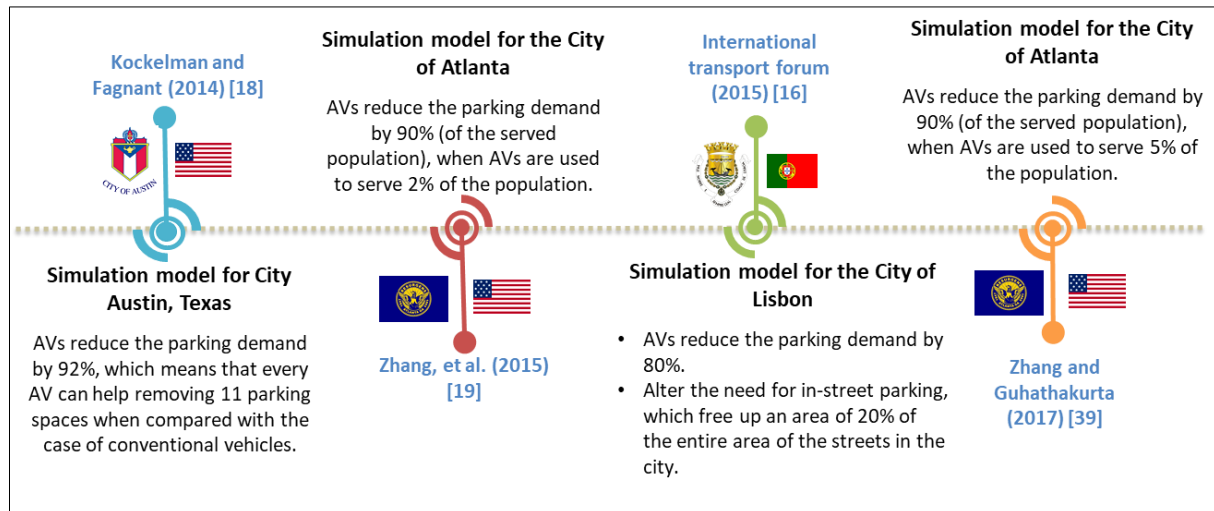


Figure 6. Summary of the simulation studies showing the changes in the parking demand and the required parking spaces

#### 4.6. Implications of AVs on the Environment

In general, transportation is considered the main source of pollution across different countries. For example, the share of transportation emissions is 29% and 25% of the total greenhouse gas emissions in the USA and Canada [45, 46]. Out of this 25%, it is estimated that around 72% of the total emissions come from road transport and 44% of this 72% comes from cars or the running vehicles on the streets [47]. Thus, it is crucial to search for a sustainable transportation system that and some of the previous environmental studies show that AVs have the potential to reduce the emissions consumed from the transportation system as summarized in Figure 7. AVs have the potential to reduce the energy consumed and transportation emissions because of multiple factors such as the platooning that allows from saving 15-20% of the energy consumed [14, 35, 38], and the smooth driving that allows for 15% reduction in the transportation emissions and fuel consumptions. Finally, AVs open the way towards the application of the optimal traffic assignment of AVs, which focuses on reducing the vehicle total travel time across the entire network and thus saves more fuel and reduces the produced traffic emissions.

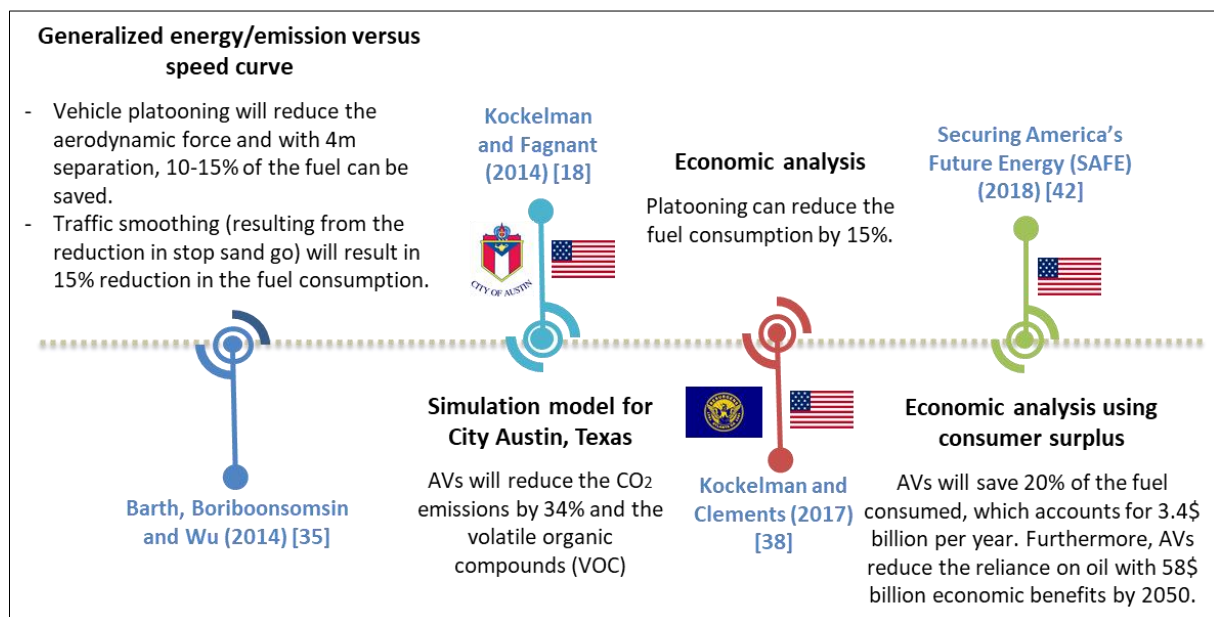


Figure 7. Summary of the simulation studies showing the impacts of AVs on the emissions and fuel consumption

#### 4.7. Implications of AVs on the Economy

The implications of AVs are expected to influence different aspects of the economic system and business companies that are unable to adapt to this change will incur significant losses. In general, it is expected that the economic value of AVs will be huge and increase over time while opening new business opportunities and professions. Figure 8 summarizes the results of previous studies that analyzed the impact of AVs on the economic systems. In general, the economic value of AVs comes from their ability to reduce the human error and improve traffic safety by 90%, the increase in the land use value as parking lots can be used for other developments, and the new business opportunities created.

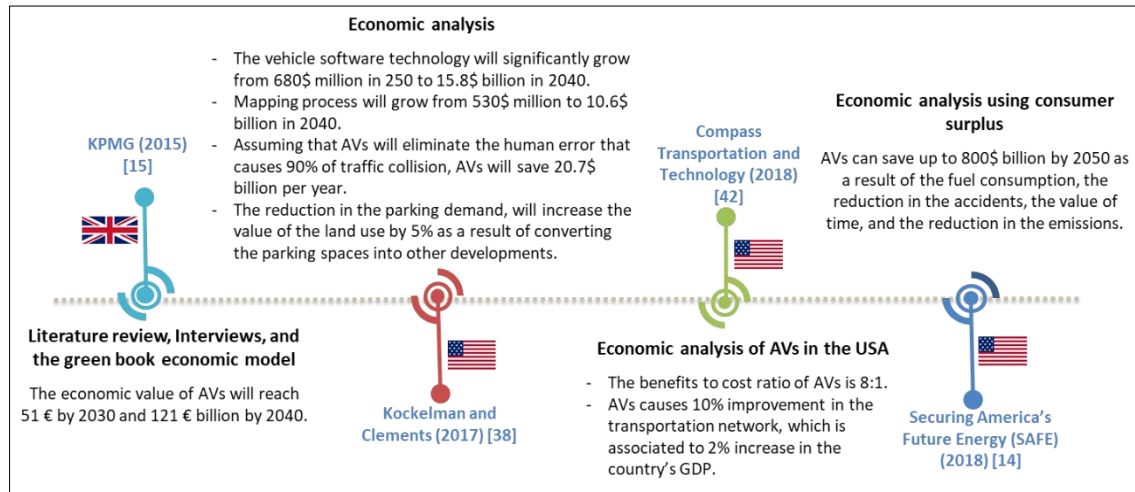


Figure 8. Summary of the results of previous studies analyzing the impact of AVs on economies

#### 4.8. Impacts on the Equity

While AVs have the potential to improve equity, AVs might pose new equity concerns. Figure 9 summarizes the impact of AVs on equity. For example, AVs can improve the accessibility for people with limited transportation modes, AVs might replace the truck drivers and add new concerns for people with lower educational levels. A detailed discussion on the equity impacts of AVs is shown in Figure 9.

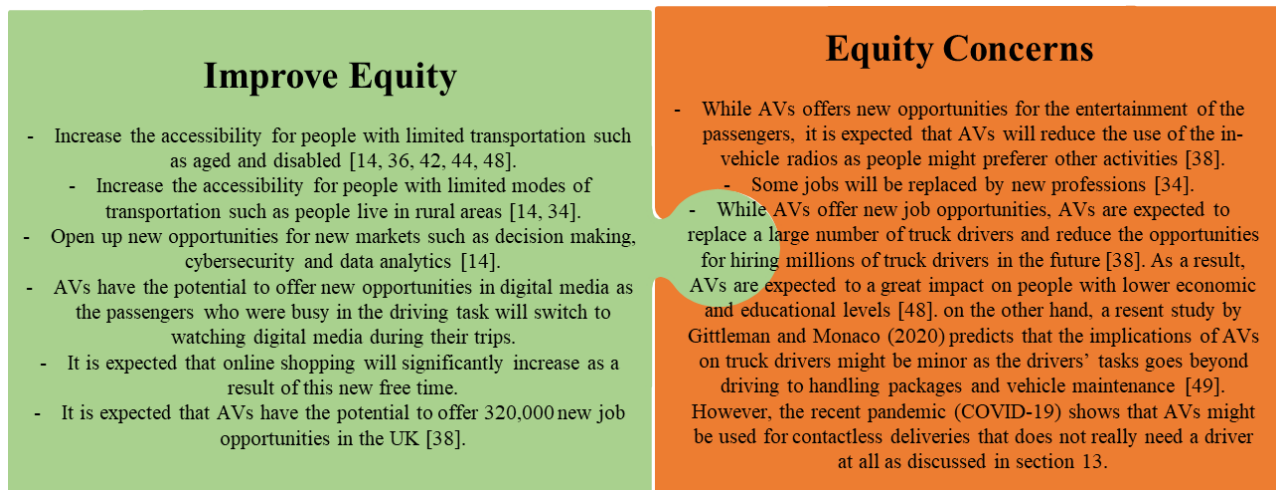


Figure 9. Summary of the implications of AVs on the equity

#### 4.9. Impacts of AVs on the Public Health

In general, AVs technology can be considered as a double aged weapon. While AVs have the potential to improve the public health and save lives as a result of the reduction in the collision rate, AVs might pose new risks to the public health such as increasing the levels of pollution and sedentarism. The extent to which AVs might be beneficial or harmful mainly depends on how AVs will be adopted in the future. For example, the adoption of diesel engine AVs will be different from the adoption of electric AVs. As a result, Figure 10 shows a detailed discussion of the impact of AVs on the public health with focus on the following branches: impact on the physical activities, air pollution, noise, stress, substance abuse, and the level of exposure to electromagnetic fields.

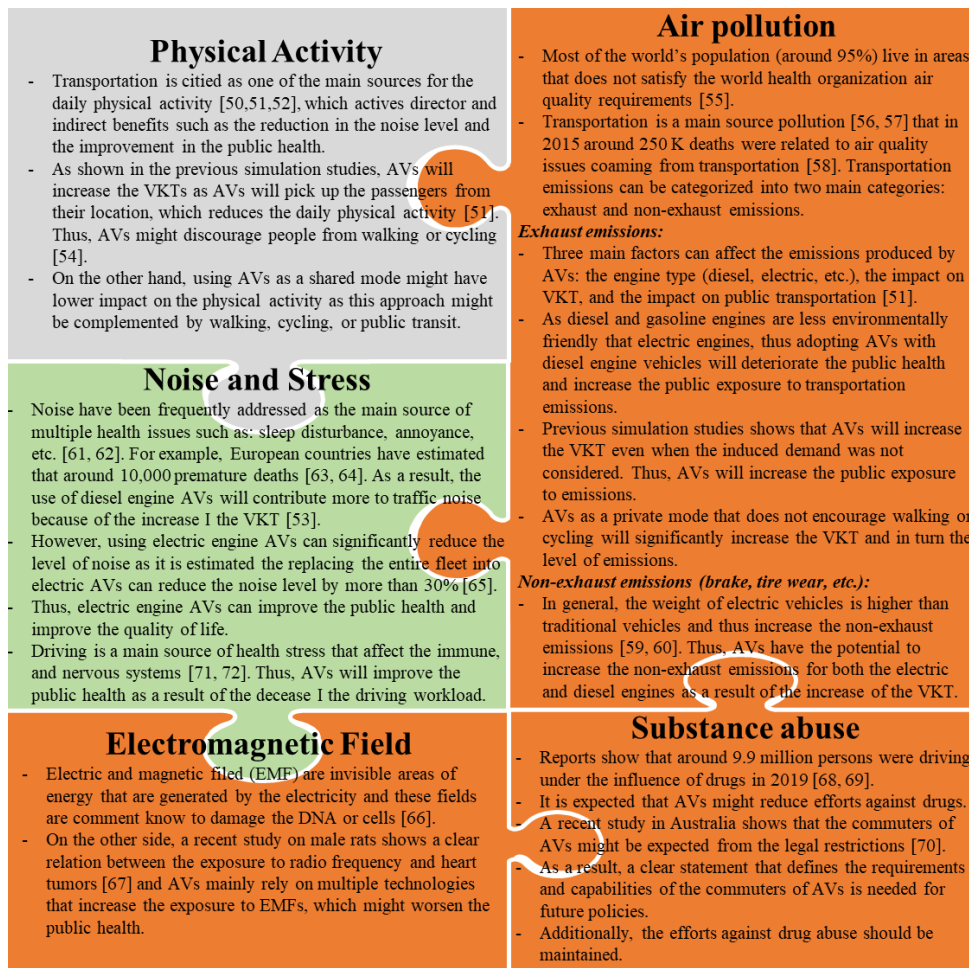


Figure 10. Summary of the impacts of AVs on the public health system

#### 4.10. Potential Benefits of AVs during Pandemics

The current pandemic forced people to change their lifestyle and adapt to new conditions. While COVID-19 have forced most of the pilot studies of AVs across the world to be halted, it is generally expected that this pandemic might be a turning point that intensifies the effort towards the development of AVs because AVs have proven their value during the current COVID-19 pandemic [73, 74]. The expected benefits of AVs during pandemics are summarized in Figure 11 and it can be seen that AVs have been used in multiple countries for the delivery process to reduce the contact between the public and control the spread of the virus. As a result, it can be concluded that AV technology is a major tool that can be used to fight pandemics in the future.

### 5. The potential Benefits and Possible Challenges of AVs in Developing Countries

The entire discussion till the moment focuses on developed countries and the implications of AVs in developed countries. This section sheds more light on the potential benefits and expected challenges of AV in developing countries. In general, rare studies focuses on studying AVs in developing countries and the main focus of these studies is analyzing the public attitude towards AVs. However, the expected benefits or the challenges of AVs in developing countries are yet to be addressed. As a result, this section analyzes the public attitude towards AVs and sheds light on the possible benefits and challenges for AVs in developing countries.

#### 5.1. International Surveys (Developing Countries vs. Developed Countries)

One of the key studies that internationally analyzed the public attitude towards AVs is the study by Kyriakidis et al. (2015) [79] that utilized an internet-based survey to collect 5000 responses from 109 countries across the globe. The result of the survey shows that people from developing countries are more optimistic towards AVs. On the other hand, respondents from developed countries highlighted that the main concern that pushes them from adopting AVs is data transmission. Figure 12 shows the relation between the levels of comfort in data transmission across the different countries with different GDP levels. The main factor that creates this difference in the level of comfort in data transmission is the perceived level of threat, which is much high in developed countries as these countries have more sophisticated computer infrastructure and witnessed multiple data misuse cases for some of the widely known companies

such as Google cases [80, 81] and Facebook cases [82, 83]. In the contrast, traffic safety is the main concern in developing countries and it is expected that traffic fatalities will be the fifth reason for death by 2030 [84]. Thus, it is expected that people from developing countries are more concerned with the basic needs which are represented as the need for safety, according to Maslow's hierarchy of needs [85]. This need makes data transmission a lower concerning issue and increases the level of comfort with data transmission in developing countries.

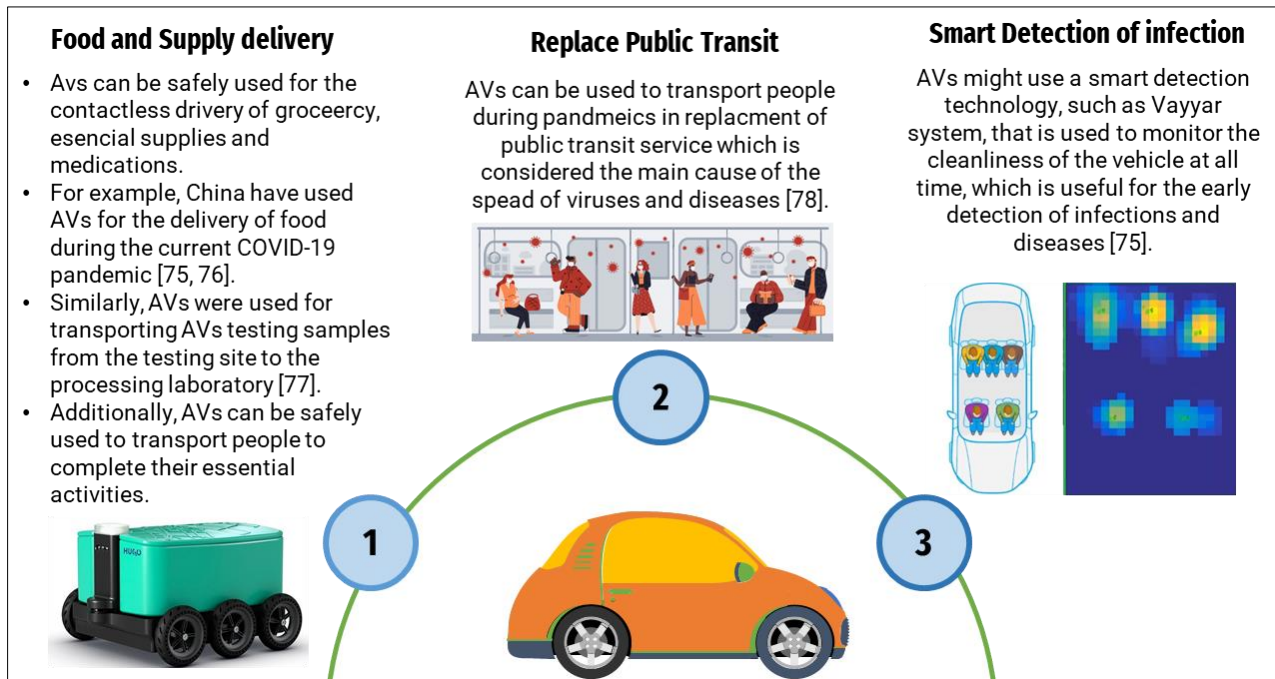


Figure 11. Summary of the benefits of AVs during pandemics

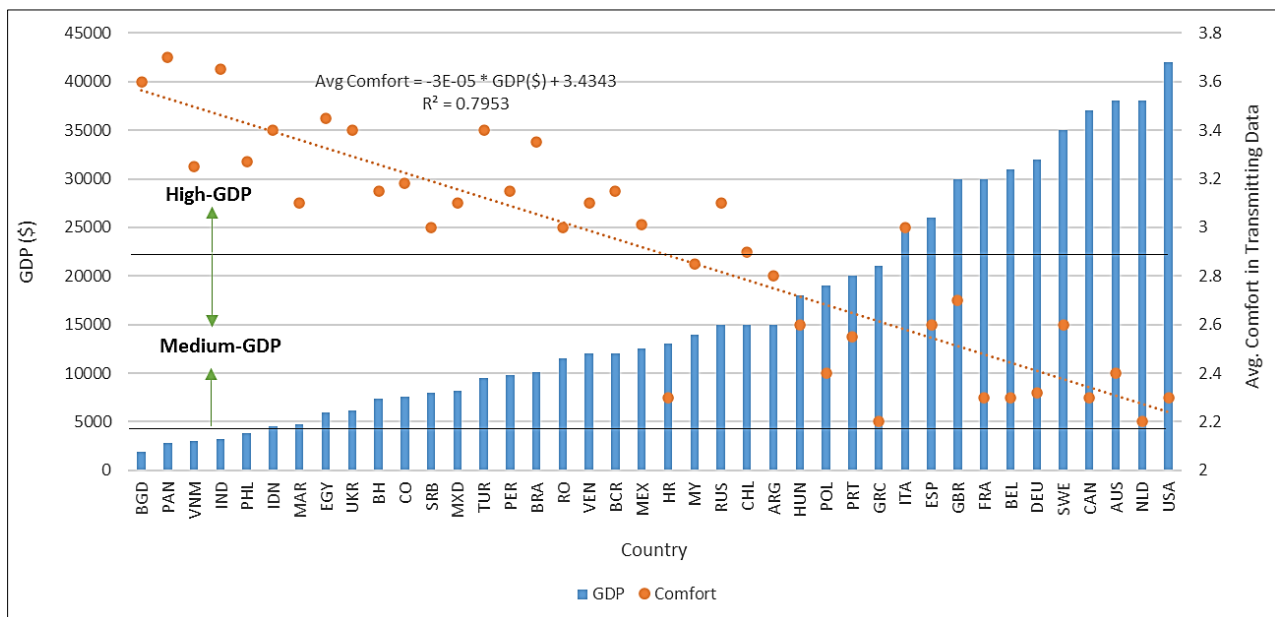
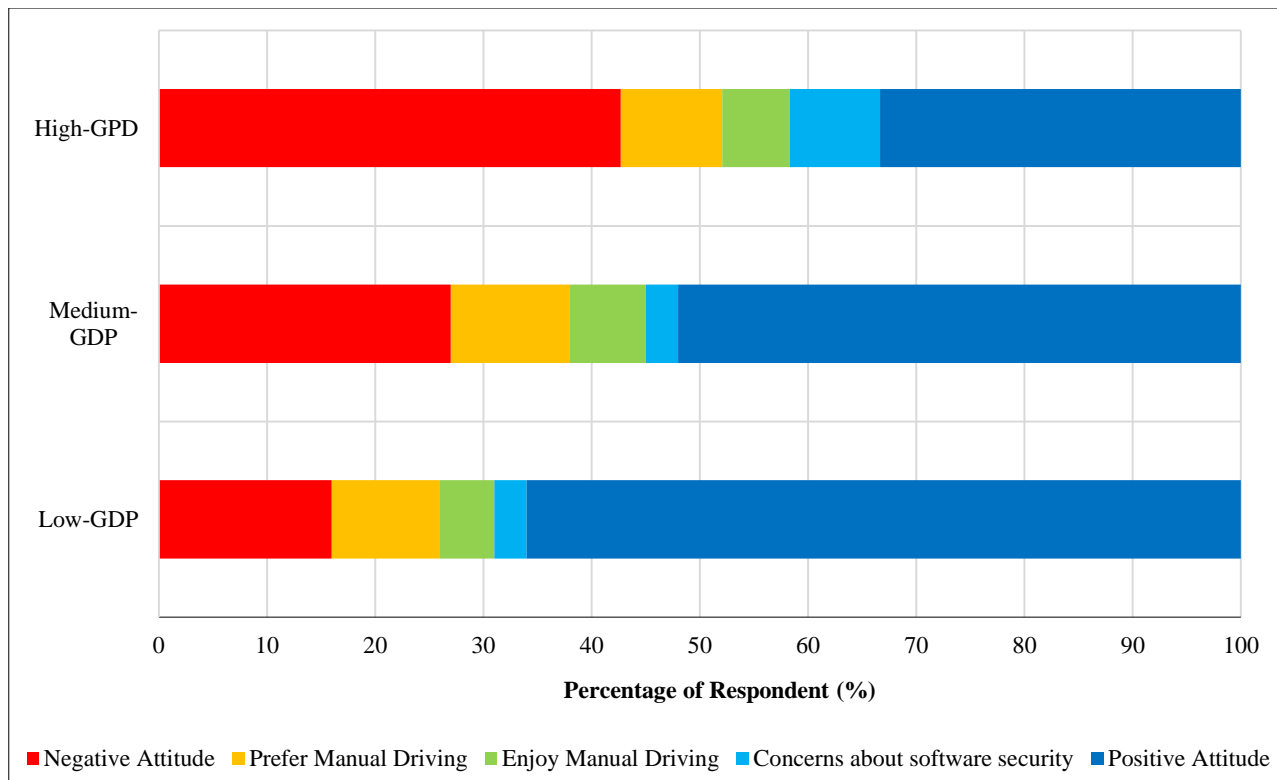


Figure 12. Relationship between the levels of comfort in data transmission across different countries with different GDP levels

Similarly, the study by Bazilinskyy et al. (2015) [86] confirmed the results presented in the study by Kyriakidis, et al. (2015) [79]. The study by Bazilinskyy et al. (2015) [86] focuses on understanding the level of acceptance of AVs across different countries based on an internet-based survey that managed to collect the responses of around 9000 respondents from 112 countries. The analysis conducted in this study was based on categorizing the GDPs into three GDP levels (high, medium, and low) as shown in Figure 13. The figure clearly shows that most of the respondents from high GDP countries prefer manual driving than people from medium and low GDP levels as 68%, 48%, and 34% of the respondents from high, medium, and low GDP levels prefer manual driving.



**Figure 13. Public attitude towards AVs across different countries with different GDP levels**

Additionally, the study by Moody et al. (2019) is considered the most recent international survey with the largest sample size. Around 40,000 respondents from 51 countries completed this survey. The results of this survey are consistent with the results of the previous two international surveys discussed above. The results show that although respondents from developed countries are more familiar with AVs technology, they are less optimistic towards AVs adoption [87] as shown in Figure 14. Additionally, the results of these three surveys are consistent with the results of other recent studies, such as Shafique et al. (2021) survey study [88], and Escandon-Barbosa et al. (2021) survey [89], that focus on analyzing the public attitude towards AVs in developing countries.

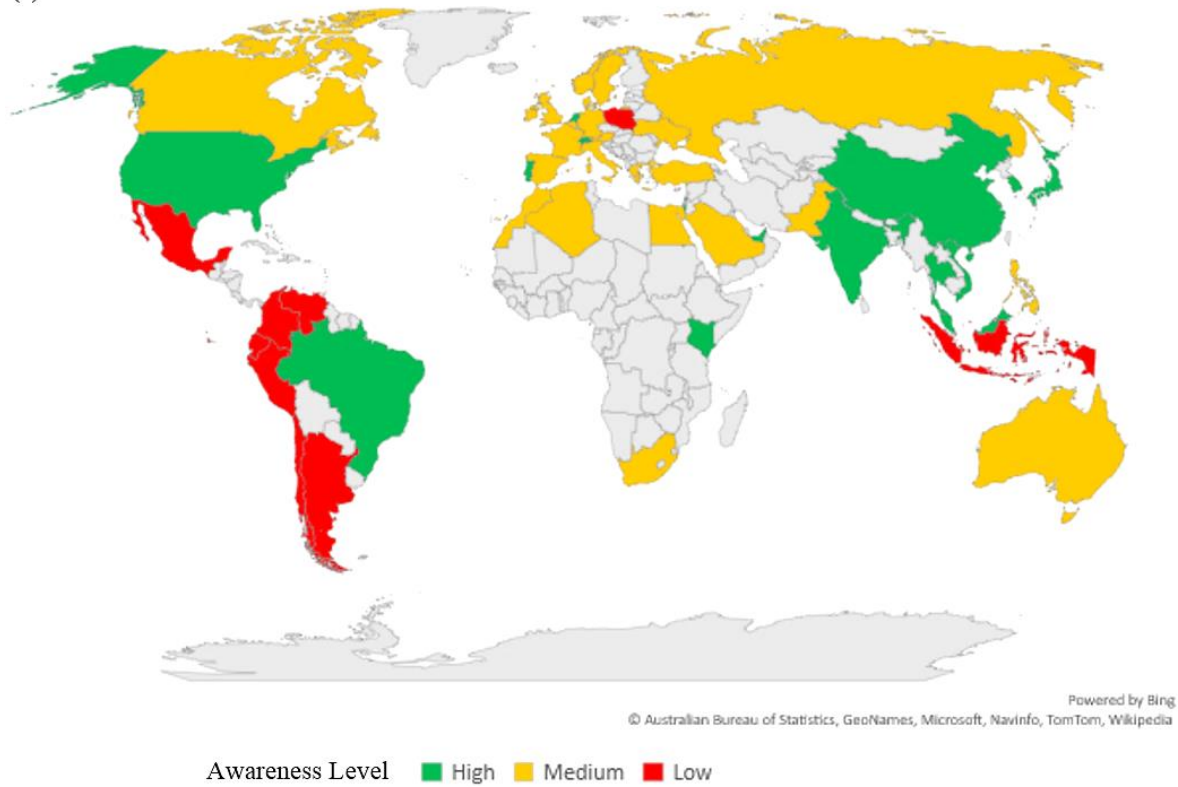
## 5.2. Motivation for the Deployment of AVs in Developing Countries

It is commonly known that the level of fatal accidents is much higher in developing countries than in developed countries. It is estimated that by 2030 fatal traffic collisions will be the fifth source of deaths in developing countries [84]. In general, the human factor is the main source that causes most of the traffic accidents and the impact of this factor increases or becomes more severe in developing countries [90]. Thus, the elimination of the human factor in AVs will save the lives of many people, especially in developing countries. Additionally, the above discussion in section 4 shows that AVs have the potential to reduce the required fleet size, reduce emissions, and pollution, which offer a healthier quality of life for people in developing countries. As a result, it can be concluded that the implication of AVs will be greater in developing countries than in developed countries. Additionally, besides this significant potential for AVs in developing countries, the level of acceptance of AVs is much higher in developing countries than in developed countries, which makes developing countries a suitable environment for the early adoption of AVs. However, AVs might face a large number of issues in developing countries starting from poor infrastructure that might represent a major obstacle in the adoption of AVs. The next subsection will shed light on the infrastructure challenges that will face AVs in developing countries.

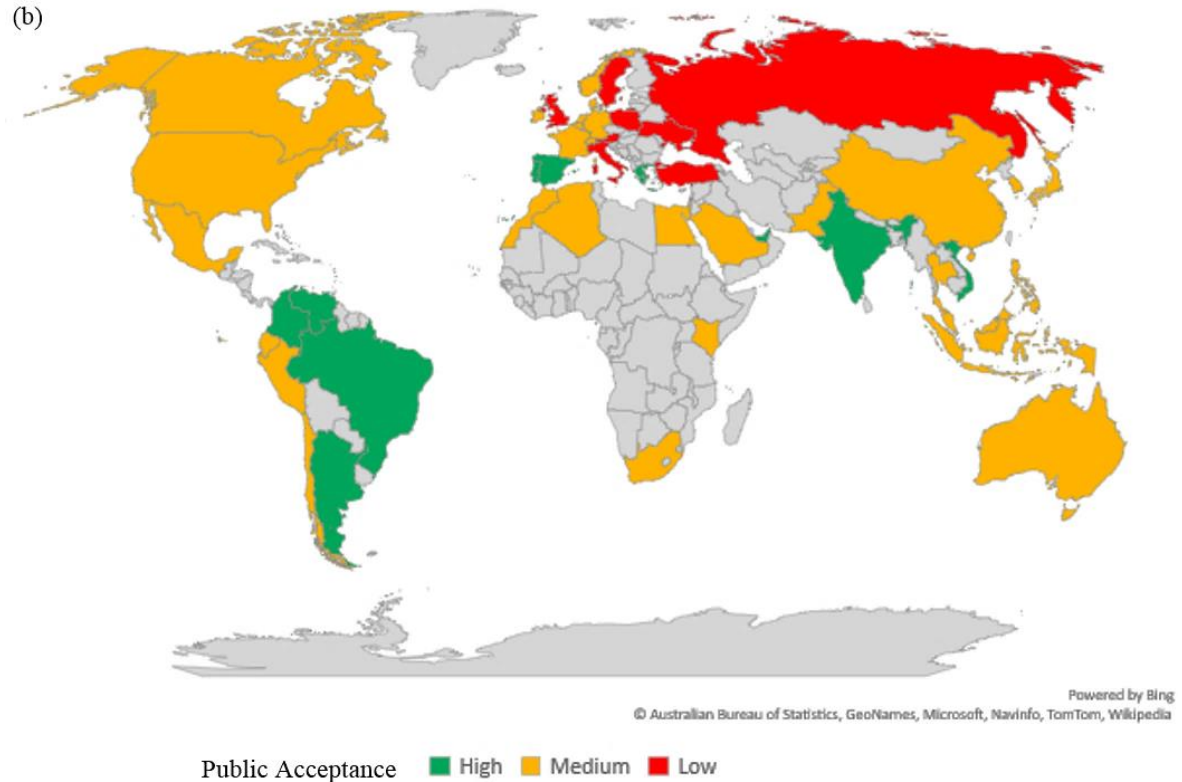
## 5.3. Infrastructure Barriers for the Safe Navigation of AVs in Developing Countries

While the level of acceptance of AVs is high in AVs, the infrastructure will be challenging for AVs to safely navigate and operate on the streets of developing countries. The main issue that will face AVs are the poor signage and marking systems, traffic management in the case of traffic incidence, parking management, securing safe harbor areas, and traffic heterogeneity. Figure 15 shows a detailed discussion on these main barriers and their implications on the behavior of AVs.

(a)



(b)



**Figure 14. Summarization of (a) the level of awareness and (b) public attitude towards AVs across different countries with different GDP levels**

### Traffic Management

- Accurate road mapping are essential for the safe routing of AVs [98]. However, the stochasticity nature of traffic incidents besides with the maintenance work change the layout of the road and locations where the vehicles can safely operate. Thus, the accurate mapping might not be enough for the detection of the incidents' location [99]. Although there are some communication methods in developed countries to sending some information to the incident location, there is no such communication in developing countries.
- Even more complex, it is hard to communicate accurate on-site information to the vehicle [100].
- Thus, the real time accurate information will create a new challenge that faces AVs in developing countries.

### Parking

- Previous simulation studies show that AVs can reduce the parking demand and in turn the number of required parking spaces [15, 100]. Additionally, the valet parking system allow the vehicles to block each other as the vehicles will be able to park close to each other. Thus, the parking lot will be able to serve larger number of AVs than conventional vehicles.
- However, the parking system in developing countries might be challenging. Firstly, the need for remote control of the vehicle is essential might expose the vehicle to cybersecurity issues and attacks. Secondly, the remote parking system requires an electronic payment system that is not supported in developing countries. Thirdly, most of the parking lot are privately owned and have inconsistent marking system that confuse the vehicle. Finally, most underground parking lots have weak or no GPS signals that does not support the safe navigation of the AVs [101].

### Traffic Heterogeneity

- Although AVs have the potential to significantly increase the transportation network capacity (both lanes and intersections), the lane capacity is significantly reduced by heterogeneity traffic as shown in Figure 16 as in developing countries [102]. In this case, both motorized, non- motorized and even pedestrians use the same traffic lanes generating a haphazard system that reduce the capacity of the transportation network [103]. This heterogeneous traffic creates new challenges that will confuse the vehicle's navigation system

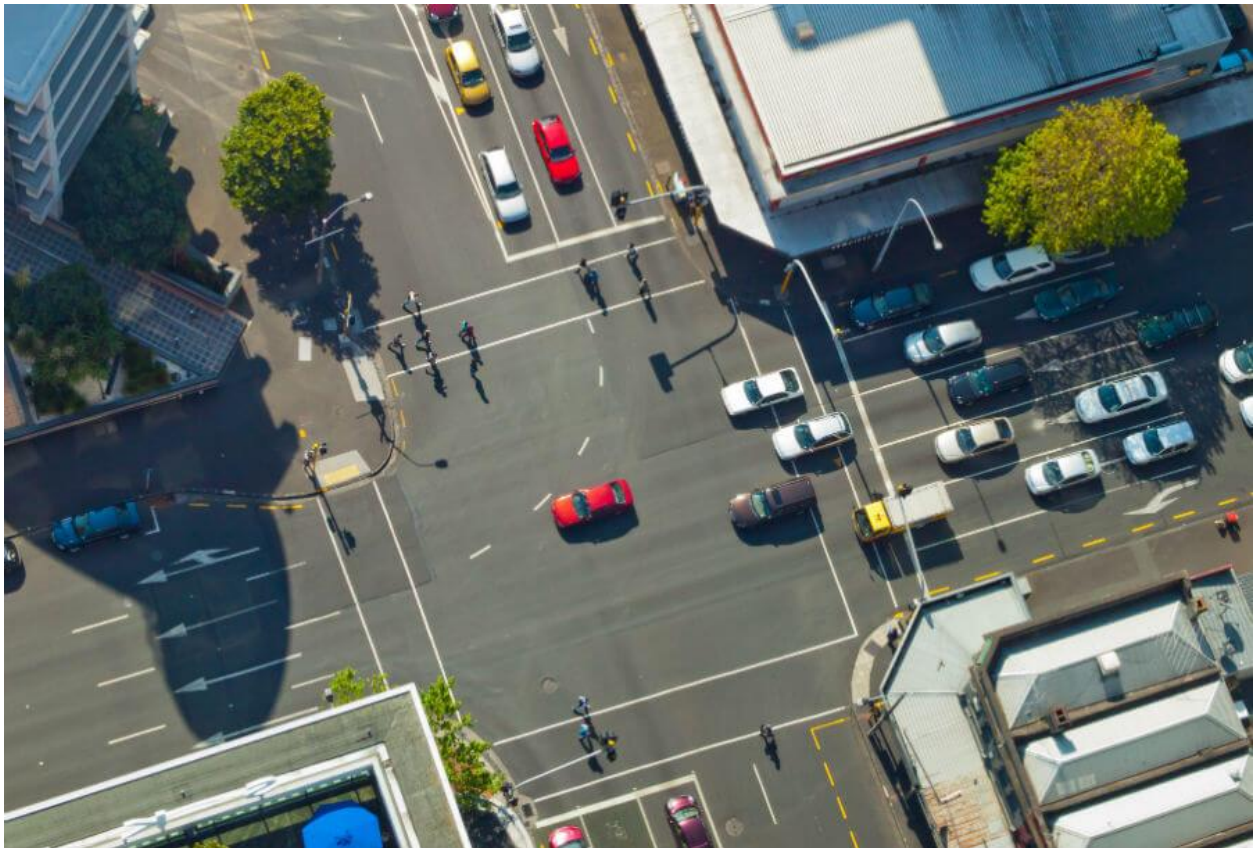
### Road Signs and Marking

- The safe navigation of AVs mainly rely on the image processing technique that requires high visibility of curves, marking, and signages [91, 92, 93]. AVs developers have frequently mentioned that the current signage and marking techniques in developed countries doesn't support the safe navigation of AVs [94, 95].
- In developing countries, the issues of marking and signs appear in a more aggressive way. For example, the study by Huq et al. (2021) [96] shows that the required marking for safe AV navigation are missing. For example, the study shows that the lack of pedestrian marking, stop lines, lane and edge marking will confuse the navigation system of AVs. thus, it is challenging for AVs to safely navigate in such an environment.
- Another main challenge is the inconsistent signage system in developing countries. Road signs are essential to send information to the drivers in a standardized way. In general, the standard color, size, font, etc. are essential for the safe traffic operations even for human drivers.
- Historically, the signage standard changed but most signs have not changed to create inconsistent signage system in the streets. As a result, this signage system is challenging for an AV to safely navigate on the streets [21, 97].
- Additionally, most roads in developing countries do not have the minimum required signs for the safe navigation of human drivers or AVs.
- Similarly, the obscured signage is another issue that add more challenges for the safe navigation of AVs. For example, signs might be obscured partially or fully because of vegetation, or other roadside infrastructure.
- Finally, most intersections in developing countries are not supported with traffic signals which create heterogeneity that confuses AVs

### Safe Harbor Area

- In the era of AVs, the drivers will be engaged in other activities, which introduces new challenges when the vehicle asks for human interaction (but the driver is busy) in the case of malfunctioning or harsh environment. In these scenarios, the vehicle will need a safe area while waiting for the driver's interaction. In developed countries, the shoulder might be used as safe harbor area for the vehicles [99, 102]. However, in developing countries, the shoulder is usually used to serve the running traffic, which makes it an unsafe area to be a safe harbor area.

Figure 15. Detailed analysis of the main challenges for the safe navigation of AVs in developing countries



(a) Homogenous Traffic at an intersection



(b) Heterogeneous traffic at an intersection

**Figure 16. Two main traffic patterns (a) Homogenous and (b) Heterogeneous**

## 6. Conclusions and Recommendations for Future Research

Vehicle automation has always attracted researchers, starting from the invention of the vehicle communication system in the 20s to the invention of the AV in the 80s. Over the last few years, significant efforts have been made by both researchers and developers with the objective of developing AVs. Despite the enthusiastic speculation about AVs,

little is known about the implications of AVs on the environment and society. Thus, this paper reviews previous studies in the area of AVs with the objective of revealing the benefits and risks of AVs and sketching out the main trends in this area to provide some directions and recommendations for the future. The analysis shows that while AVs offer multiple benefits, they also pose new risks, as summarized in Figure 17. Additionally, Figure 18 shows a map of the intertwined relations between the implications of AVs. The main outcomes of this paper can be summarized as follows:

- AVs can serve the same population with a much smaller fleet size, which will increase the vehicle utilization factor.
- For the case of shared AVs, the mobility costs or the trip costs will be significantly low and with low waiting time, which might attract public transit users. Thus, transit agencies will suffer in the era of AVs, and they should get ready for this disruption.
- In the era of AVs, trip time will not be considered an economic loss anymore as commuters will be able to benefit from this time in productive activities.
- AVs have the potential to increase the capacity of parking lots and reduce the parking demand by 80 to 90%. The combined effects of these two factors will free up parking spaces that can be used for other developments and increase the value of the land use.
- AVs will allow vehicles to travel in platoons, reducing the number of engine starts and reducing the sharp driving behavior, which reduces the energy consumed and emissions produced.
- AVs will have a significant impact on the economies and these impacts will go beyond just the reduction in the number of accidents or traffic-related impacts. For example, AVs will open up new business opportunities in a variety of fields such as: decision making, artificial intelligence, and data analytics. On the other hand, AVs might replace truck drivers and reduce the opportunities for hiring thousands of drivers.
- AVs increase accessibility for the aged and disabled. However, it must be mentioned that while it is assumed that the aged will be the early adopters of AVs technology, surveys show that the aged are the most pessimistic category towards AVs [113-115]. Thus, there is a contradiction between the two theories that needs deep analysis and further research to understand. Similarly, while it is assumed that the disabled will be among the early adopters of AVs, little is known about this category. Thus, further research studies are needed to understand the attitude of the disabled towards AVs technology.
- The impact of AVs on public health is unclear as it depends on multiple factors, such as the type of engine used for AVs (diesel, electric) and the mode of adoption (shared, shuttles, private). However, the analysis shows that while AVs pose some risks, such as the increase in the level of pollution and the reduction of daily physical activity, AVs will also offer some benefits, such as a reduction in stress and noise.
- During pandemics, AVs can be safely used for delivery purposes, and transport people to their essential activities while maintaining isolation and sterilization to control the spread of the infection or virus.
- While traffic safety is a major issue in developing countries, AVs can save a large number of lives because of the elimination of human error, which is the major cause of accidents. Thus, the benefits of AVs in developing countries might be greater in developing countries than in developed countries. However, the implications of AVs for developing countries have yet to be tackled. For example, no simulation study can be found in the literature for analyzing the expected implications of AVs in developing countries. Thus, further research studies are required to quantify the impacts of AVs on developing countries. On the other hand, AVs face multiple challenges that need to be addressed before the deployment of AVs, such as: poor signage and marking systems, traffic management in the case of traffic incidence, parking management, securing safe harbor areas, and traffic heterogeneity.
- Regulatory action is the main factor that determines to what extent AVs can affect our lives and our plants, as the broader implications of AVs mainly demand how the technology will be adopted, which can be controlled by regulatory actions.

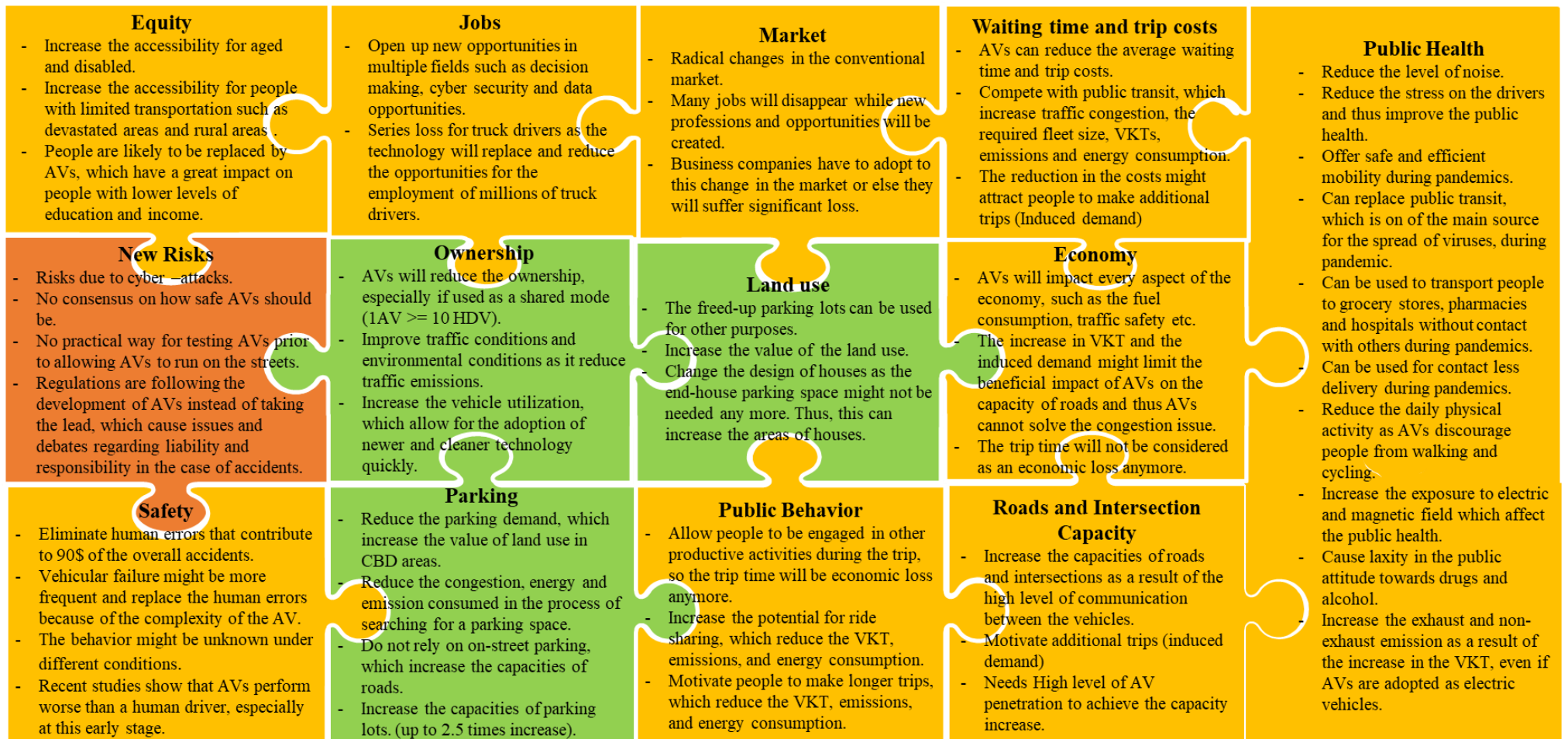
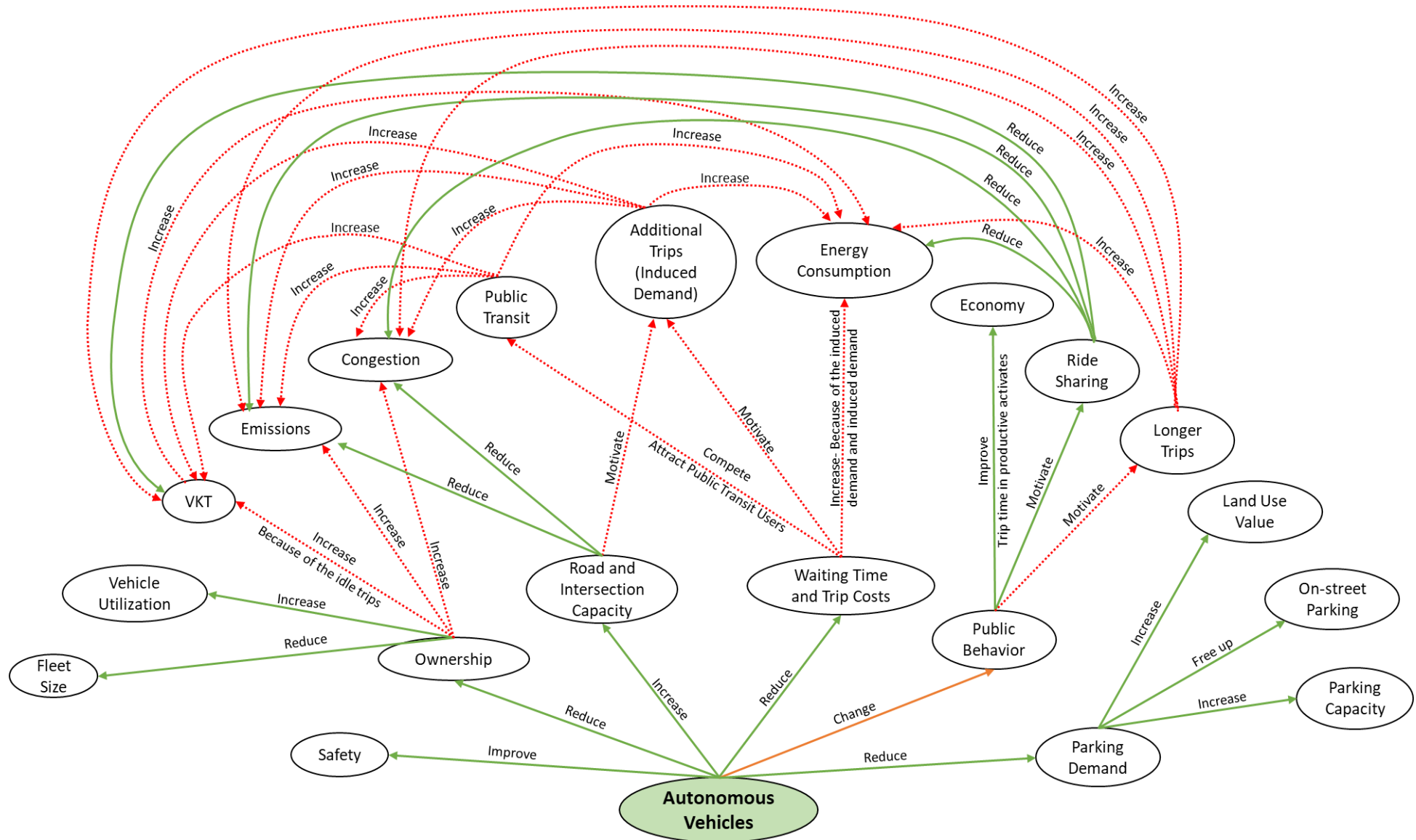


Figure 17. Summary of the implications of AVs on the different aspects (green color= benefit, red= risk, orange= risks and benefits)



**Figure 18. Mapping the intertwined relation between the implications of AVs (green= benefit, red= risk, orange= uncertain change)**

## 7. Declarations

### 7.1. Data Availability Statement

The data presented in this study are available in article.

### 7.2. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 7.3. Conflicts of Interest

The authors declare no conflict of interest.

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