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Readiness Assessment for Autonomous Vehicles: A Comprehensive Evaluation of Rural Road Infrastructure Suitability

Juiz de Fora
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Dissertação apresentada ao Programa de Pós-Graduação em Ambiente Construído da Universidade Federal de Juiz de Fora como requisito parcial à obtenção do título de Mestre em Ambiente Construído. Área de concentração: Ambiente Construído.

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RESUMO

O advento de veículos autônomos (VAs) representa uma evolução promissora na busca pela mobilidade segura, sustentável e eficiente. Apesar dos anos em desenvolvimento, alcançar veículos totalmente autônomos permanece um desafio. Paralelamente aos avanços técnicos, há uma necessidade premente de compreender os impactos da mobilidade autônoma no sistema de transporte. Nesse sentido, observa-se uma lacuna existente na determinação clara dos requisitos que uma rodovia rural deve atender para viabilizar o tráfego de VAs de maneira eficiente. Por isso, esta dissertação tem como objetivo identificar elementos críticos de infraestrutura que contribuem para a prontidão de uma rodovia rural para o tráfego de VAs e propor uma classificação qualitativa para essa prontidão. Para atingir os objetivos, o estudo se fundamentou em uma revisão sistemática qualitativa da literatura, apoiada por técnicas de análise temática. A análise foi categorizada entre elementos de infraestrutura física e digital. No que tange à infraestrutura física, o estudo investigou a relação entre elementos como projeto geométrico, sinalização, pavimentação e zonas de obras. A padronização e a definição de critérios mínimos, especialmente na sinalização, revelaram-se cruciais para o tráfego eficiente de VAs, enquanto zonas de obras foram apontadas como obstáculos potenciais. A análise da infraestrutura digital concentrou-se em elementos de comunicação e no mapeamento digital. Destacou-se a importância das redes celulares, especialmente a 5G, em rodovias rurais, particularmente em cenários em que os VAs passem a operar como veículos autônomos e conectados (VACs). Com base na análise realizada, foram discutidos os principais pontos para os quais agências governamentais e autoridades de transporte brasileiras devem se concentrar para viabilizar o tráfego de VAs nas rodovias do país. Além disso, foram apresentadas tentativas preliminares de categorização da prontidão das rodovias para o tráfego de VAs. Com base nessas tentativas e na análise conduzida neste estudo, uma nova classificação, mais abrangente, foi proposta. Dessa forma, o estudo contribui para orientar os esforços necessários por parte dos interessados na promoção da mobilidade autônoma em rodovias rurais, sobretudo no contexto brasileiro.

Palavras-chave: Veículos autônomos; Infraestrutura rodoviária; Prontidão; Rodovias rurais; Rodovias brasileiras.

ABSTRACT

The advent of Autonomous Vehicles (AVs) represents a promising evolution in the pursuit of safe, sustainable, and efficient mobility. Despite being under development for an extended period, the realization of fully autonomous vehicles remains a challenge. In parallel with technological progress, there is an urgent need to comprehend the implications of autonomous mobility on the transportation system. In this regard, there is a notable gap in clearly defining the requirements a rural road must meet to enable the efficient traffic of AVs. Therefore, this dissertation aims to identify critical infrastructure elements contributing to the readiness of a rural road for AV traffic and propose a qualitative classification to assess this readiness. The study relies on a qualitative systematic literature review and employs thematic analysis techniques to achieve these objectives. The analysis was categorized between elements of physical and digital infrastructure. The study delves into the relationships between elements such as geometric design, signage, pavement, and work zones in examining physical infrastructure. Standardization and establishing minimum criteria, particularly in signage, emerged as pivotal for ensuring the efficient flow of AV traffic, with work zones identified as potential challenges. The analysis of digital infrastructure focuses on communication elements and digital mapping. The study underscores the significance of cellular networks, especially 5G, in rural areas, particularly when AVs transition to Connected and Autonomous Vehicles (CAVs). The discussion of key considerations for Brazilian government agencies and transportation authorities to facilitate AV traffic on the nation's roads is rooted in the analysis findings. Additionally, the dissertation presents initial attempts to categorize road readiness for AV traffic, building upon these efforts and the conducted analysis to propose a more comprehensive classification. Therefore, this study offers valuable insights to guide stakeholders in promoting autonomous mobility on rural roads, particularly within the Brazilian context.

Keywords: Autonomous vehicles; Road infrastructure; Readiness; Rural roads; Brazilian roads.

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF ABBREVIATIONS AND ACRONYMS

ADAS	Advanced Driver Assistance Systems
ANATEL	National Telecommunications Agency
AV	Autonomous Vehicle
CAV	Connected Autonomous Vehicle
C-ITS	Cooperative Intelligent Transportation Systems
CNT	National Confederation of Transport
DAB	Digital Audio Broadcasting
DARPA	Defense Advanced Research Projects Agency
DSRC	Dedicated Short-Range Communication
FSD	Full Self-Driving
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
LEF	Load Equivalency Factors
LiDAR	Light Detection and Ranging
LKA	Lane Keeping Assist
MBST	Brazilian Traffic Signage Manual
MUTCD	Manual of Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
ODD	Operational Design Domain
PIARC	World Road Association
PRT	Perception and Reaction Time
RFID	Radio-Frequency Identification
RSU	Roadside Units
SAE	Society of Automotive Engineers
TCD	Traffic Control Device
TSC	Transport Systems Catapult
TSR	Traffic Sign Recognition
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRUs	Vulnerable Road Users

INDEX

1 INTRODUCTION

1.1 BACKGROUND

Autonomous vehicles (AVs) are a promising technology in the automotive industry because they promote more efficient, sustainable, and safer mobility. Currently, approximately 1.35 million people die every year worldwide as a result of road accidents (WHO, 2021). Driver inattention is the leading cause of these events (Bucsuházy et al., 2020), and human factors, in general, may be related to 94% of them (Singh, 2015). Hence, the emergence of autonomous vehicles is highly anticipated, as it has the potential to reduce crashes and save lives.

The impacts of autonomous vehicles are likely to be experienced in various ways. Firstly, they will be linked to modifying cities and urban spaces. According to Zakharenko (2016), AVs are expected to change how cities are designed, reducing the need for parking spaces, easing congestion, and making streets safer. Additionally, Duarte and Ratti (2018) observed that autonomous vehicles will transform cities by creating more efficient and sustainable transportation systems, enabling better land use and urban planning, and improving accessibility.

The issue of greater sustainability in the transport sector is also closely linked to AVs. As Iglinski and Babiak (2017) explain, AVs can operate more energy-efficiently than traditional cars through features such as predictive driving and platooning, which will reduce their carbon footprint. However, as indicated by Wadud, Mackenzie, and Leiby (2016), an expected impact of AV adoption concerns the increased demand for car travel, which would be associated with increased greenhouse gas emissions. In addition, the authors highlight that the energy source used to fuel these vehicles will also determine whether this new form of mobility will effectively be more sustainable.

However, the most noteworthy impacts of AVs will be experienced directly within the transportation system. According to Friedrich (2016), the introduction of AVs should lead to a reduction in congestion and travel time, as well as an improvement in road safety. Nevertheless, the author warns that improvements in vehicle performance may lead to increased demand for transport, which could negate some of these benefits. Furthermore, Fagnant and Kockelman (2015) point out that as AVs have the potential to make transportation more accessible, safe, and convenient, this may lead to an increase in car use in urban and suburban areas, as well as a reduction in demand for public transport and active modes of transportation, such as walking and cycling. Therefore, Martínez-Diaz and Soriguera (2018) emphasize that the adoption of AVs must occur together with policies that encourage vehicle sharing and multimodality.

AVs are being tested in more than 50 cities globally, which is anticipated to grow further (Bloomberg; Aspen, 2019). Nevertheless, the deployment of AVs is not expected to follow a uniform pattern worldwide but will instead depend on the readiness of each country to adopt the technology. Hence, KPMG developed the Autonomous Vehicles Readiness Index, which assesses a country's preparedness in four key areas: consumer acceptance, policies and legislation, technology and innovation, and infrastructure (KPMG, 2021). While the first three factors, particularly consumer acceptance, have been extensively analyzed in the literature, the relationship between AVs and infrastructure needs to be better explored.

The proper functioning of AV sensors and realizing the safety and mobility benefits this technology promises are intrinsically linked to maintaining adequate road infrastructure. As Johnson (2017) argues, AVs may only fully deliver their potential benefits with appropriate infrastructure for their traffic. In the United States, the National Highway Traffic Safety Administration (NHTSA, 2016) also highlights the importance of maintaining adequate road infrastructure for AV sensors to function correctly and improve performance. Thus, investing in AV-ready infrastructure is crucial to harnessing this technology's potential benefits fully. However, the question arises: Which specific elements of road infrastructure will impact the operation of AVs, and how will this operation be affected? Exploring this issue is essential to comprehensively understand the intersection between autonomous technology and road infrastructure.

1.2 OBJECTIVES

The overall objectives of this study are to identify the critical infrastructure criteria that contribute to the readiness of roadways for autonomous vehicle traffic and to suggest a qualitative classification for this readiness. The specific objectives of the study are:

- to identify the significant challenges and opportunities for autonomous vehicle traffic on roadways;

- to assess the current state of infrastructure readiness for autonomous vehicles on Brazilian roadways, identifying strengths and weaknesses in the existing infrastructure and potential areas for improvement; and
- to suggest a timeline for necessary adjustments to be implemented.

1.3 PROBLEM STATEMENT

Road transport is predominant in Brazil's transportation matrix, responsible for the transportation of 65% of cargo and 95% of passengers in the country, according to the National Confederation of Transport (CNT, 2022a, 2023). Additionally, the total length of the Brazilian road network is over 1.7 million kilometers (CNT, 2023). Despite this number, only 34% of Brazilian roads are classified as "good" or "excellent" in terms of their general condition (CNT, 2022a), which indicates a disregard for the transportation mode that stands out the most in the country.

These poor road conditions and the high dependence on road transport contribute to a significant number of traffic accidents in Brazil each year. In 2022 alone, the number of accidents on federal highways in Brazil was 64,447, with 52,948 of them involving casualties (CNT, 2022b). This number implies seven accidents with casualties for every 10 km of the federal road network. Although there is a high expectation that AVs will significantly reduce the number of accidents (Singh, 2015), this prediction is still being confronted by literature (Mueller; Cicchino; Zuby, 2020). Nevertheless, it remains evident that the safety advantages of AVs will be realized when the road infrastructure is appropriately prepared for them.

The costs of accidents in Brazil are staggering, with R$12.92 billion (about US$2.55 billion) spent on accidents in 2022 (CNT, 2022b). With such high costs, it is worth exploring the possibility of investing in infrastructure optimized for AVs to help mitigate these expenses. However, identifying the ideal infrastructure requirements for efficient AV traffic is the first step in developing such infrastructure.

Thus, the problem statement of this study is twofold:

- there is a need to identify adequate infrastructure requirements for AV-efficient traffic; and
- there is a need to provide guidelines for the classification of roads according to their readiness for AV traffic.

So, this study serves as a basis for defining road infrastructure requirements for AVs. It can assist in developing future standards and guidelines for road infrastructure and design. This research contributes to the growing body of literature that studies the effects of AV adoption on the transportation system.

1.4 STUDY STRUCTURE

This dissertation comprises six chapters. The first chapter introduces the main concepts, outlines the research objectives, and presents the problem statement that guides the study. The second chapter offers an overview of autonomous vehicles, including their historical evolution, current developmental status, and the challenges and predictions surrounding this technological innovation. It also presents the fundamental concepts related to the operation of sensors in autonomous vehicles.

The third chapter of this study presents the methodology used in detail. Chapter 4 analyzes the impact of physical and digital infrastructure conditions on the operation of AVs. Chapter 5 discusses the readiness of Brazilian roads for integrating autonomous mobility and presents and proposes classifications of roads based on AV traffic readiness. Finally, Chapter 6 presents the final remarks.

2 AUTONOMOUS VEHICLES: AN OVERVIEW

2.1 HISTORICAL ANTECEDENTS

The concept of autonomous vehicles has long captured the imagination of engineers and enthusiasts alike. The first recorded attempt at vehicle automation can be traced back to 1926 when the Houdina Radio Control Corporation developed a radio-controlled car model named the "Linriccan Wonder" (Bimbraw, 2015). Despite initial excitement, progress was slow in the following decades.

In the 1950s, it was believed that autonomous vehicles could be activated by electronic devices embedded in the road, requiring the construction of electronically controlled streets. While such streets were considered in the UK and parts of the US, funding was ultimately withdrawn in both cases (Davidson; Spinoulas, 2015). Even in the 1960s, artificial intelligence (AI) enthusiasts struggled to reverse-engineer systems, which involved three steps: sensing, processing (shaping the outside world and making decisions), and reacting with appropriate movements (Weber, 2014). Although the first and last steps could be accomplished with available technology, the intermediate step demanded machine intelligence, which had yet to be developed.

Due to this obstacle, the first autonomous vehicle prototype only emerged in 1986. At that time, the German researcher Ernst Dickmanns enabled a vehicle to drive autonomously for over 20 km at a 96 km/h peak speed on an empty road (Davidson; Spinoulas, 2015). The vehicle used in the experiment was a modified Mercedes-Benz 500 SEL van equipped with camera, laser, and radar sensors and a computer system that could process sensor data and control the vehicle's steering, throttle, and brakes. Although further improvements were still necessary for AVs to be integrated into the transportation system, Dickmanns' experiment continues to serve as a foundation for further advancements in autonomous vehicle technology.

The experiment conducted by Dickmanns was part of the Eureka PROMETHEUS project, a collaborative European research endeavor involving automakers, research institutions, and universities. It was the most extensive research and development program regarding autonomous mobility (Oagana, 2016). It started in 1986 and was completed in 1994, aiming to develop an autonomous vehicle that could operate safely and efficiently on public roads. The Eureka PROMETHEUS project shed light on some of the challenges faced by AVs that have already been addressed, such as autonomous lane keeping, adaptive cruise control, and automatic emergency calling systems (Van Brummelen et al., 2018). Despite the project's premature conclusion, new projects and events focused on AV development emerged in the 1990s and 2000s.

In 1995, Carnegie Mellon University launched the "No Hands Across America" event to showcase the potential of autonomous vehicle technology for long-distance travel. During the event, a self-driving vehicle successfully traveled over 2849 miles (approximately 4585 km) from Pittsburgh, Pennsylvania, to San Diego, California (Bimbraw, 2015).

New advancements were made in 1998 with the ARGO Project in Italy, in which researchers from the University of Parma allowed a modified Lancia Thema to drive autonomously on several roads and under different environmental conditions (Bertozzi; Broggi; Fascioli, 2000). The development of both "No Hands Across America" and the ARGO Project exposed new AV problems, such as vision-based object detection and tracking, perception in unfavorable lighting conditions, improvement of obstacle and road marking detection, complexities of urban driving, and perception in difficult weather conditions (Van Brummelen et al., 2018). The last two still concern the automotive industry.

New efforts in the development of autonomous vehicles were employed in the early 2000s with the emergence of the "Grand Challenge" promoted by the Defense Advanced Research Projects Agency (DARPA) of the United States. The Challenge was a competition to develop autonomous vehicles that could navigate through a desert course without human intervention. In its first edition in 2004, some teams competed for the US$1 million prize, but the Challenge was unsuccessful as the vehicles only traveled a few miles before crashing (Weber, 2014). New editions were held in 2005 and 2007, with the latter in a simulated urban environment (Davidson; Spinoulas, 2015). The DARPA Grand Challenges highlighted the challenges of autonomous driving in complex environments and marked the beginning of the expansion of AV research.

The increased attention towards AVs resulted in the 2010s being characterized as the "race for automation." Although some traditional automotive companies, including General Motors and Toyota, were already developing autonomous vehicles, their progress remained limited. They mainly focused on driver assistance systems instead of fully autonomous technology. However, the "race for automation" gained momentum when Big Tech companies decided to participate. In 2009, Waymo (a subsidiary of Alphabet Inc., Google's parent company) initiated a project to develop autonomous vehicles (Waymo, 2023). In contrast, Tesla started investing in AV development in 2014 with the launch of the AutoPilot system (Tesla, 2023a). More recently, other big tech companies have also joined the "race for automation," including Apple, Amazon, and Uber.

2.2 CURRENT STATE OF DEVELOPMENT

The growing interest in developing autonomous vehicles has underscored the importance of categorizing them based on their level of automation. To address this need, the Society of Automotive Engineers (SAE) introduced the SAE J3016 standard in 2014, which provides a framework for classifying the levels of vehicle automation. The SAE classification system spans from Level 0, representing automation, to Level 5, which signifies full automation (SAE, 2021). Alongside these levels, various Advanced Driver Assistance Systems (ADAS) are used to augment the safety and driving experience of the driver, such as adaptive cruise control, lane departure warning, and collision avoidance systems. Table 1 provides a comprehensive breakdown of each automation level, including a description of the level of autonomy and the required functions and capabilities of the vehicle.

Table 1 – SAE levels of automation

SAE Level	Function	Definition
0	No Automation	The human driver is responsible for all aspects of driving. There is no automation, and the vehicle has no features that assist with driving.
1	Driver Assistance	The vehicle has a single feature that assists the driver, such as adaptive cruise control or lane departure warning. The human driver is still responsible for all other aspects of driving.
2	Partial Automation	The vehicle has two or more features that assist with driving, such as adaptive cruise control and lane-keeping assistance. These features work together to control acceleration, braking, and steering, but the human driver must remain in control and be prepared to take over at any time.
3	Conditional Automation	The vehicle can take complete control of driving in certain conditions, such as on a highway. The human driver is still required to be present and be prepared to take over when the vehicle requests it.
4	High Automation	In most conditions, the vehicle can take complete control of driving, but the human driver may still need to take over in some situations. The vehicle can operate without a driver, but only in specific geographic locations or under certain conditions.
5	Full Automation or Driverless cars	The vehicle can take complete control of driving in all conditions, and the human driver is not required to be present or be prepared to take over at any time. The vehicle can operate without a driver, and no geographic limitations or specific conditions are required for its operation.

Source: Adapted from SAE (2021).

Despite the rapid development of ADAS, no company could achieve full automation (level 5). However, some companies are closer to achieving this goal. For instance, Waymo launched its autonomous taxi service, Waymo One, in 2018 in Phoenix, Arizona (Waymo, 2023). Currently, Waymo One operates vehicles equipped with ADAS that ensure level 4 automation. In this case, there is no need for a human driver to supervise the vehicle, which can operate autonomously under specific conditions. These conditions, often related to weather, road types, and traffic situations, constitute the vehicle's Operational Design Domain (ODD).

Other companies have also achieved level 4 automation. Cruise, a subsidiary of General Motors, has also begun operating a level 4 autonomous taxi service in three cities in the United States: San Francisco (California), Austin (Texas), and Phoenix (Arizona) (Cruise, 2023). On the other hand, Tesla has been focused on providing autonomous mobility for private vehicles and is the only company to do so. In 2014, the company launched the Autopilot system, which offers traffic-aware cruise control and autosteer (Tesla, 2023b). However, the autopilot was designed to assist the driver in driving tasks and still requires the driver's full attention at all times. Therefore, it is classified as level 2 automation.

A few years later, in 2020, Tesla launched a more advanced autonomous vehicle system, Full Self-Driving (FSD). The system's new functions include highway navigation, lane changing, and autonomous parking. In addition, the traffic and stop sign control function can be found in its beta version, and the company is also working to develop an autosteer for urban streets soon (Tesla, 2023b). Although the company intends to achieve level 5, with FSD's current features, it can still be considered level 2. The company clarifies to its customers that "features require active driver supervision and do not make the vehicle autonomous" (Tesla, 2023b).

Nevertheless, the use of different terms such as "self-driving" and other commonly used terms by other companies, such as "driverless" or "autonomous" as synonyms can be problematic since these terms can cause different perceptions among the population (Kassens-Noor et al., 2021). Therefore, the possibility of companies making explicit to their customers a name consistent with the ADAS that the vehicle has would be very beneficial for the future acceptability of autonomous mobility.

The terms employed by companies that develop autonomous vehicles may also encounter regulatory issues. The regulation of AVs varies from country to country; however, it is generally still developing and adapting to new technologies. In the United States, for example, the Department of Transportation launched the report "Ensuring American Leadership in Automated Vehicle Technologies," the fourth version of which was released in January 2020. The report provides a comprehensive guide for the safe and efficient implementation of AVs in the country, intending to strengthen national leadership in this area (U.S. Department of Transportation, 2020).

Meanwhile, in Europe, the European Commission published a proposal for regulating AVs in 2018, including safety requirements, data privacy, and legal liability (EUR-LEX, 2018). However, the proposal is still under discussion, and there is no set date for its implementation. In Brazil, the regulation for autonomous vehicles is still limited. The Brazilian Traffic Code (CTB) does not provide for the circulation of such vehicles (Brasil, 1997). Nonetheless, during a webinar held in December 2020, the

National Traffic Secretariat (Senatran) informed that it intends to regulate AVs shortly. Therefore, just like in Brazil, the regulation of this technology is expected to occur in many countries during the 2020s.

The primary challenge in regulating autonomous vehicles revolves around determining responsibility in the event of accidents. AVs will inevitably experience malfunctions, and the ethical dilemmas related to accidents are frequently debated in the literature (Goodall, 2014; Bonnefon; Shariff; Rahwan, 2016). Indeed, accidents involving vehicles operating in autonomous mode have already been documented. Perhaps the most well-known of these incidents occurred in Tempe, Arizona, in 2018, when a level 3 autonomous vehicle from Uber struck and killed pedestrian Elaine Herzberg. In response to the accident, Uber suspended autonomous vehicle tests globally. The company resumed autonomous mobility and delivery tests in 2020 and operates in Las Vegas (Nevada) and Washington, D.C. (Uber, 2023). However, the debates around the expected behavior of AVs have been ongoing throughout this period, emphasizing the urgent need for clear regulations and guidelines surrounding AVs to ensure public safety.

2.3 CHALLENGES AND PREDICTIONS

Despite recent technological advancements in AVs, significant obstacles still need to be addressed before they can become a reality. One major challenge is the typical autonomous vehicle’s difficulty making left turns, as Chafkin (2022) highlighted. Additionally, deploying fully automated driving systems without safety drivers onboard will take at least a decade, with even longer transitions in winter climates and rural areas (Leonard; Mindell; Stanton, 2020). Despite optimistic predictions that AVs will be operating on public roads by 2030, these forecasts may not be entirely realistic as financial interests often drive them and may not be based on specific AV experience (Litman, 2023).

Due to their reliance on public infrastructure and higher external costs, adopting new vehicles requires more planning and regulation than other technologies (Litman, 2023). Although previous studies have relied on market penetration rates of different technologies to predict the deployment of AVs, such as that of Lavasani and Jin (2016), this approach may be uncertain. For comparison purposes, the case of smartphones in Brazil can be considered. The first smartphone launched in the country was the iPhone 3G in 2008. The high prices of these devices made access to them challenging for the population. However, around 2012, smartphones began to gain popularity worldwide. According to the National Continuous Household Sample Survey, in 2021, 82.7% of the Brazilian population had access to a smartphone (IBGE, 2022). Nevertheless, such a sharp market penetration curve for autonomous vehicles is not expected.

Comparing AVs with other vehicle technologies may be uncertain due to their complexity and expected higher costs. Public perception and willingness to pay are two substantial factors that can compromise the adoption curve of AVs. A study by Kyriakidis, Happee, and De Winter (2015) showed that most respondents (around 56%) are not willing to pay more for an autonomous vehicle compared to a conventional one. Confidence in autonomous driving is relatively low, with about 50% indicating they would feel unsafe in an autonomous vehicle on a highway.

The uncertainties inherent in the development of AVs and the public perception surrounding them make predicting the implementation of this technological innovation highly questionable. Nonetheless, Litman (2023) has attempted to make a prediction. The author assumes that level 5 AVs will be available for commercialization by the end of the 2020s. However, Litman (2023) emphasizes that during the first decade, only a minority of new vehicles are likely to be fully autonomous, with market shares increasing as their performance improves, prices decline, and consumers gain confidence. Furthermore, by 2045, up to half of new vehicle sales could be autonomous, but without mandates, market saturation will probably take several decades, and some drivers may continue to choose human-operated vehicles due to costs and preferences. Table 2 summarizes the predictions for each decade.

Table 2 – Predictions for autonomous vehicles

Stage	Decade	New Sales	Fleet	Travel
Development and testing	2020s	0%	0%	0%
Available with a large price premium	2030s	2-5%	1-2%	1-4%
Available with a moderate price premium	2040s	20-40%	10-20%	10-30%
Available with a minimum price premium	2050s	40-60%	20-40%	30-50%
Standard feature included on most new vehicles	2060s	80-100%	40-60%	50-80%
Saturation (everybody who wants it has it)	2070s	?	?	?
Required for all new and operating vehicles	?	100%	100%	100%

Source: Litman (2023).

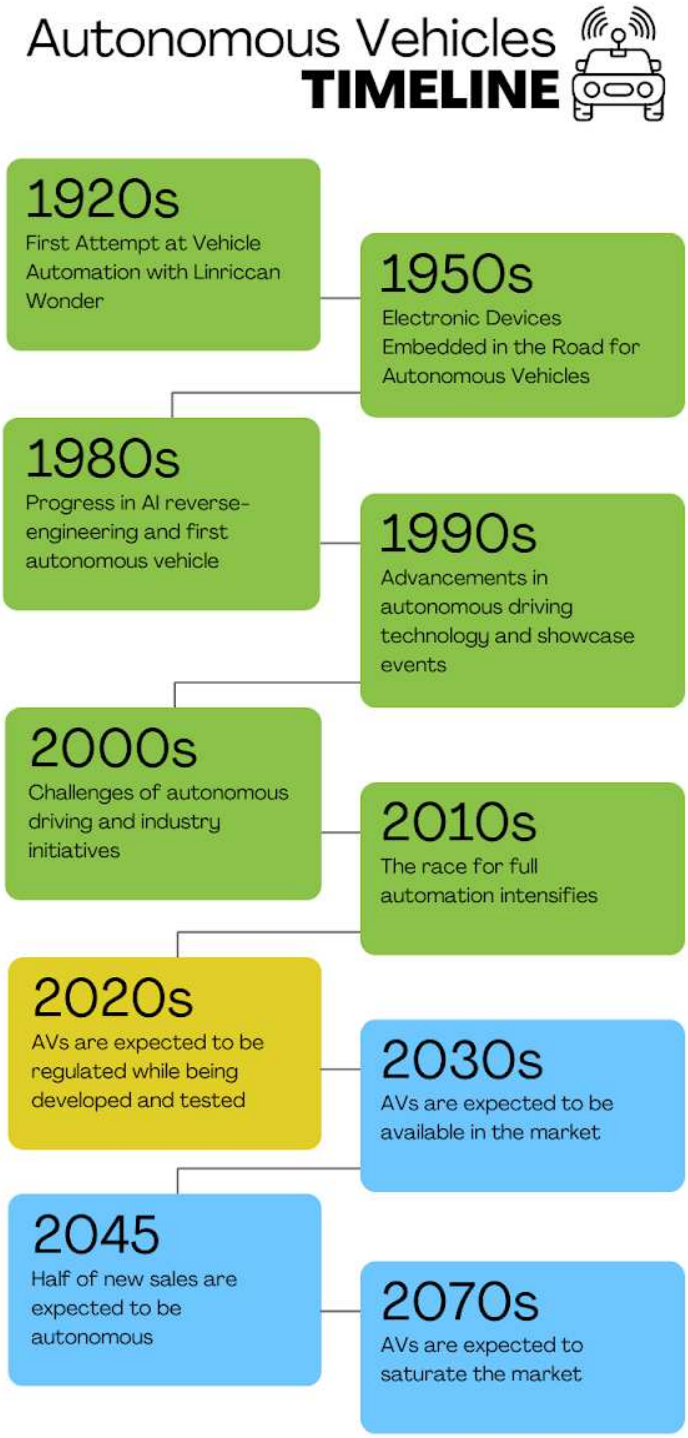
In summary, while AVs will play a central role in the future of the transportation sector, their deployment is still uncertain. These vehicles have enormous potential to revolutionize mobility, but that still depends on some technological advances, greater public acceptance, and more affordable costs. Notably, it is plausible to assume that commercial vehicles such as taxis, long-haul freight trucks, and buses are expected to be among the first to be automated (Litman, 2023). This pioneering can be attributed to their low labor costs and predictable travel conditions. Thus, commercial vehicle automation represents the first step in the autonomous mobility revolution. Furthermore, higher automation levels are expected to reach private vehicles and public transportation as AV technology evolves.

2.4 TIMELINE

The development of autonomous vehicles can be traced back to the 1920s, when the first attempt at vehicle automation was made. However, it was not until recent decades that significant progress was made in the field. Nowadays, AVs are in the sights of major technology companies and vehicle manufacturers worldwide, with heavy investments being made in this cutting-edge technology.

As AV technology continues to advance, many eagerly anticipate when these vehicles will become available for commercial use on a large scale. Some early projections suggest that this could happen in the 2030s, while the 2020s will still be dominated by debate over the regulation of this technological innovation. Figure 1 provides a detailed timeline of the development of autonomous vehicles, showcasing key events that have shaped the evolution of this innovative technology over the years.

Figure 1 – Autonomous vehicles timeline



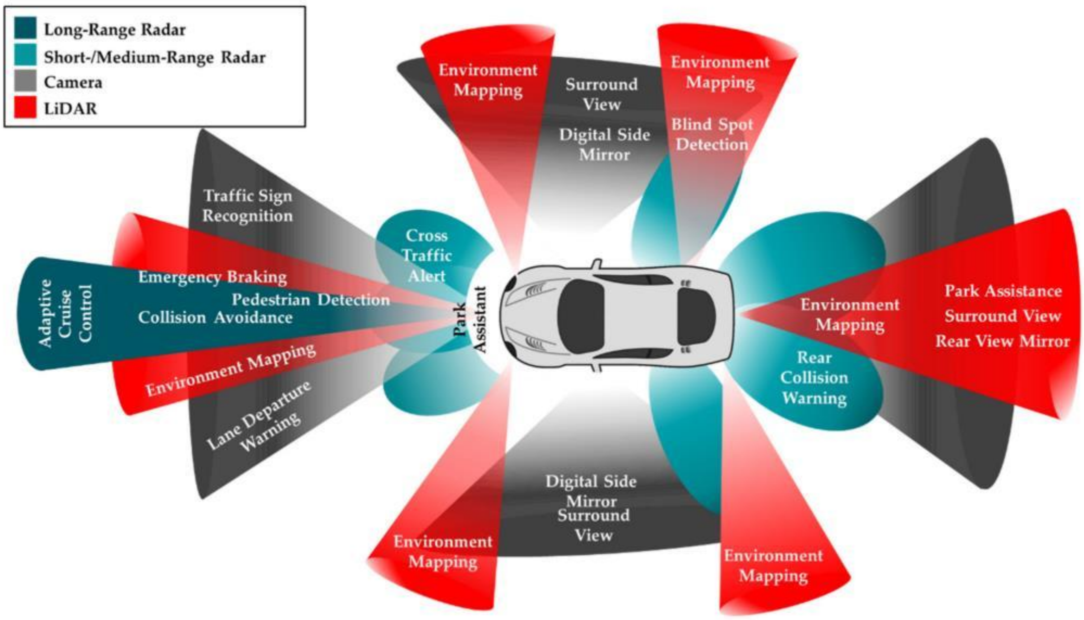
Source: Author (2023).

2.5 SENSOR TECHNOLOGIES

Sensors assume a pivotal role in real-time data collection from the surrounding environment of AVs. This data encompasses crucial information concerning other vehicles, pedestrians, and Vulnerable Road Users (VRUs), as well as details about road conditions and traffic signs, among other relevant factors. Through the utilization of advanced sensor technology, AVs gain the capability to perceive and interpret their surroundings, forming the foundational basis for their operational framework.

The operational spectrum of AVs involves integrating various sensor types, each tailored for specific applications. This study delves explicitly into three critical sensors significantly influencing AV operations: cameras, light detection and range (LiDAR), and radar. This section expounds upon the distinctive applications associated with these sensors, and Figure 2 visually delineates them.

Figure 2 – Sensors' applications



Source: Yeong et al. (2021).

2.5.1 **Cameras**

In AVs, cameras represent the human vision. They are fundamental optical devices for acquiring visual information in real time. Thus, AVs can obtain detailed information about static and dynamic objects. Cameras are relevant for categorizing and tracking these objects due to computational vision power to analyze characteristics like shape, color, and movement. So, these capabilities allow the vehicle's perception system to identify road signs, traffic lights, and road lane markings.

As cameras constitute inexpensive sensors, different kinds can be applied to meet specific detection and monitoring requirements. Monocular cameras, for example, refer to those with a single optical lens to capture images of the surrounding environment. Monochromatic monocular cameras are responsible for identifying detailed information in shades of gray based on the object's contrast and texture, regardless of color. Additionally, RGB monocular cameras can be especially useful in identifying traffic signals and signs as they differentiate objects based on their colors.

Although monocular cameras effectively capture images of the environment, they fall short of accurately perceiving depth and distance. To address this limitation, stereo cameras, also known as binocular cameras, are employed in a stereoscopic layout to imitate the depth perception observed in animals' vision. These cameras offer superior spatial perception by capturing images of an object from two distinct angles. The difference between the vision from monocular and stereo cameras is exhibited in Figure 3.

Figure 3 - Difference from monocular to stereo vision

Source: Singh (2022).

Moreover, infrared cameras can detect the thermal radiation emitted by objects and surfaces. This technology is highly effective in conditions of low visibility, such as during the night or in adverse weather conditions. In addition, infrared cameras can detect any thermal anomalies in vehicles, making them extremely valuable for preventive maintenance and detecting faults in vehicle components.

2.5.2 **Radar**

A radar is a sensor that emits electromagnetic waves at radio or microwave frequencies into the surrounding environment. When these waves encounter objects, they reflect back to the sensor. By precisely measuring the time it takes for the wave to be reflected and analyzing changes in its frequency and amplitude, the system can determine the distance, direction, and speed of the objects hit.

In autonomous vehicles, different types of radar operate at various frequencies to perform specific functions. Short-range radar, for example, helps perform short-range functions, such as parking assistance and collision avoidance at low speeds. Medium-range radar allows the detection of objects at medium range, within a few hundred meters, which helps with adaptive cruise control and lane-keeping systems. Finally, long-range radar detects obstacles and other vehicles over longer distances, such as vehicles ahead in distant lanes.

However, radar operations can face some difficulties. The most notable of these concerns is sensitivity to adverse weather conditions. Heavy rain, snow, or fog can affect the sensor's performance, as water particles can absorb or disperse waves, reducing detection effectiveness. In addition, radar waves are prone to electromagnetic interference from other sources, which can also compromise the radar's reliability.

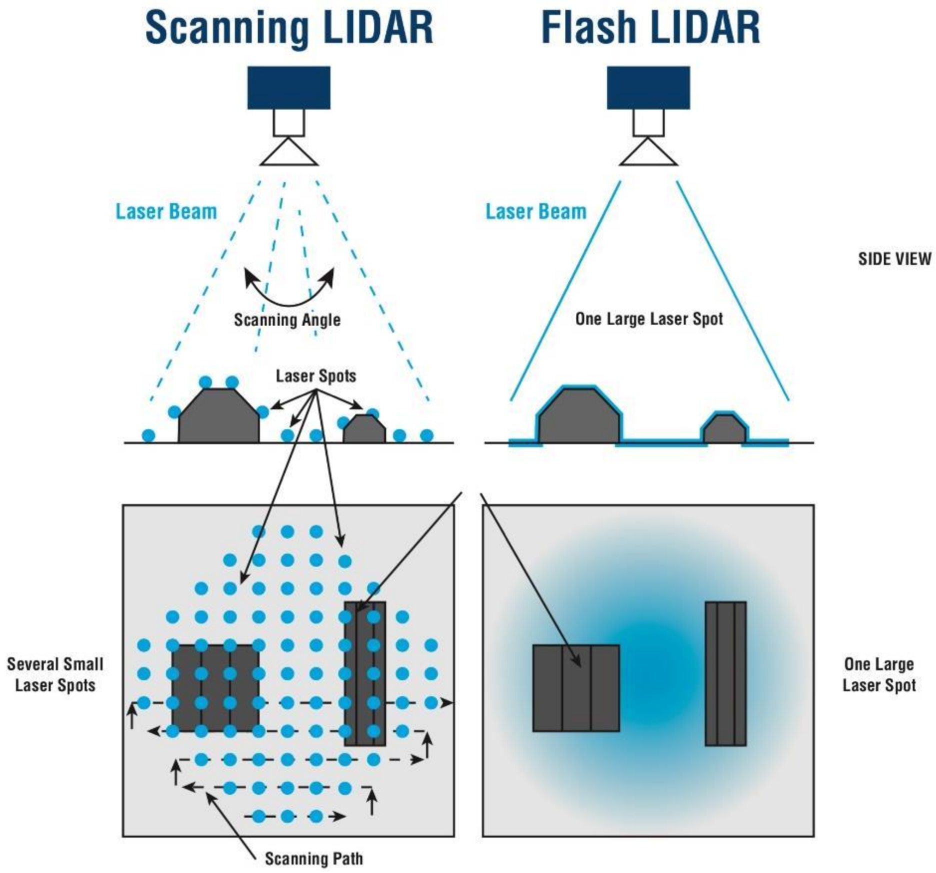
2.5.3 **LiDAR**

A LiDAR, the acronym for Light Detection and Ranging, is a sensor that emits pulses of laser light highly directed at the surrounding environment. When the sensor emits light, part of it is reflected back when it hits an object. The LiDAR then records the amount of light reflected and the time it took to return. Using this information, the distance to the object can be accurately calculated.

LiDARs scan continuously, which helps them generate a series of three-dimensional points, also known as a "point cloud". Thus, based on the analysis of the points, they can define the position, size, and shape of the objects identified. Compared to cameras and radar, LiDARs provide a more precise and detailed representation of their surroundings with greater resolution. They are also less susceptible to electromagnetic interference from other electronic sources and work more efficiently in low visibility conditions.

As with cameras and radars, there are different types of LiDARs. Mechanical spinning LiDARs, also known as scanning LiDARs, use mechanical components to direct the laser beams in various directions. This type of LiDAR can cover a wide area around the vehicle, providing 360º perception horizontally. On the other hand, flash LiDARs eliminate the rotating part. They use a single laser to obtain the entire scene practically instantaneously, which is valuable in situations that require rapid detection of moving objects. While mechanical spinning LiDARs are traditionally integrated into the vehicle's roof, flash LiDAR integration is more versatile, as it can occur in various car parts, including windshields and headlights. The differences between those two types of LiDAR are shown in Figure 4.

Figure 4 - Differences between mechanical spinning LiDAR and Flash LiDAR



Source: ASC (2023).

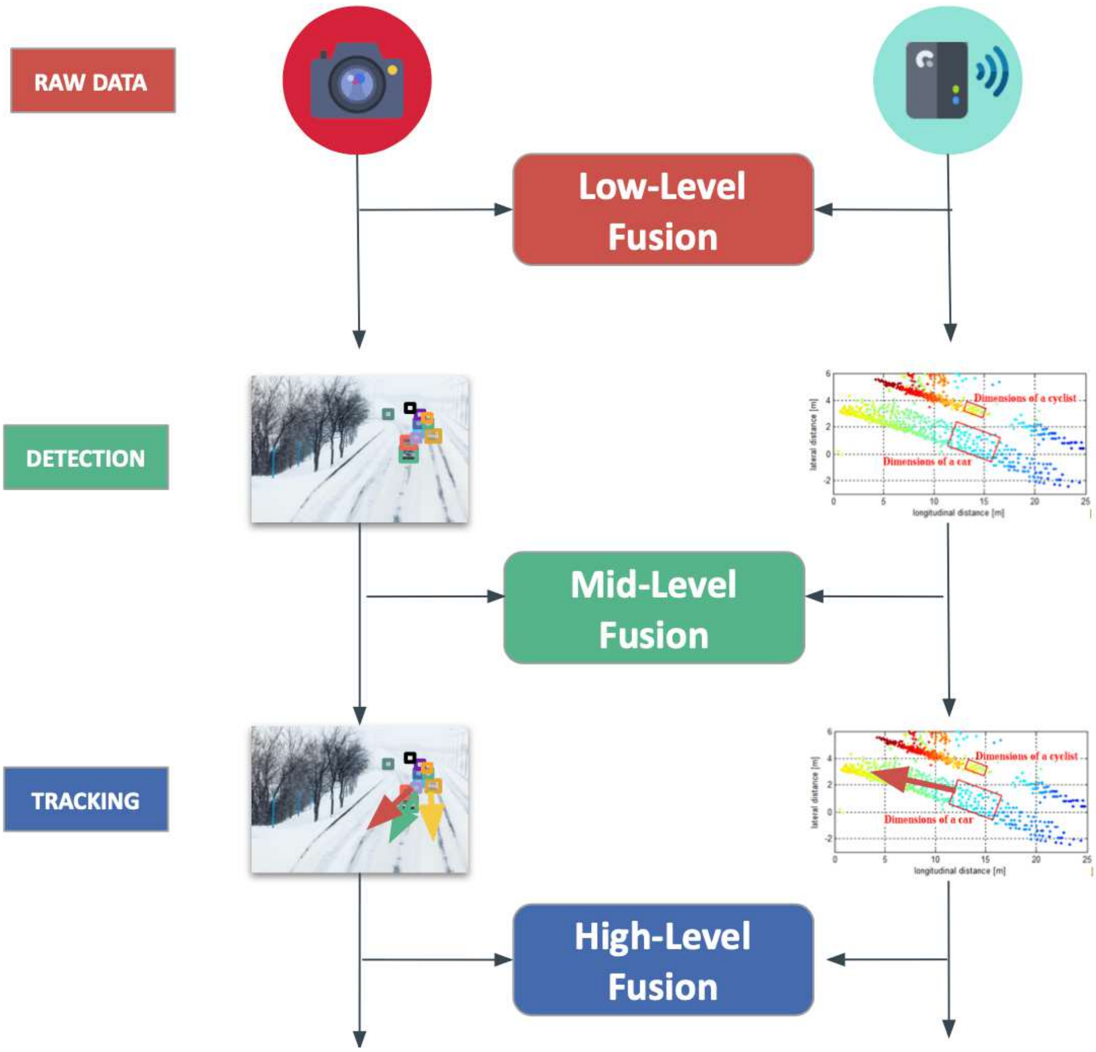
2.5.4 **Sensor Fusion**

The individual limitations of each sensor make the sensor fusion process essential in AVs. This process offers notable advantages, mainly because data redundancy can provide more reliable information about the surrounding environment. For this reason, data from different sensors such as cameras, radar, and LiDARs must undergo sensor fusion.

Some algorithms are needed to combine this data. One of the most widely used methods for this combination is the Kalman filter, which is applied to predict a system's future state using state estimates and measurements. It is particularly effective in environments with Gaussian uncertainties, i.e., especially when there is noise in sensor measurements or external interference. Thus, it can provide velocity and position estimates in AVs. On the other hand, the particle filter is another sensor fusion method widely used in AVs. Unlike the Kalman filter, the particle filter is better suited to situations with significant, non-Gaussian uncertainties, making it more applicable in challenging situations.

Sensor fusion can occur in three ways: low-, mid- or high-level. In the case of low-level sensor fusion, the raw data from each sensor is initially merged and, at a later stage, undergoes additional processing. In this type of fusion, the system uses low-level information such as colors and distances to create a richer representation of the environment. Mid-level sensor fusion integrates sensor data at an intermediate level of abstraction, bridging the gap between low-level raw data and high-level semantic understanding. On the other hand, high-level sensor fusion involves the sensors individually processing their own data before fusing it with other sensors. In this case, understanding the environment becomes more profound, enabling AVs to make more intelligent decisions, such as choosing safe driving paths. Figure 5 illustrates the different levels of sensor fusion.

Figure 5 - Sensor fusion by abstraction level between a camera and a radar



Source: Think Autonomous (2021).

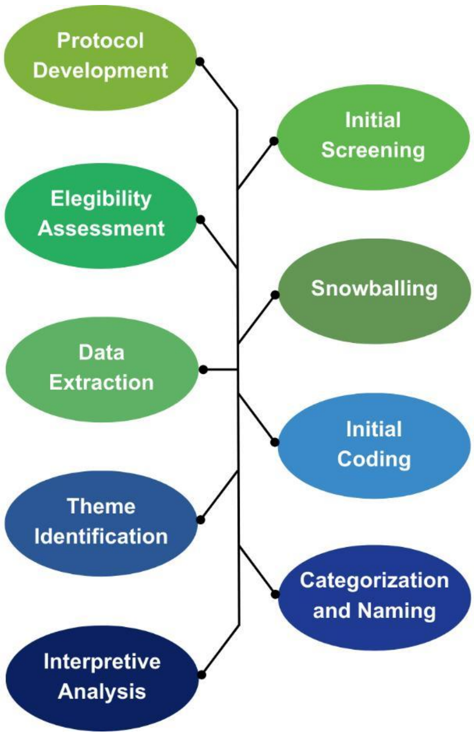
In short, sensor fusion is a crucial aspect of autonomous driving. It overcomes the limitations of individual sensors and enables the vehicle to handle better challenging situations that may arise during the driving process. Thanks to sensor fusion, autonomous vehicles become better equipped to deal with the unpredictable and variable conditions of the real world.

3 METHODOLOGY

According to the definition proposed by Merriam and Tisdell (2009), the present study consists of qualitative research, which is particularly suited to investigating complex and context-bound issues. Qualitative research is known for its exploratory nature, focusing on understanding the meaning of experiences from the participants' perspectives. It involves describing and interpreting data through an iterative process of analysis. (Merriam; Tisdell, 2009). This approach is particularly suited to investigate phenomena that are not easily quantifiable and to gain in-depth insights into complex issues.

The first part of this dissertation consisted of a qualitative systematic review based on the guidelines provided by Booth, Sutton, and Papaioannou (2016). Subsequently, the investigation incorporated components of thematic analysis, adhering to the framework articulated by Braun and Clarke (2016). Figure 6 illustrates the main steps of the study, with the green boxes representing the stages of the qualitative systematic review and the blue boxes representing the steps derived from the thematic analysis.

Figure 6 - Flowchart of the methodology steps



Source: Author (2023).

3.1 THE QUALITATIVE SYSTEMATIC REVIEW

According to Booth, Sutton, and Papaioannou (2016), qualitative systematic reviews integrate or compare the results of individual qualitative studies and aim to identify and synthesize themes or constructs that emerge from the data. These reviews go beyond merely summarizing findings and aim to provide a comprehensive and nuanced understanding of a particular phenomenon or issue. Conducting a qualitative systematic review involves a rigorous and transparent approach to searching, screening, selecting relevant studies, and extracting and synthesizing data from those studies.

Defining the review protocol is the first step toward conducting a qualitative systematic review. This stage involves determining search databases, language, search terms (strings), Boolean operators, time period, and inclusion and exclusion criteria. For this study, the following search databases were included: Scopus, Web of Science, IEEE Xplore, TRID, and Google Scholar, with searches conducted in the English language. The search strings and Boolean operators consisted of terms listed in Table 3, with searches limited to record titles and covering the last ten years, i.e., starting from 2013. Following the definition of the review protocol, an initial search was conducted to verify whether the search strings, Boolean operators, and time period specified returned an appropriate number of records for the research.

Table 3 – Search strings

Focus	Key strings
Automation	Autonomous OR self-driving OR driverless OR automated OR connected
	AND
Vehicles	Vehicles OR car OR driving
	AND
Road Infrastructure	Road OR infrastructure
	AND
Infrastructure Assessment	Requirement OR upgrade OR design OR readiness OR preparedness OR infrastructure

Source: Author (2023).

As a continuation of the review protocol definition, the inclusion criteria were established as follows:

- the record addresses the introduction of autonomous vehicles in rural environments or a general context;
- the record mentions at least one aspect of the impact of autonomous vehicle adoption on the road infrastructure;
- the record was published in a peer-reviewed scientific journal or conference proceedings or consists of a technical report published by a reputable institution;
- the record was published within the last 10 years, i.e., in 2013 or later;
- the record is written in English.

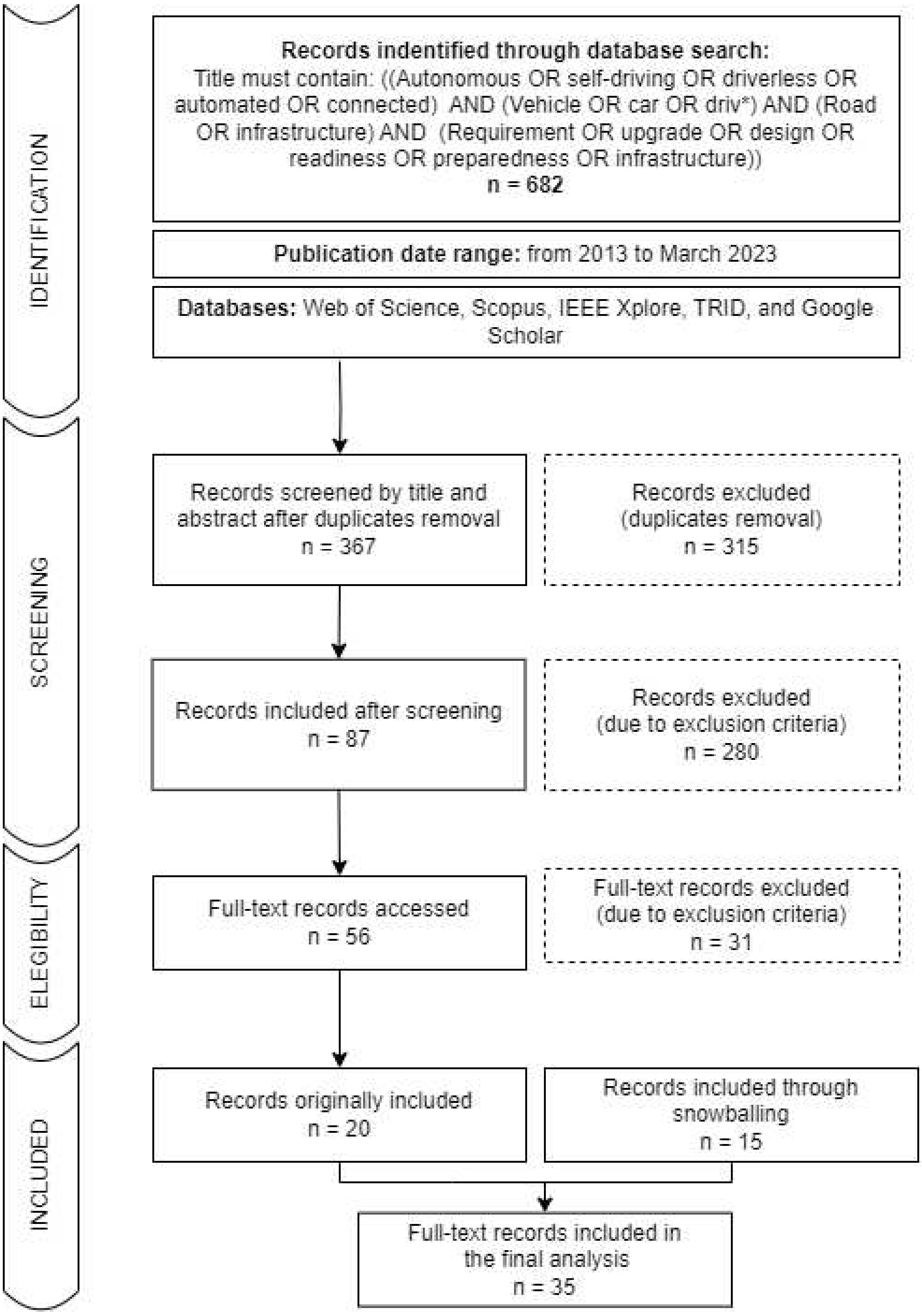
Moreover, the following exclusion criteria were established:

- the record discusses the introduction of autonomous vehicles solely within urban environments;
- the record fails to mention any practical implications of adopting autonomous vehicles on road infrastructure;
- books, book chapters, in-press articles, or those without peer review;
- the record was published before 2013;
- the record is not written in English.

The search in the five previously mentioned databases retrieved a total of 682 records. All records were imported into Mendeley software, which was used for managing and detecting duplicates. Subsequently, records underwent an initial screening, with their titles and abstracts evaluated based on the inclusion and exclusion criteria. After this stage, eligible records proceeded to the next step, which consisted of a full-text eligibility assessment. During this phase, records were evaluated to determine if they met the inclusion and exclusion criteria.

After assessing the eligibility of records, a snowballing search was conducted. This involved reviewing the reference lists of eligible records to identify additional relevant studies not found during the initial database search. The snowballing search was done systematically and transparently, with all relevant studies included in the final analysis. The snowballing process continued until no new studies were identified or until the point of saturation was reached, where no further information could be added to the analysis. The studies that were retrieved through snowballing also underwent an eligibility assessment, and any eligible studies were included in the final review. Figure 7 provides an overview of the qualitative systematic review process.

Figure 7 - An overview of the qualitative systematic review process



Source: Author (2023).

Finally, data from the selected articles was exported to a *.csv* file and organized in an electronic spreadsheet. The spreadsheet contained the record's title, author, year, and publication type (journal article, conference proceedings, or technical report). It was used to organize and analyze the data. For reference, a model of this spreadsheet is available for consultation in Appendix A of this dissertation.

3.2 THE THEMATIC ANALYSIS

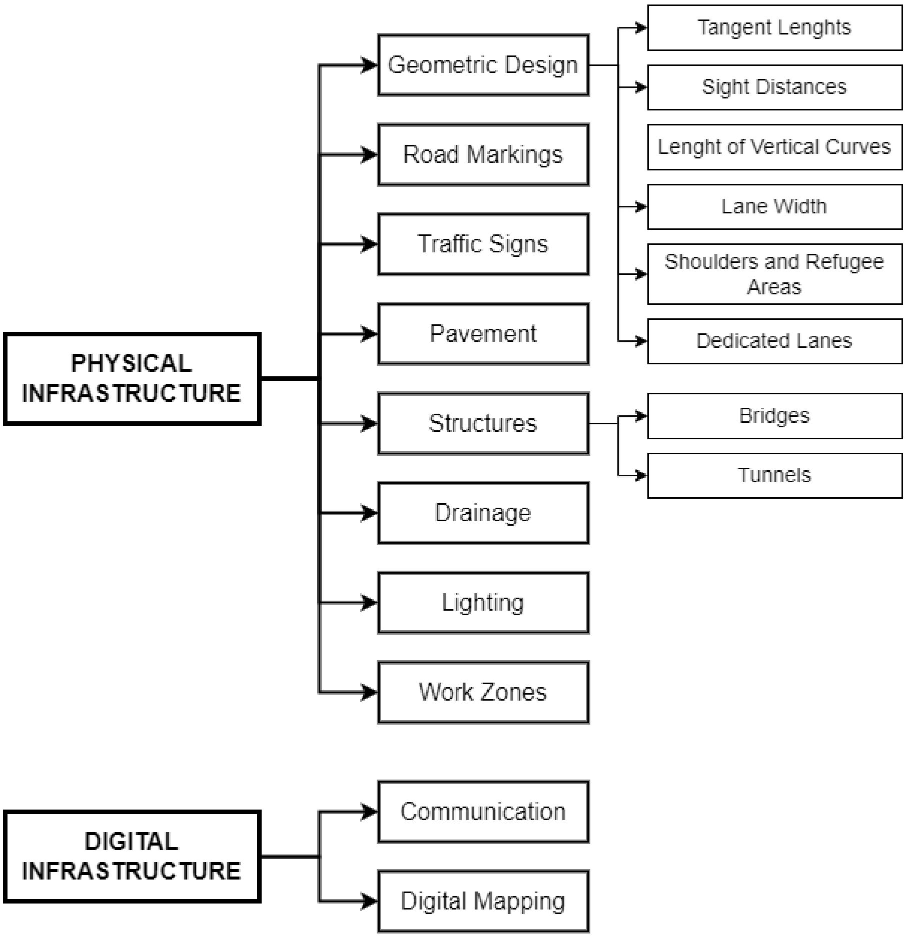
Thematic analysis is a widespread method used in qualitative research, as it allows the identification of patterns within the data. According to Braun and Clarke (2006), thematic analysis involves identifying, analyzing, and reporting themes within the data while being attentive to the context in which they occur. Different types of data and research questions can be addressed and answered with this approach, as it requires a flexible yet systematic approach. In the context of this study, the thematic analysis's underlying concepts were employed to inform the analysis of the text data from the selected records.

For the development of this stage, the selected records were integrated into NVivo 14 software, in which some steps of thematic analysis were applied. The initial coding process was conducted after thoroughly examining the records. This process involved systematically organizing the data into meaningful units and assigning codes to represent the content of each unit, which were created inductively from the data itself. The initial coding enabled the identification of patterns and themes within the data and helped develop a preliminary understanding of the data.

After initial coding, similar codes were grouped into themes to identify more significant patterns within the data when applicable. Themes can be discerned as meaning patterns found within the encoded data. A meticulous inspection of the connections between codes was required to identify these themes, seeking out recurring patterns and deviations and considering the data's context. The approach to analyzing new data was iterative, ensuring that themes were verified, refined, or modified as necessary.

At the end of the identification and verification process, themes must be organized through categorization and naming. This process involves grouping related themes under broader categories and giving each category a descriptive and meaningful name. After some adjustments, the stratified analysis that structured this dissertation is displayed in Figure 8.

Figure 8 - Categorical division of analyzed content



Source: Author (2023).

The final stage based on the thematic analysis process in this study was the interpretative analysis. This phase involved examining the relationships between the identified themes and interpreting their meaning concerning the research objectives. It was possible to draw inferences and conclusions about the data through interpretative analysis, contributing to theoretical and practical knowledge development. The outcomes of the interpretive analysis are presented and discussed in this study. They also served as a basis for the development of evaluation frameworks for each of the established categories, providing a comprehensive assessment of the readiness of roads for autonomous vehicles.

4 ANALYSIS

4.1 IMPACTS IN PHYSICAL INFRASTRUCTURE

In the realm of transportation, the impact of physical infrastructure on AV operation is a common topic of discussion in the literature. This study’s physical elements comprise the concrete, tangible elements constituting the structural foundation and framework for vehicular movement. They generally encompass a spectrum of components intricately woven into the built environment, thereby shaping the overall landscape of road transportation.

This subsection is divided into some topics to provide a detailed analysis of the physical infrastructure factors that affect AVs' efficient and secure operation. These topics include geometric design, road markings, traffic signs, paving, road structures, drainage, lighting, and work zones.

4.1.1 Geometric Design

The literature has extensively explored the topic of adapting road geometrical design to the operation of autonomous vehicles. Several papers are dedicated to analyzing changes that could or should be made to the geometric design guidelines for rural roads with the introduction of AVs. For instance, Othman (2021) and Khoury, Amine, and Saad (2019) investigated these changes from the perspective of the American Association of State Highway and Transportation Officials (AASHTO), in its Green Book guidelines, while Intini et al. (2019) and Guerrieri et al. (2021) carried out similar analyses, considering the guidelines in force in other countries, especially Italy.

In general, changes made to most geometric design elements of rural roads tend to make them more flexible rather than rigid. So, the operation of AVs is already feasible and appropriate considering the current guidelines for some elements in the design of rural roads, such as tangent lengths, sight distance, vertical curve lengths, and lane width. However, this study briefly explores these four criteria to identify the changes that could be most cost-effective in a fully autonomous scenario.

On the other hand, other criteria, such as the design of shoulders, refuge areas, and exclusive lanes, should be stricter with the introduction of AVs, even in a mixed-traffic scenario with human-operated vehicles. For this reason, the necessary adjustments to these elements are also explored in this subsection.

4.1.1.1 Tangent Lengths

In a driving environment that is safe for humans, long stretches of straight roads can be a problem as they may cause drivers to feel bored and fatigued (Intini et al., 2019). This behavior can lead to drivers either falling asleep at the wheel or speeding up, both of which are associated with an increased number of accidents.

For this reason, limiting the maximum value for the length of a tangent is a factor strictly associated with human behavior and could be dispensed with in a possible scenario of exclusive AV traffic. According to Intini et al. (2019), AV users may not even pay attention to straight lengths since they will be occupied with other activities.

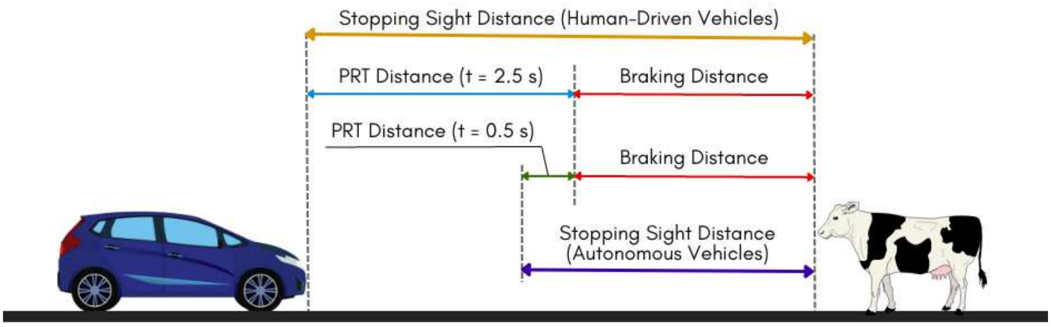
4.1.1.2 Sight Distances

Sight distance is defined as the distance that must be clear in front of a vehicle to enable timely detection of obstacles and facilitate appropriate reactions to unforeseen conditions. It is a crucial parameter in road design as it directly influences safety measures. Determining sight distance is fundamental to ensuring the safety of the transportation system, as it provides the vehicle with the necessary lead time to initiate braking maneuvers and thereby avert potential collisions.

In the case of AVs, sight distances are also expected to be more flexible. This adaptability arises from the fact that visibility distance is currently intricately linked to the driver's Perception and Reaction Time (PRT), i.e., the time the driver takes to detect an obstacle or perceive anomalies in the road conditions and react to it. PRT includes the time it takes for the driver's eyes to register visual information, process it, and make a decision, like swerving or braking.

As Guzek et al. (2012) indicated, PRT for humans typically falls within the range of 1.2 to 2.2 seconds. Notably, AASHTO (2018) advocates for a more cautious approach, recommending a 2.5-second PRT in geometric design. In contrast, insights from Cucor et al. (2022) and Khoury, Amine, and Saad (2019) propose a considerably shorter PRT for AVs, ranging from 0.5 to 0.8 seconds. A PRT of 0.5 seconds would lead to a considerable decrease in Stopping Sight Distance (SSD), as shown in Figure 9. This variance is attributed to the distinct nature of AVs, in which sensors detect obstacles so that the vehicle can initiate the necessary maneuvers to avert collisions. Thus, the reduction in PRT for AVs is inherently tied to the efficiency and rapidity of sensor performance.

Figure 9 - Stopping sight distance for autonomous vehicles



Source: Adapted from Othman (2021).

For instance, as verified by Intini et al. (2019), employing a long-range radar with the capability of detecting obstacles up to 300 meters and assuming an exceptionally brief vehicle reaction time coupled with optimal friction conditions reveals the potential for a vehicle traveling at 130 km/h to decelerate safely and avert collisions. Intini et al. (2019) underscore that the requisite speed for collision avoidance diminishes to 100 km/h under wet road conditions due to the compromised road grip. Under comparable circumstances, a human-operated vehicle would necessitate an even more restrained speed. In the given instance, the maximum speed required for collision avoidance with the detected obstacle can be capped at 80 km/h, even in dry conditions.

Furthermore, optimizing sight distance conditions may attain heightened efficacy by factoring in the potential for communication between vehicles and the sensors embedded in road infrastructure — a topic poised for exploration in the subsequent section. As elucidated by Farah et al. (2018), under specific scenarios, such as crest curves, the limitations on sight distance would exhibit insignificant alteration when contemplating AV traffic without connectivity. Tengilimoglu, Carsten, and Wadud (2023a) further corroborate this observation, extending it to instances involving sharp horizontal curves.

However, contemplating the potential integration of an adept digital infrastructure and the implementation of vehicle-to-infrastructure (V2I) communication, posited by Cucor et al. (2022), presents an alternative scenario. In this context, the sensors embedded in the road infrastructure could transmit real-time information regarding obstacles directly to the vehicles. Consequently, the scope of obstacle detection surpasses individual sensors' immediate coverage, affording vehicles foreknowledge of unforeseen conditions even before their sensors register them, which could also contribute to reduced visibility distances.

In a broader context, enhancing sight distances necessitates a comprehensive grasp of the characteristics and limitations of AVs. Tengilimoglu, Carsten, and Wadud (2023a) highlight the importance of internationally standardized sensor parameters to elucidate and refine this optimization process. However, given that the existing parameters tailored for human sight distances are already robust and notably cautious, accommodating AV requirements may warrant modifications to these criteria.

4.1.1.3 Length of Vertical Curves

Vertical curves serve a crucial function in connecting various gradients along a highway, with essential determinants for their design encompassing factors like the radius of curvature, slope, and visibility. These curves manifest in two primary types: sag curves, which introduce a depression in the topography, and crest curves, which elevate the road surface.

Concerning sag curves, the length determination undergoes meticulous examination guided by geometric road design standards like those outlined by AASHTO (2018). The calculation of this length is contingent on four vital criteria: passenger comfort, drainage control, general aesthetic considerations, and, notably, headlight sight distance. AASHTO (2018) provides explicit equations, denoted as Equations 1 and 2, to precisely calculate the length of sag curves.

$$L_{sag} = \frac{AS^2}{(200(H + S\tan\beta))}, if\ S < L \qquad \text{(Eq. 1)}$$

$$L_{sag} = 2S - \frac{200(H + S\tan\beta)}{A}, if\ S > L \qquad \text{(Eq. 2)}$$

Where:

- L is the length of the sag vertical curve [m];
- A is the algebraic difference in grades [percent];
- S is the light beam distance [m], taken to be equal to the sight distance;
- H is the height of the headlight above the roadway surface [m]; and
- β is the inclined angle of the headlight beam.

The advent of autonomous mobility presents an opportunity for revisions in the established parameters governing H and β. Currently, calculating the length of a vertical sag curve is mainly justified under low illumination conditions, where headlights are essential to ensure vehicle safety. However, the function of headlights, which provide illumination to enable the detection of objects on the road, will presumably be replaced by sensors such as LiDAR. These sensors will make it possible to detect objects even in the absence of lighting.

Consequently, it becomes pertinent to reevaluate the H and β parameters, traditionally associated with headlight characteristics, to better align with the capabilities of LiDAR technology. Presently, AASHTO (2018) adheres to a standard of 0.6 meters for H and 1 meter for β. However, in the context of autonomous mobility, a recalibration is proposed: H could be adjusted to 1.84 meters, reflective of the height of LiDAR positioned atop the vehicle, as suggested by Othman (2021). Additionally, a value of 13.4º for β, as proposed by Khoury, Amine, and Saad (2019), could be vonsidered under such autonomous conditions. The implication of adopting these elevated values for H and β lies in the potential to embrace shorter sag curve lengths.

In the case of crest curves, the justification for more flexible length criteria arises from the strategic placement of sensors. Established geometric road design guidelines, once more exemplified by AASHTO (2018), dictate the determination of crest curve lengths, a process expounded through Equations 3 and 4.

$$L_{crest} = \frac{AS^2}{100(\sqrt{2h_1} + \sqrt{2h_2}}, if\ S < L \quad \text{(Eq. 3)}$$

$$L_{crest} = 2S - \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{A}, if\ S > L \quad \text{(Eq. 4)}$$

Where:

- L is the length of the vertical curve [m];
- A is the algebraic difference in grades [percent];
- S is the sight distance [m];
- h_1 is the height of the eye above the roadway surface [m]; and
- h_2 is the height of the object above roadway surface [m].

The eventual transition to total AV traffic prompts a noteworthy alteration concerning the parameter h_1. In this scenario, the conventional role performed by the human driver's eyes is slated for replacement by alternative sensors, notably LiDAR, as emphasized by Othman (2021) and Khoury, Amine, and Saad (2019). LiDAR, positioned above the vehicle, is characterized by a height value of 1.84 meters (Othman, 2021), surpassing the 1.1-meter height adopted by AASHTO (2018) for the driver's eyes. Notably, the length of the crest curves diminishes with an increase in h1. Therefore, more flexible sizing criteria could be adopted for this element in a fully autonomous mobility scenario.

Although the practical implementation of alterations to the length of vertical curves is contingent upon the comprehensive adoption of autonomous vehicles in the long term, such changes can yield substantial improvements in the economic landscape. As indicated by Rana and Hossain (2023), applying new criteria for dimensioning these curves could translate into notable reductions in embankment (7.67% less) and cutting (47.22% less) requirements during highway construction. In essence, these proposed modifications would culminate in developing more efficient road structures, offering safety assurances and tangible benefits in saving resources.

4.1.1.4 Lane Width

Presently, road designs establish lane widths by considering not only vehicle dimensions but also accounting for the tolerance accommodating reckless driver behavior. As highlighted by Amelink et al. (2020), this tolerance encompasses both the horizontal variation of the vehicle within the lane and the requisite space for maneuvering without infringing upon the adjacent lane.

According to Farah et al. (2018), the heightened precision in positioning control afforded by autonomous vehicles raises the prospect of reducing the width of cross-sectional elements, including lanes. This reduction may even be linked to the possibility of establishing new lanes exclusively dedicated to AV traffic. This subject will be explored further in this dissertation.

Anyway, anticipating the dimensions of future AVs remains a complex task, but literature already provides estimates for lane dimensions for AV traffic. On a more optimistic note, Othman (2021) proposes a lane width of 2.4 meters for roads designed to accommodate AVs. Conversely, an empirical study by García, Camacho-Torregrosa, and Padovani Baez (2020) involving automation level 2 vehicles suggests that a lane width of at least 2.75 meters is essential for the safe operation of AVs. This study underscores that in lanes narrower than 2.5 meters, human control of the vehicle becomes imperative.

Similarly, Marr, Benjamin, and Zhang (2020) recommend a minimum lane width of 2.8 meters, particularly emphasizing this necessity for narrow lanes lacking edge road markings. In line with a more conservative analysis proposed by Intini et al. (2019), a minimum lane width of 3 meters is advocated, primarily to accommodate public transport and larger vehicles.

4.1.1.5 Shoulders and Refuge Areas

Road shoulders already constitute a crucial element in road geometric design, serving various purposes such as emergency stops, accommodating broken-down vehicles, and facilitating vehicle maintenance operations. With the emergence of AVs, the importance of road shoulders is expected to become even more critical. These areas will be crucial in emergency recovery situations like technical failures or unexpected obstacles (Intini et al., 2019). Additionally, road shoulders can be designated safe stops in planned scenarios, particularly when the ODD for level 4 vehicles concludes.

The indispensable role of shoulders on highways with AV traffic implies that road segments lacking shoulders could pose significant challenges. As Nowakowski, Shladover, and Chan (2016) noted, structures such as bridges, tunnels, or entire road sections already devoid of shoulders present operational difficulties for these vehicles. Therefore, Tengilimoglu, Carsten, and Wadud (2023a) suggest that additional safety measures are necessary in such situations to account for potential obstacles caused by AVs, although specific details still need to be provided.

Road shoulders are often considered safe areas to stop, but using them for this purpose needs to be evaluated carefully. Ulrich et al. (2017) highlighted that some indications show that stopping AVs on shoulders is associated with a notable safety risk. Consequently, considering the shoulder as a stopping area at the ODD conclusion is not considered the safest option. Ideally, according to Amelink et al. (2020), AVs should proceed to a spacious parking area, facilitating a change of control to a human driver if necessary. This consideration becomes especially pertinent when defining the parameters of the vehicle's ODD.

However, the potential advantage of using the shoulder as a literal safe haven is worth considering, given its constant availability. Nevertheless, considering the associated safety risks for emergency stops on shoulders, it is recommended that passengers wait outside the vehicle while awaiting maintenance, as advised by Transport Systems Catapult (TSC, 2017).

On the other hand, if additional safe refuge areas beyond the shoulder are incorporated into road design, meticulous consideration is required to determine the frequency and spacing of these areas, a responsibility falling on road authorities (TSC, 2017). Liu et al. (2019) add that this analysis must be thorough to avoid emergencies where AVs must stop in the middle of the road.

4.1.1.6 Dedicated Lanes

A key consideration in the context of road infrastructure for AVs revolves around the potential implementation of dedicated lanes exclusively for these vehicles. This consideration becomes particularly interesting when mixed traffic scenarios arise involving the coexistence of level 4 or 5 AVs with lower-level vehicles.

As suggested by Konstantinopoulou and Ljubotina (2020) and Lyon et al. (2017), dedicated lanes are closely tied to heightened traffic safety. Consequently, the decision to incorporate such lanes should be a significant factor in the initial design phase of a highway. Despite the safety advantages, consistently providing dedicated lanes on all roads may not be economically feasible. Amelink et al. (2020) recommend that design guidelines specify the areas, types of roads, and traffic volume situations where including dedicated lanes is advisable.

In addition to the possibility of designing dedicated lanes, AV traffic could have a wholly segregated infrastructure. However, as Johnson (2017) and Mihalj et al. (2022) point out, this alternative can be costly and challenging in areas with limited space. Therefore, the more economically viable approach might be introducing dedicated lanes solely for AV traffic, especially considering the potential reduction in roadway width presented earlier in this dissertation. This reduction could facilitate the creation of new lanes serving as dedicated lanes, further encouraging the formation of vehicle platoons.

Indeed, implementing platooning activities further accentuates the advantages of adopting dedicated lanes. In dedicated lanes, as highlighted by the World Road Association (PIARC, 2019) report, the absence of mixed traffic enhances the predictability of other vehicles' behavior, thereby reducing uncertainty and risks associated with the maneuvers of non-AV vehicles. Thus, this lane segregation underscores the potential synergies between dedicated lanes and platooning activities, emphasizing improved safety outcomes in dedicated AV traffic environments.

4.1.2 **Road Markings**

Among physical infrastructure attributes, road markings stand out as extensively studied regarding their impact on AV performance. In the realm of autonomous mobility, cameras are the sensors responsible for detecting road markings and allowing the vehicle to follow them, ensuring accurate positioning within the lane. Currently, certain ADAS leverage this foundation, exemplified by functions like Lane Keeping Assist (LKA), Lane Departure Warning (LDW), and Lane-centering Control, which must be improved to support higher levels of automation.

According to a report by TSC (2017), the standards for road marking design do not require any changes with the introduction of autonomous mobility since they are already well-established. Therefore, AV operation should be based on existing standards. According to Milford, Garg, and Mount (2020), AVs have demonstrated satisfactory performance even without road markings within urban areas. It should be noted, however, that this particular finding cannot be extrapolated to rural environments, which are the primary focus of this study.

According to Gopalakrishna et al. (2021), three critical factors must be considered to optimize autonomous vehicle traffic concerning road markings: uniformity, design, and maintenance. The study revealed that the lack of uniformity in road markings is a significant issue frequently raised by the AV industry in the USA. This issue occurs because, while the local Manual of Traffic Control Devices (MUTCD) serves as the basis for US agencies, there is flexibility in this code that allows for different practices to be adopted in different regions, which poses a significant challenge. Therefore, Gopalakrishna et al. (2021) emphasize the necessity of prioritizing the standardization of road markings. Mocanu, Nitsche, and Saleh (2015) further stress the importance of standardizing road markings' color, luminance, and shape.

From a technical standpoint, standardizing road markings is crucial to ensure their interpretability by machines. However, global standardization can be challenging due to each country's varying regulatory requirements (Amelink et al., 2020; Ulrich et al., 2017). Given the impracticality of global standardization, Lu et al. (2019) propose a solution wherein each country maintains its own digital repository of road markings and traffic signs, accessible through a cloud platform. This approach enables AVs to adjust their databases accordingly when crossing borders.

Yet, the application of standardization can pose challenges in other domains. TSC (2017) highlights the difficulty of proposing standardization in private areas like parking lots and service stations. This obstacle can make it challenging for AVs to operate in these areas. Additionally, Huggins et al. (2017) raise a pertinent point regarding the necessity to establish standards for removing outdated markings that are no longer in use. These findings, therefore, highlight that standardization can be a challenging practice.

Regarding the second criterion highlighted by Gopalakrishna et al. (2021) — design — road markings must be visible and detectable by AVs during the day and at night in dry and wet road conditions. Irrespective of the road condition, AVs encounter heightened challenges in daytime operations under intense sunlight, primarily due to visual interference (Gopalakrishna et al., 2021; Marr; Benjamin; Zhang, 2020). Therefore, the design considerations for road markings should encompass the brightness and contrast relative to adjacent surfaces on the highway to enhance their effectiveness under varying conditions.

In addition to the influence of sunlight, regarding weather conditions, Mihalj et al. (2022) note that fog can pose a more significant obstacle to the operation of AVs than rain. This complication is attributed to the insufficient contrast conditions that arise in heavy fog. However, heavy rain can also present a potential challenge due to road markings' altered brightness and contrast conditions. To address issues related to wet road surfaces, Konstantinopoulou and Ljubotina (2020) suggest the installation of rumble strips on the edges or in the center of lanes. This approach aims to enhance the detection of road markings under adverse weather conditions.

Moreover, Huggins et al. (2017) and Mihalj et al. (2022) highlight additional factors influencing the legibility of road markings for AVs. These factors include variations in shapes (such as box dots), the use of different colors (yellow and white lines), the condition of the markings (whether faded, worn, or damaged), and the presence of unique lines or shapes, like zig-zag markings. As noted by Johnson and Rowland (2018), in countries where yellow lanes indicate construction zones instead of marking the division between lanes for opposite directions, this color discrepancy has led to issues in the LKA functionality of automation level 2 vehicles.

In the broader context of road marking colors, Pike, Barrette, and Carlson 2018 indicate that AVs more effectively detect white markings than yellow ones. However, the Federal Highway Administration (FWHA, 2018) notes that white markings on new concrete surfaces can compromise human legibility and present additional challenges for AVs. The PIARC (2019) report further highlights the difficulty of applying white lines in snowy conditions. Hence, selecting a marking color should consider various factors to ensure AVs' safe and efficient operation.

Furthermore, concerning the third criterion emphasized by Gopalakrishna et al. (2021) — maintenance — adherence to specific parameters outlined by the European Road Federation is necessary. These parameters include:

- A retroreflectivity of at least 150 mcd/m²/lx for road markings in dry conditions and a recommended minimum retroreflectivity standard of 35 mcd/m²/lx in wet conditions;
- A recommended minimum contrast standard of level 3 to 1 for road markings, implying that the luminance of the markings should be at least three times greater than the luminance of the sidewalk; and

- A minimum width requirement for longitudinal markings, set at 6 inches or 15 cm.

However, some studies suggest that among the specified parameters, some may take precedence over others. Xue, Irannezhad, and Karl (2022), for instance, assert that preserving contrast holds greater significance than maintaining the width of the marking. For this reason, Konstantinopoulou and Ljubotina (2020) recommend that contrast stripes adjacent to road markings should be two inches or 5 cm wide. Similarly, Konstantinopoulou, Jamieson, and Cartolano (2020) conclude that the width of markings is not as crucial as their condition. Additionally, their proximity to materials like concrete shoulders can pose challenges for AVs regarding detection.

Moreover, additional challenges faced by AVs in recognizing road markings may encompass the following: potential confusion of markings with bitumen lines used to seal cables or drainage elements, possible misidentification with pavement cracks, challenges presented by lane markings in work zones, and difficulties with discontinuous markings (Huggins et al., 2017; Najeh et al., 2020; TSC, 2017). In addition, Mocanu, Nitsche, and Saleh (2015) underscore the importance of appropriately removing residues from old road markings to prevent confusion and ensure accurate detection of current markings. Figure 10 highlights the issues involving past road markings and poor contrast.

Figure 10 - Issues involving road markings

Source: TSC (2017).

As for the absence of markings, Ritter, Kollmus, and Gasser (2020) note that it is unclear to what extent AVs can safely compensate for this. Hence, the regular maintenance of road markings, recommended every 13 months, according to Najeh et al. (2020), becomes crucial. Tengilimoglu, Carsten, and Wadud (2023b) emphasize that this maintenance routine can assist AVs in addressing challenges associated with vision technology, including variable lighting and adverse weather conditions.

After analyzing the detection of road markings by AVs, an insightful observation is that road markings will be dispensable with an adequate digital infrastructure. This change requires either connected vehicles, as noted by Amelink et al. (2020) and Ulrich et al. (2017), or reliance on digital maps, as Cucor et al. (2022), PIARC (2019), and Tengilimoglu, Carsten, and Wadud (2023b) emphasized. The subsequent section of this paper delves further into this topic. However, Farah et al. (2018) express reservations about this shift, citing the higher susceptibility of digital infrastructure to failure. Similarly, Johnson and Rowland (2018) underscore the ongoing importance of maintaining road markings even in a fully operational digital infrastructure, as pedestrians, cyclists, and public transport users may still rely on these markings for orientation.

4.1.3 **Traffic Signs**

Similar to road markings, vehicles with lower levels of automation can already detect traffic signs and make decisions based on them. This ability is achievable through the ADAS Traffic Sign Recognition (TSR) function. With TSR, autonomous vehicles can recognize road signs using their sensors, particularly cameras.

The safe operation of AVs relies heavily on their ability to recognize traffic signs. In contrast to human drivers, who can interpret signs intuitively, AVs lack this capability (TSC, 2017). Therefore, these vehicles must be able to identify traffic signs designed based on human perception. Harrington et al. (2018) stress the importance of ensuring that AVs have maximum visibility of traffic signs in all weather conditions and seasons to meet this requirement.

The current implementation of TSR implies that AVs will encounter some challenges in detecting road signs that have already been acknowledged. According to Gopalakrishna et al. (2021), some of these challenges include the lack of uniformity at the national level, difficulty in recognizing speed limit signs, the presence of text on signs, and the occlusion of signs due to vegetation. The PIARC (2019) report adds that theft is a noticeable challenge. Additionally, Huggins et al. (2017) raise several other challenges, including the inconsistency and/or absence of signage, variations in lighting, the legibility of electronic signs, and issues related to vandalism.

Specifically, the inconsistency of signage poses a significant challenge. This inconsistency can manifest in various ways, encompassing damaged signs, irregularities in terms of size, color, and text font, as well as variations in the design of signs (Huggins et al., 2017). According to the authors, vehicle manufacturers often complain about specific problems, such as speed limit signs with a circle or ring around the number in some cases but not others. Furthermore, Huggins et al. (2017) emphasize that traffic signs containing additional textual information can inhibit interpretation by AV systems. This information typically includes when the rules apply or whether the traffic sign applies only to specific vehicle categories.

In further exploration of sign design, Seraj et al. (2021) revealed that AVs exhibit greater ease in detecting signs bearing distinct shapes, such as "stop" or "give way" signs. However, the authors also identified challenges for AVs in recognizing numbers on speed signs. This difficulty was further corroborated by Roper et al. (2018), who found that vehicle systems often struggle to differentiate between digits 3, 6, and 8 on speed limit signs indicating 30 km/h, 60 km/h, and 80 km/h.

Furthermore, according to Mihalj et al. (2022), AVs must face the complexity of recognizing signs with multiple meanings, such as those attached to moving buses or trucks, as well as signs contingent on weather conditions, time, or the type of vehicle. The environment becomes even more intricate when a main highway is adjacent to a service road or entrance/exit ramp. In these instances, Huggins et al. (2017) conclude that signs may be misread due to their proximity to the main road.

In addition, AVs are also frequently reported to have problems with LED electronic signs. This issue arises from difficulties in legibility attributed to "bleeding" problems between characters caused by the luminance levels of the LEDs, creating a flashing effect (Huggins et al., 2017; Mihalj et al., 2022). To address this concern, Gopalakrishna et al. (2021) underscore that electronic signs must adhere to a standard refresh rate, ideally exceeding 200 Hz, to ensure more consistent and reliable detection.

Retroreflectivity also plays a role in TSR performance. However, unlike road markings, it is still not possible to quantify the threshold at which this condition becomes problematic for traffic signs. According to Gopalakrishna et al. (2021), excessive retroreflectivity can be detrimental, potentially obstructing the sensors of AVs. Nonetheless, it is imperative to establish minimum standards for this criterion. Seraj et al. (2021) support this idea, revealing that the impact of reflective conditions is significantly more substantial than that of climatic variations. Continuing on the topic of lighting, Xue, Irannezhad, and Karl (2022) point out the potential influence of glare and shadow conditions on the accuracy of machine reading for traffic signs.

As for vandalism, Huggins et al. (2017) highlighted its substantial impact on the visibility of traffic signs. In practical terms, a study by Babić et al. (2021)revealed that graffiti can render more than 98% of traffic signs unrecognizable. This issue is due to the obscuration of critical information by graffiti, posing challenges for both AVs and human drivers in identifying the signs.

Furthermore, another concern Huggins et al. (2017) highlight is signs positioned at the road's edge, susceptible to impacts from passing vehicles. While these impacts might not topple the sign, they can alter its orientation. Consequently, when a sign is improperly repositioned, its legibility is compromised, posing challenges for AVs. Similarly, signs rotated in relation to their original orientation can pose an obstacle. A practical study conducted by Roper et al. (2018) determined that the TSR function effectively recognizes signs rotated up to 45 degrees. However, signs may become incomprehensible to AVs at more severe angles, around 75 degrees.

Undoubtedly, akin to road markings, achieving standardization is the most significant challenge for the recognition of road signs by AVs. Once more, Huggins et al. (2017) emphasize the desirability of international consistency in traffic signs. Similarly, Konstantinopoulou and Ljubotina (2020) propose that standardizing sign types, symbols, shapes, heights, locations, and orientations could address some quality, visibility, and clarity issues AVs encounter. However, the PIARC (2019) report still identifies several obstacles to standardization, including:

- Differences in units: use of the metric system rather than the imperial system;
- Differences in shapes: use of diamonds, pentagons, or triangles for warning signs;
- Variation of colors: use of orange for temporary signs as provided for in the MUTCD and blue for mandatory information as provided for in the Vienna Convention; and
- Diversity of languages.

The transition toward digital infrastructure also opens up possibilities for reevaluating the role of traditional road signs. Liu et al. (2019) and Lu et al. (2019) suggest that the reliance on physical road signs might decrease as digital infrastructure becomes more prevalent. Amelink et al. (2020) support this idea by predicting that permanent signs will be accessible digitally by 2040. However, the importance of machine-readable information for temporary signs remains crucial.

Despite concerns about exclusively relying on digital formats for physical infrastructure elements, as discussed earlier regarding road markings, digitization has notable advantages. The PIARC (2019) report emphasizes that the combination of digitization and standardization can yield benefits in terms of redundancy. However, the report underscores that initially prioritizing standardization is more cost-effective.

Roper et al. (2018) propose prioritizing standardization on expressways, given the high traffic volume and the anticipated debut of advanced automation in these areas, to address immediate concerns. To enhance TSR accuracy, Pérez et al. (2010) suggest incorporating Radio-Frequency Identification (RFID) technology into traffic signs, improving readability for AVs. Similarly, Mihalj et al. (2022) recommend adopting hardware and software redundancy measures to ensure system reliability and availability. This approach, coupled with camera-based detection, could leverage LiDAR to offer detailed 3D information on sign position and reflectivity, ultimately enhancing TSR.

4.1.4 **Pavement**

Unlike the evident effects observed with road markings and traffic signs, the influence of road surface conditions on AVs' operation and vice versa will only be fully understood with the widespread adoption of higher automation levels. Nevertheless, the literature extensively discusses this topic, focusing on three factors Chen, Balieu, and Kringos (2016) highlighted: road capacity, vehicle speed, and lateral control. These factors will likely contribute to pavement wear when AVs are extensively adopted.

The introduction of AVs is anticipated to bring about effects like a decrease in the headway distance between vehicles and a rise in vehicle demand, potentially leading to an increase in road capacity. Considering this expectation, the research conducted by Chen, Balieu, and Kringos (2016) found that, for a 100% increase in capacity, the rut depth should increase by more than 35%.

Conversely, the correlation between the operational speed of AVs and pavement wear is of lesser concern on rural roads. The effects are typically more noticeable in urban areas, attributed to low-speed limits and narrow lanes — characteristic features of urban roads contributing to pavement wear (Johnson; Rowland, 2018). In quantitative terms, Chen, Balieu, and Kringos (2016) revealed that by elevating the speed limit of a road from 10 km/h to 50 km/h, pavement wear is halved.

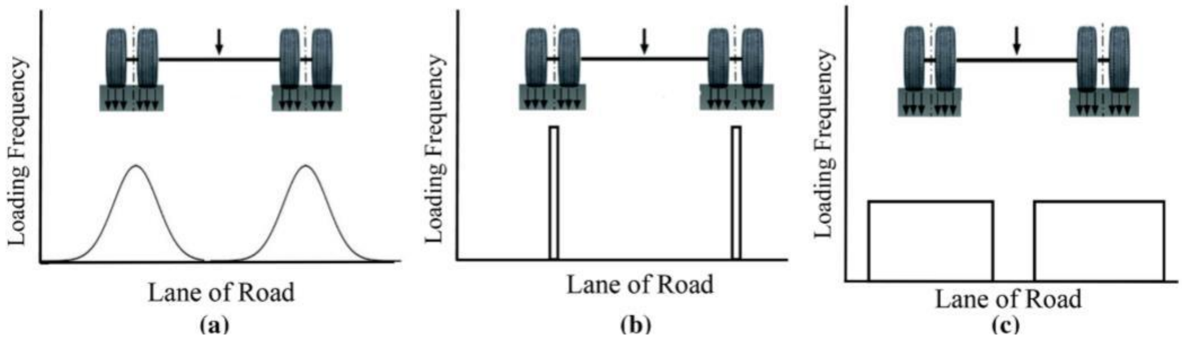
Nevertheless, one of the most notable factors to consider regarding physical infrastructure is the relationship between pavement degradation and lateral control. Automation, facilitated by automatic alignment, tends to enhance the ability of vehicles to stay within their lanes (Amelink et al., 2020). However, this improvement can lead to an augmented formation of ruts in the pavement.

Some studies have attempted to quantify the impact of lateral control, which is closely tied to wheel wander, i.e., the imprecise movement of a vehicle's wheels. According to Chen, Balieu, and Kringos (2016), with a wheel wander distance of 0.26 m, typical for conventional vehicles, the resulting rut depth is 0.43 mm. However, if the potential for AVs to eliminate lateral movement is considered (i.e., a wheel wander of 0 m), the study identified that the groove depth could increase to 1.19 mm. Similarly, Zhou et al. (2019) noted that the reduced tendency of AVs to wheel wander is linked to a 30% increase in pavement wear and a 20% reduction in its overall lifespan.

Moreover, the reduction of wheel wander can be indirectly influenced by a decrease in lane width, thus minimizing variability in lateral movement. Farah et al. (2018) suggest that this adjustment becomes particularly relevant if lane division control relies on vehicle communication rather than traditional road markings, thereby minimizing inaccuracies in lateral movements. Therefore, the potential space savings resulting from reduced lane width may outweigh any additional maintenance costs on the road surface (Manivasakan et al., 2021; Othman, 2021). However, a comprehensive cost-benefit analysis is essential in this scenario.

Thus, to minimize the negative impacts of AV operation on pavement wear, Tengilimoglu, Carsten, and Wadud (2023a) suggest a balanced approach involving speed limits, cross-section widths, and implementing a uniform lane-use strategy. The literature acknowledges this strategy as one of the most recommended measures for optimizing pavement performance. As emphasized by Othman (2021) and Rana and Hossain (2023), this approach entails programming vehicles to operate more uniformly across the entire width of the lane. Figure 11 compares Load Equivalency Factors (LEF) related to wheel loading distribution on a traffic lane. The comparison includes scenarios for (a) human-driven vehicles, (b) autonomous vehicles with zero wander, and (c) autonomous vehicles with a uniform distribution of wheel loading.

Figure 11 - Loading distribution for different wanders

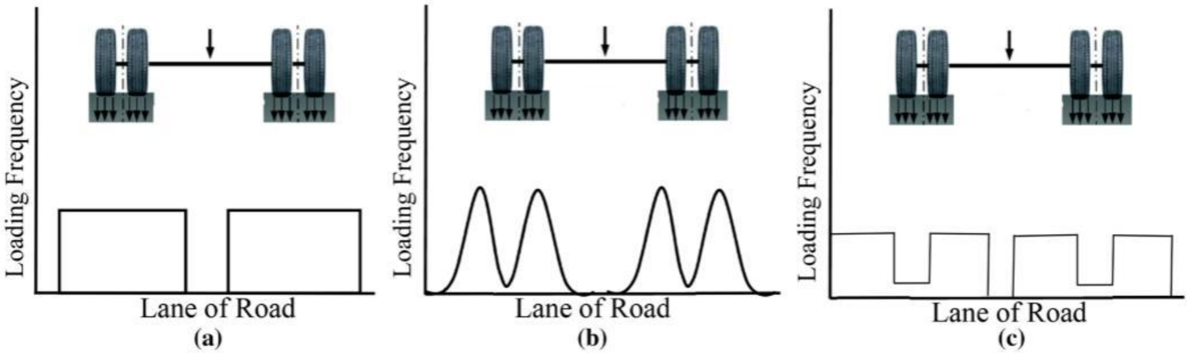


Source: Rana and Hossain (2023).

In a more technical context, Chen et al. (2019) explored the potential implementation of other lateral control modes in AVs. The two-section uniform distribution mode involves regulating AVs to achieve an even lateral spread within two defined lane sections, contributing to a more uniform stress distribution on the pavement surface. This mode allows AVs to occupy diverse positions in each section while maintaining overall uniformity. According to the study, applying this mode leads to a maximum 35% reduction in fatigue damage compared to the static lateral position mode. It extends the time required for pavement maintenance by up to 2.3 years.

Alternatively, lateral control using the double-peak Gaussian mode, also explored by Chen et al. (2019), involves guiding the lateral distribution of autonomous vehicles along a Gaussian curve with two peaks. In this scenario, autonomous vehicles cluster at two distinct points on the road. While less efficient than the two-section uniform distribution mode, it remains a viable consideration. The study indicates that employing this mode can reduce fatigue damage by up to 10% compared to static lateral control. Figure 12 presents a comparison of LEF concerning wheel loading distribution on a traffic lane across different modes, encompassing (a) uniform distribution, (b) double-peak Gaussian, and (c) two-section uniform loading distribution.

Figure 12 - Loading distribution for different control modes



Source: Rana and Hossain (2023).

The outcomes from Chen et al. (2019) align with the research conducted by Noorvand, Karnati, and Underwood (2017), who suggest an optimized scenario wherein autonomous trucks operate in separate lanes from non-autonomous trucks. In this setup, with an evenly distributed lateral control of autonomous trucks, there would not be a significant need to increase pavement thickness for enhanced efficiency. Consequently, the authors emphasize that alterations in pavement design would not be imperative, even with a vehicle fleet comprising up to 90% autonomous trucks.

However, examining the implications of autonomous vehicle operations on pavement design necessitates a parallel consideration of the reciprocal influence of pavement conditions on AV performance. Surface irregularities, including asphalt patches within cracks, surface depressions, and debris, hold sway over the efficacy of AVs. Gopalakrishna et al. (2021) underscore a prevailing uncertainty concerning AVs' adaptability to prominent road pathologies. Huggins et al. (2017) accentuates the adverse impact of potholes, positing that they can significantly impede the efficient functioning of AVs. The rationale lies in the transmission of impact to the steering mechanism upon encountering a pothole, potentially inducing steering wheel rotation (Wang; McKeever; Chan, 2022). Such occurrences may precipitate vehicular departure from the road at elevated speeds, particularly when confronted with deep potholes.

As posited by Johnson, 2017, potholes within a traffic lane pose a heightened risk, especially in scenarios where high-speed platooning is implemented. Najeh et al. (2020) advocate for recalibrating pavement maintenance intervals to a cycle of every 132 months (equivalent to 11 years) with the advent of AVs. This adjustment finds justification in the augmented impact on the road surface attributable to the platooning of heavy vehicles.

As suggested by Amelink et al. (2020), an alternative approach to mitigate the rise in life cycle costs of the pavement is to introduce variability in the lanes designated for platooning. Additionally, the studies conducted by Liu et al. (2019) and Xue, Irannezhad, and Karl (2022) propose that if specific lanes are exclusively allocated for AV traffic, materials characterized by increased stiffness and resistance to deformation, such as asphalt concrete, could be contemplated for the surface layer. Subsequently, there could be a potential for heightened maintenance frequency for the other pavement layers as a future measure.

Despite predictions, there is currently limited data available for agencies to assess the actual impacts of AVs on roads, as noted by Gopalakrishna et al. (2021). Many studies fail to consider the consequences of mixed traffic involving both AVs and human-operated vehicles, which also requires evaluation. However, the potential increase in pavement wear may not be significant unless the AV fleet maintains a considerable size or the level of automation reaches a high degree. Peloton Technology (2019), for instance, noted that in Level 1 truck platooning, permanent rutting, and pavement fatigue are mitigated due to the natural variation in driver control of each truck.

Immediate concerns regarding pavement conditions revolve around runway friction. Konstantinopoulou and Ljubotina (2020) highlight that the inability to estimate the coefficient of friction is a major factor leading to runway departures in the context of AVs. Additionally, as noted by Nitsche, Mocanu, and Reinthaler (2014), essential functions of AVs, such as collision avoidance systems, depend on an adequate coefficient of friction on the surface to execute emergency maneuvers effectively.

However, when vehicles are interconnected in the future, they will be able to adjust their speed more predictably to avoid abrupt braking, as suggested by Johnson, 2017. Consequently, as Montanaro et al. (2019) highlighted, AVs can potentially decrease accidents caused by skidding, given their ability to anticipate such situations through friction estimates. Hence, as Liu et al. (2019) emphasize, materials with lower slip resistance may be considered for the surface layer, although maintaining sufficient friction remains crucial.

4.1.5 **Structures**

4.1.5.1 Bridges

Current bridge design guidelines may require revision to accommodate the demands of AVs. This necessity arises because the design process for these structures currently does not consider the formation of truck platoons, potentially leading to additional overloading of the bridges. Consequently, numerous studies in the literature consistently advocate for the structural reassessment of bridges (Amelink et al., 2020; Huggins et al., 2017; Liu et al., 2019; Sanusi et al., 2022). Interventions, including strengthening measures, will be essential, particularly for long-span bridges.

Although bridge design guidelines exhibit variations from country to country, there are shared principles. As highlighted by Huggins et al. (2017), these guidelines typically rely on assumptions about the expected number of vehicles traversing the bridge concurrently, as well as other physical attributes, including the composition of vehicle types, axle spacing, and loads. The authors emphasize the necessity for these guidelines to delve into the specific effects of AV platoons on bridges, particularly in the context of heavy vehicle groups characterized by minimal gaps and limited lateral clearance.

According to Tohme and Yarnold (2020), the primary factors influencing the suitability of bridges for AV traffic include the number of trucks in a platoon and the distance between them. However, Thulaseedharan and Yarnold (2021) suggest that the spacing between trucks in a platoon has a moderate impact on bridge load demands, while the number of trucks has a relatively minor effect. Therefore, Sanusi et al. (2022) and Othman (2021) propose a less intrusive approach by advocating for increased spacing between trucks in platoons. Nevertheless, Thulaseedharan and Yarnold (2021) emphasize the need to address the most influential factor in the impact of AVs on bridges: the type of truck involved in the platoon, considering its size and weight.

In addition to the challenges related to platooning, Lyon et al. (2017) suggest that AVs may encounter additional difficulties when crossing bridges due to the absence of barriers and environmental lanes surrounding them. Furthermore, PIARC (2019) and TSC (2017) reports emphasize the need to reevaluate various aspects of bridge strength. This reassessment should encompass factors such as potential vehicle collisions with the bridge supports or its surface. Additionally, according to Sanusi et al. (2022), existing bridge design guidelines not only neglect the consideration of platooning but also overlook the potential capacity increase achievable by adding a new lane — facilitated by reducing lane width).

Nonetheless, as stated by Manivasakan et al. (2021) and TSC (2017), it is essential to acknowledge that adapting bridges on rural highways for AV traffic entails considerable financial implications. Therefore, according to PIARC (2019), the enhancement of bridge strength should be undertaken strategically. In other words, it is not imperative to reinforce every bridge; rather, the focus should be on critical bridges along freight transportation routes. Consequently, Othman (2021) suggests that constructing new bridges in a scenario of complete autonomous mobility offers a more conducive environment for establishing and adhering to new criteria tailored to support platooning.

4.1.5.2 Tunnels

The traversal of tunnels poses a complex challenge for AVs. Hence, Amelink et al. (2020) underscore the necessity for tailored provisions to ensure the precise positioning of vehicles and the secure operation of truck platoons within these structures. Notably, this demands a thorough examination of issues about lighting variations and the effective functioning of location services.

Concerning the first factor, Konstantinopoulou and Ljubotina (2020) highlight that a vehicle equipped with a machine vision system may experience a temporary reduction in camera visibility or complete blindness upon entering or exiting a tunnel. This phenomenon arises from abrupt changes in lighting conditions, leading to confusion in the vision sensors. The proposed solution to this issue involves adapting the vehicle rather than modifying the infrastructure. In this context, a paper by Bertozzi et al. (2011) suggests implementing a vision-based system capable of detecting the proximity of tunnel entrances or exits. This system enables other ADAS to adjust camera parameters, mitigating the impact of temporary blindness.

As for location systems, Konstantinopoulou and Ljubotina (2020) underscore the reliance of AVs on the Global Positioning System (GPS), a technology susceptible to inaccuracies and failures within tunnel settings. Consequently, the authors posit the necessity of a vehicular-centric adaptation to counter this issue. Proposing a solution, Konstantinopoulou and Ljubotina (2020) suggest integrating a fuzzy logic system capable of integrating GPS information with visibility measurements. This integration is envisioned to yield a more precise positional calculation for vehicles navigating through tunnels, thereby addressing the challenges posed by the inherent limitations of GPS technology in such contexts.

However, certain modifications directly to the tunnel infrastructure itself must be contemplated to guarantee the secure operation of AVs. Ulrich et al. (2017) highlighted that implementing new emergency systems and routes may become imperative, particularly in extensive tunnels. The rationale behind this proposition lies in the acknowledgment that platooning will allow more vehicles to occupy a tunnel simultaneously, increasing the risk of fire.

4.1.6 **Drainage**

Effective drainage systems play an essential role in upholding road safety. Insufficient drainage can lead to water accumulation on the paved surface, giving rise to hydroplaning and diminished traction. Johnson (2017) underscores the existing uncertainty regarding how AVs will perceive elements such as water on the road and flooding. Nevertheless, it is anticipated that AVs will exhibit superior performance in mitigating hydroplaning and skidding compared to their human-operated counterparts.

This observation may support the research findings of Tengilimoglu, Carsten, and Wadud (2023b), indicating that stakeholders perceive drainage as the physical infrastructure criterion with the most negligible impact on the safe operation of automation level 4 vehicles. However, the literature emphasizes challenges that AVs encounter in situations of insufficient drainage, in addition to the conventional challenges experienced by human-operated vehicles.

As highlighted by Tengilimoglu, Carsten, and Wadud (2023a), the primary challenges in insufficient drainage conditions encompass difficulties detecting road markings and identifying road edges on wet surfaces. The PIARC (2019) report highlights that AVs have an advantage in accessing real-time digital mapping. This benefit allows them to receive information on the friction state of the pavement surface, a topic to be further discussed in the subsequent section.

In summary, Tengilimoglu, Carsten, and Wadud (2023a) highlight the need for further research to comprehensively understand the implications of insufficient drainage on the autonomous vehicle fleet. Unlike well-explored elements such as road markings and signage, the research landscape regarding drainage and its impact on AVs is not yet consolidated.

4.1.7 **Lighting**

Similar to the limited research on drainage, the literature concerning the influence of lighting conditions on the functionality of AVs is relatively scarce. Nonetheless, it is crucial to acknowledge the potential repercussions of lighting conditions on these vehicles' operation, particularly in identifying traffic signs and entering and exiting tunnels.

As posited by Cucor et al. (2022) and Huggins et al. (2017), lighting conditions encompassing dim light and shadows may adversely impact the precision of AVs in detecting and recognizing traffic signs. Additionally, addressing the tunnel-related considerations, Ulrich et al. (2017) emphasize the potential necessity for specific lighting requirements, specifically to mitigate challenges arising during tunnel entry and exit due to abrupt alterations in the ambient lighting environment.

According to Tengilimoglu, Carsten, and Wadud (2023a), lighting color, intensity, and positioning can affect AVs' performance. However, additional in-depth research is warranted to delve more profoundly into the nuanced impact of these factors. A speculative proposition by Wang, McKeever, and Chan (2022) suggest that an optimal scenario would entail the absence of trees near roads to preclude complications associated with shadows.

Furthermore, an initial recommendation by Konstantinopoulou and Ljubotina (2020) to address lighting challenges involves enhancing lighting conditions, ensuring both brightness and quality, and positioning lights in closer proximity. In conclusion, the author emphasizes that inadequate lighting poses a heightened risk of traffic accidents for AVs compared to human-operated vehicles.

4.1.8 **Work Zones**

Road work zones present a formidable challenge for AVs. These environments undergo frequent alterations in infrastructure and traffic conditions, rendering them unpredictable for the seamless functioning of AVs. Consequently, in the study conducted by Tengilimoglu, Carsten, and Wadud (2023b), work zones were pinpointed as the foremost physical infrastructure factor significantly impacting the safe operation of AVs.

As per Huggins et al. (2017), road works constitute a notable disruption to regular services, potentially leading to an uptick in vehicle accidents. Nonetheless, the report from TSC (2017) emphasizes the need to distinguish between works occurring on high-speed highways and those on other roads, given the distinct challenges associated with each classification. The report underscores that roadworks encompass various traffic management measures and alterations to the road, such as the redirection of vehicles by authorized individuals or members of the public. This complexity can pose challenges for AVs in interpretation and navigation.

Mocanu, Nitsche, and Saleh (2015) highlight another obstacle related to the clarity of lane markings, emphasizing potential ambiguity between permanent and temporary lanes. Furthermore, according to Gopalakrishna et al. (2021), using temporary Traffic Control Devices (TCDs), as shown in Figure 13, instead of road markings can cause problems for AVs as these devices are typically less consistent and uniform than permanent markings. This lack of uniformity can make it difficult for AVs to navigate accurately. Additionally, as Huggins et al. (2017) pointed out, road work events can introduce several changes in lane width and orientation throughout the day. Consequently, construction zones' dynamic and complex nature poses a significant challenge for AVs.

Figure 13 - TCDs in work zones

Source: TSC (2017).

Hence, addressing the challenges presented by road works zones might necessitate implementing suitable digital infrastructure. As outlined by Xue, Irannezhad, and Karl (2022), functionalities such as communication features and digital maps, which will be discussed in the following section, are virtually essential for ensuring the safe operation of Level 4 or higher AVs within construction zones. In the context of communication, Poe et al. (2019) emphasize the importance of installing sensors on barricades and cones to monitor real-time traffic conditions continuously. These sensors facilitate immediate communication with the vehicle, providing data on the work zone's location, the status of lane closures, and traffic speeds.

Another significant point Amelink et al. (2020) raise is standardizing guidelines for road works across various countries and regions. In this context, standardization should encompass not only temporary road markings and equipment, such as cones and barricades, but also their proper positioning. Furthermore, the author emphasizes the necessity of harmonizing how information about the work, including its location and layout, is conveyed to AVs. This approach is crucial to eliminate ambiguities or misunderstandings in the interaction between AVs and road works.

4.2 IMPACTS IN DIGITAL INFRASTRUCTURE

The literature has comparatively explored the impact of digital infrastructure conditions on the operation of AVs to a lesser extent than the impact of physical infrastructure. This characteristic is possibly justified by the attainability of higher levels of automation even in the absence of robust digital infrastructure. Nevertheless, specific digital infrastructure criteria must be fulfilled to optimize autonomous mobility and enhance operational efficiency. This section delves into these criteria, focusing on two key aspects: communication and digital mapping.

4.2.1 **Communication**

Communication is pivotal in facilitating the exchange of information between vehicles and the environment, encompassing interactions with other cars and the road infrastructure. Notably, this functionality extends beyond the concept of an AV, as the vehicle concurrently functions as a connected vehicle.

Communication facilitates various forms of interconnection among vehicles, ranging from vehicle-to-vehicle communication (V2V) to vehicle-to-infrastructure communication (V2I) and vehicle-to-everything communication (V2X). Manivasakan et al. (2021) point out that the communication network represents the core technology for enabling V2X and connected autonomous vehicle systems. These technological advances are based on basic types of communication, including short-range V2V to short and medium/long-range V2I (Amelink et al., 2020). Thus, establishing a robust communication network forms the basis for enabling vehicles to engage with their surroundings.

As delineated in the previous section, incorporating V2X connectivity raises inquiries regarding the obsolescence of both vertical and horizontal road signs. Nevertheless, the insights provided by PIARC (2019) underscore that, notwithstanding the deployment of digital infrastructure accompanied by meticulous harmonization of signage, additional benefits related to information redundancy may be noted. In addition, AVs endowed with V2X technology can promptly relay real-time information to authorities concerning issues, including signage, road markings, and other maintenance-related problems.

Another significant advantage associated with integrating digital infrastructure for AVs is the role of V2X communication in enhancing safety within tunnels and facilitating the detection of emergency vehicles equipped with flashing lights (Xue; Irannezhad; Karl, 2022). Additionally, V2X connectivity is a prerequisite for alleviating sight distance criteria, bestowing substantial advantages upon AVs compared to traditional vehicles (Farah et al., 2018). These benefits underscore the transformative potential of V2X communication in the domain of road transport.

In the realm of connectivity for AVs, communication should involve various wireless communication technologies. Nevertheless, Huggins et al. (2017) underscored that uncertainty persists regarding which technologies can effectively facilitate this process. Eventually, it becomes imperative to delineate the communication methods to be adopted, with the primary criteria influencing the choice being latency (referring to the delay in sending and receiving communications) and data rate (measured in MBps), as highlighted by PIARC (2019).

According to PIARC (2019), the communication methods employed for Cooperative Intelligent Transportation Systems (C-ITS) can currently be categorized into three groups:

- Short-range communication: This approach involves ITS-G5, a Dedicated Short-Range Communication (DSRC) technology based on Wi-Fi with a reserved frequency band of 5.9 GHz. ITS-G5 offers limited geographical coverage, low latency, bidirectional communication capacity, and the use of small data packets.
- Long-range communication: This category includes cellular networks such as UMTS (3G), LTE (4G), and 5G. With a wider geographical range, varying latency from low to medium, bidirectional communication, and the utilization of larger data packets.
- Wide Area Broadcasting: This method relies on radio waves, for example, Digital Audio Broadcasting (DAB). Wide Area Broadcasting boasts a broad geographical reach, latency ranging from medium to high, limitations to one-way communication, and the use of medium-sized data packets.

TSC (2017) indicates that selecting a communication protocol for AVs is still in the developmental phase, with three contenders gaining prominence: mobile data networks (specifically 4G and 5G), ITS-G5, and a hybrid approach combining both. Ulrich et al. (2017) and Amelink et al. (2020) suggest that DSRC is expected to predominate in V2V communication, whereas mobile data networks will ensure V2I communication. A survey with stakeholders conducted by Wang, McKeever, and Chan (2022) revealed that participants believe any available communication channels can be applied in all contexts.

However, participants in the survey conducted by Wang, McKeever, and Chan (2022) also highlighted that cellular technology should be predominant in the near future. This preference is attributed to its substantial consolidation and the time required to develop alternative technologies. According to Mihalj et al. (2022), the efficiency of cooperative driving and intelligent road infrastructure does not depend solely on the availability of the communication medium but, in particular, on the number of vehicles equipped with suitable technology. In numbers, Cucor et al. (2022) emphasize the importance of ensuring a communication service availability of at least 99.99% to meet the real-time communication demands of AVs. Given its widespread presence in the current landscape, this requirement underscores the potential initial adoption of cellular technology.

Indeed, the advent of the 5G network could significantly influence the establishment of vehicular communication. This impact is substantial because increased automation requires real-time data transfer with low latency (Mihalj et al., 2022), a notable feature in 5G. Integrating this network into autonomous and connected vehicles would facilitate communication within a range of approximately 2 km, which can enhance activities like platooning. Additionally, the PIARC (2019) report highlights promising attributes of 5G, such as reduced delays, heightened reliability, and high-capacity data transmission, potentially enabling applications like detailed 3D mapping.

On the other hand, DSRC can bring certain advantages when used for short-range communication between vehicles. These advantages are primarily due to its extremely low latency and reduced susceptibility to fluctuations compared to 5G. In an ideal scenario of vehicular communication, a latency of less than 1 ms is anticipated (Cucor et al., 2022). Additionally, DSRC's dedicated frequency range, typically at 5.9 GHz (in the case of ITS-G5), enhances its consistency, although it remains susceptible to congestion (Mihalj et al., 2022). The authors also emphasize that DSRC can effectively support a range of up to 300 meters, but its performance may be constrained as the range increases or vehicle density rises.

In general, wireless networks are most commonly mentioned in the literature as a means to establish connectivity in the context of autonomous and connected vehicles. However, certain studies highlight the potential use of fiber optic cables in communication devices deployed along roadsides, referred to as Roadside Units (RSU). For example, Sanusi et al. (2022) mention that these units can be integrated into existing infrastructure elements like traffic signal poles or dynamic message sign structures. Saeed, Alabi, and Labi (2021) also underscore that, as higher levels of automated vehicles become operational, utilizing fiber optic cables could be beneficial, particularly for facilitating 5G connectivity. Nevertheless, Johnson (2017) notes that fiber optic cables may have cost implications and be restricted to urban environments.

Hence, the importance of utilizing fiber optic cables will likely be questioned. Findings from a survey conducted by Tengilimoglu, Carsten, and Wadud (2023b) revealed that stakeholders and experts frequently do not prioritize the availability of fiber optic cables and broadcast communication (such as DAB) as significant factors in preparing infrastructure for AVs. Interestingly, participants considered these two aspects the least important within the infrastructure criterion based on the conducted research.

To organize the content regarding communication methods for autonomous and connected vehicles, Table 4 summarizes the essential information about the discussed approaches.

Table 4 - Features of digital infrastructure technologies (to be continued)

Digital Infrastructure Technology	**Description and abilities**	**Range/availability**	**Limitations**
DSRC (Dedicated Short-Range Communications)	DSRC was developed with the primary goal of enabling technologies that support safety applications and communication between vehicle-based devices and infrastructure to reduce collisions. DSRC is the only short-range wireless technology that provides: designated licensed bandwidth, fast network acquisition, low latency, priority for safety applications, interoperability, and security and privacy.	Coverage varies depending on transmitter power and receiver sensitivity. However, this type of communication is generally best suited for one-way or two-way short to medium-range wireless communication. Because it is a dedicated wireless transmission method (based on the IEEE802.11p standard), it works independently of cellular networks, Wi-Fi networks, and satellite availability.	The limiting factor of DSRC is that it was specifically developed for short-range communication between V2V and V2I. It only supports relatively small data messages. The focus has been on enabling warning applications, not automation.
3G Cellular (Third generation cellular network or Universal Mobile Telecommunications Service – UTMS)	The 3G cellular network finds applications in wireless voice telephony, mobile internet access, fixed wireless internet access, video calls, and mobile TV. The 3G network operates on the UMTS platform, which utilizes wideband Code Division Multiple Access (WCDMA) for both downlink and uplink data transfers.	Multiple 3G networks operate worldwide in different frequency bands. Coverage depends on the distance from the nearest cell tower and may vary between carriers. Capacity on the network in terms of usable data rates can vary significantly depending on congestion and the number of devices connected to any individual base tower. The peak data rates published by the service providers are listed as peak values.	A limitation of cellular technologies is that they require additional antennas at each base station to increase data transmission rates. Being a public cellular network, which is not dedicated for sole use by AVs, it is prone to be unreliable in terms of capacity and availability as data rates may be significantly less than the peak data rates, and service outages may be experienced by the service provider. Coverage is affected by obstructions (i.e., buildings, vehicles, trees, and hills) which act to reduce the signal level available at the mobile device. Requires a data plan.

Table 4 - Features of digital infrastructure technologies (continued)

Digital Infrastructure Technology	Description and abilities	Range/availability	Limitations
4G – LTE (Long Term Evolution) (Fourth generation cellular network)	The 4G – LTE network technology, with a typical range of 5 km from the base station, ensures strong signal strength for communication. It offers Quality of Service (QoS) provisions, achieving latency of less than 5 ms in the radio network and meeting excellent requirements for AV latency. Employing different interfaces for downlink and uplink, the LTE network optimizes wireless connections, providing peak speeds of up to 100 Mbps for downlink and 50 Mbps for uplink.	LTE supports deployment on different frequency bandwidths, as noted. Allows high-speed data communication (reception: 100 Mbps or higher and transmission: 50 Mbps or higher). Low-delay transmission (less than 5ms).	Requires additional antennas at the base station locations for increased data transmission. Coverage is affected by obstructions (i.e. buildings, vehicles, trees and hills) which act to reduce the signal level available at the mobile device. Additional handshakes required across cellular services could possibly result in some latency issues – which must be considered. Requires a data plan.
5G (Fifth Generation Cellular Networks)	The 5G network builds on the 4G LTE network but with enhanced peak download and upload speeds and lower latency. Increased peak data rate, 3 Gbps (downlink) and 1.5 Gbps (uplink). Low latency (1 ms) and high capacity (3 Gbps).	5G technology is expanding globally, with ongoing implementations in various regions. While not fully available worldwide yet, significant progress has been made in its deployment. The availability and coverage of the 5G network can vary widely depending on location and telecommunications operators' progress.	The cost of infrastructure could be high initially. Technologies are still evolving. Requires a data plan.
Wi-Fi	The Wi-Fi or Wireless Local Area Network (WLAN) primarily uses the 2.4 GHz frequency and is based on the IEEE 802.11 standards.	Wi-Fi technology is widely adopted worldwide and is available in many parts of the globe. It is commonly used in urban environments, homes, businesses, educational institutions, and public places, providing wireless connectivity for mobile devices and computers. The range of these networks is very limited (perhaps up to 10-20 meters).	Range, latency, and contention issues are problematic for Wi-Fi. However, if connections are not critical for security and are only required for high-capacity, low-criticality updates, such as mapping, this can be a usable form of communication.

Source: Adapted from Huggins et al. (2017).

4.2.2 **Digital Mapping**

Digital maps can assist in AVs' safe and efficient operation by visually representing the surrounding physical environment. These maps are constructed in layers using Geographic Information Systems (GIS), with each layer dedicated to specific types of information. According to Amelink et al. (2020), this information assists the vehicle in comprehending its exact position, planning beyond sensor range, maintaining contextual awareness of the environment, and possessing local knowledge of traffic rules.

Employing digital maps in AVs can significantly complement the function of sensors. Sensors offer real-time visibility of the vehicle's immediate surroundings, while maps provide a broader perspective, allowing vehicles to anticipate critical situations. In this context, Ritter, Kollmus, and Gasser (2020) refer to these maps as "extended sensors" because they enable the anticipation of road conditions beyond the limited range of onboard sensors. This capability allows vehicles to adjust maneuvers in response to the anticipated scenario.

Nevertheless, not all maps intended for use in AVs will be identical. Cucor et al. (2022) suggest that there might be variations in accuracy and the extent of additional information offered regarding road infrastructure. Maps must possess high detail, precision, and a wealth of attributes for optimal effectiveness. This condition encompasses features such as a three-dimensional portrayal of road geometry with decimeter accuracy (Farah et al., 2018). Additionally, the PIARC (2019) report indicates that digital maps can form the basis for developing digital twins — a concept where real-time data supplements static maps, generating a dynamic digital depiction of the built environment.

In addition to creating digital map databases, AVs should be guaranteed to ascertain their location precisely on the provided map. Huggins et al. (2017) propose accomplishing this using the Global Navigation Satellite System (GNSS) for absolute positioning, complemented by onboard sensors for determining relative position. Furthermore, AVs may incorporate Satellite-Based Augmentation Systems (SBAS) to enhance GNSS accuracy. This suggestion becomes particularly valuable as Wang, McKeever, and Chan (2022) indicate that the precision of digital maps should be below 10 centimeters.

Indeed, the survey conducted by Tengilimoglu, Carsten, and Wadud (2023b) involving stakeholders and experts highlighted the crucial nature of the "positioning and location" criterion as the foremost infrastructure requirement for AVs. Huggins et al. (2017) further underscore that, at present, various positioning challenges must be addressed to guarantee the secure functioning of AVs. The challenges mentioned by the authors include issues related to tunnels, urban canyons, and multi-level parking, as well as concerns such as spoofing (the transmission of false GNSS signals), manipulation or interference with signals, solar flares, and the inherent susceptibility of GNSS to failures.

Digital maps will likely become more established after the introduction of AVs. This delay is because, as (Mihalj et al., 2022) indicate, a certain level of AV adoption is necessary for high-definition digital maps to be economically viable for their providers. Additionally, the question arises regarding which entity will be responsible for providing these maps. According to Wang, McKeever, and Chan (2022), the development of digital maps should not be seen as the duty of Independent Operating Organizations (IOOs). Instead, the authors propose that specialized companies in the industry gradually make these maps available to other AV-related companies as the technology matures.

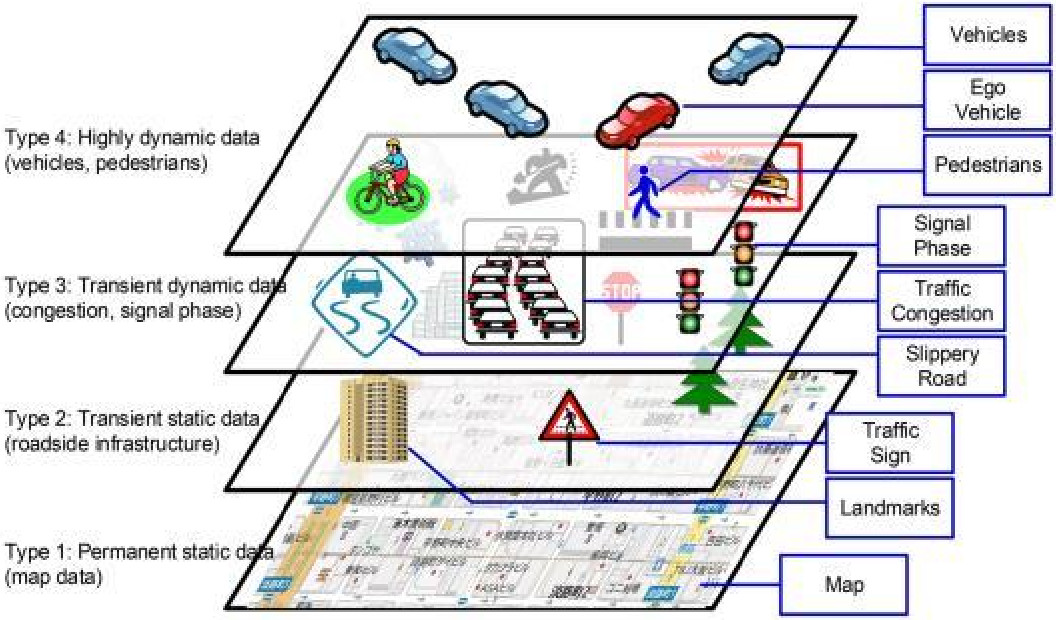
Another observation regarding digital maps is that they should operate bi-directionally. In this sense, they must be able to receive information from the vehicle fleet about potential incidents and also provide it (Ritter; Kollmus; Gasser, 2020). Harrington et al. (2018) also emphasize the need for real-time map updates, incorporating information on work zones, temporary road closures, weather conditions, and other relevant factors.

However, in the case of work zones, the real-time compliance of traffic management layouts may not always match the previously agreed-upon designs. This discrepancy arises because, in these situations, road workers manually position traffic cones, which can be reallocated without prior notice (TSC, 2017). Therefore, Xue, Irannezhad, and Karl (2022) emphasize the demand for changes in current practices in work zones to address this specific issue.

In the broader context, digital maps are expected to gradually substitute physical infrastructure components, including lane markings and signs. This shift towards dynamic digital equivalents can potentially reduce the need for physical maintenance of these elements. However, Tengilimoglu, Carsten, and Wadud (2023b) emphasize that for this transition to happen, AVs must have reliable and timely access to all digitized and constantly updated information, a process that may take some time.

As the implementation of digital maps advances, the variety and sophistication of these tools will likely continue to expand, ranging from basic navigation maps to more dynamic and robust maps. In this context, the research by Shimada et al. (2015) proposes the concept of a Local Dynamic Map, wherein information can be organized in layers that correspond to the progression of mapping technology. Figure 14 illustrates the types of layers according to Shimada et al. (2015).

Figure 14 - Layers of a digital map



Source: Shimada et al. (2015).

5 DISCUSSION

5.1 ADAPTATIONS TO BRAZILIAN ROADS

Examining the suitability of road infrastructure for AV traffic in the Brazilian context brings attention to the significant challenge posed by the country's vast territorial expanse. The extensive dimensions of the country and its substantial road network present challenges in achieving the safe operation of AVs. Adapting the national-scale road infrastructure comes with considerable temporal and economic costs. This section delves into the opportunities and challenges of preparing Brazilian highways for AV traffic, relying on insights from agencies' reports and current manuals and guidelines in Brazil.

5.1.1 **Physical Infrastructure**

Once more, the discussion on physical infrastructure begins with the geometric design of roads. Concerning this criterion, the analysis of this study has concluded the following conditions:

- The design of elements such as tangent length, sight distance, vertical curve length, and lane width already allows AVs' safe operation by current guidelines. Adjustments can be made to optimize the design of these elements only if a scenario of fully autonomous mobility is considered, which is still hypothetical at the moment.
- Although AVs can operate on road sections without shoulders, this is highly undesirable due to uncertainties about their behavior in emergencies. Given their reliance on sensors and algorithms, it is crucial to ensure adequate space for AVs to react to unexpected events.
- In addition to shoulders, designing safe refuge areas is recommended. These areas serve a similar purpose to shoulders but provide additional safety measures.
- Lastly, while not essential for AV operation, dedicating lanes exclusively for AVs could bring benefits such as facilitating platooning, enhancing efficiency and safety, and reducing interactions with conventional vehicles. However, creating an entirely separate infrastructure for AV traffic is currently unfeasible.

In Brazil, the immediate adaptation of the mentioned elements faces significant challenges. The main issue is the absence of shoulders on approximately 44% of the studied Brazilian road network, as indicated by CNT (2022a). This issue poses a formidable obstacle to short-term adjustments. The challenge is exacerbated by the fact that, among the roads with shoulders, nearly 15% exhibit poor conditions or are even destroyed (CNT, 2022a). Although the lack of shoulders does not make it impossible to operate AVs, it introduces potential safety concerns. Adapting to this situation in the Brazilian context will require substantial investments, time, and considerable effort.

Furthermore, the presence of safe refuge areas can pose challenges in Brazil. Adapting and expanding the existing infrastructure to meet this criterion is particularly difficult. In the United Kingdom, which has considerably smaller dimensions, these areas are commonly found on highways where the shoulder has been converted into an additional lane (TSC, 2017), as shown in Figure 15. These areas will become even more helpful when AVs are fully operational on such road sections.

Figure 15 - An emergency refuge area in the United Kingdom

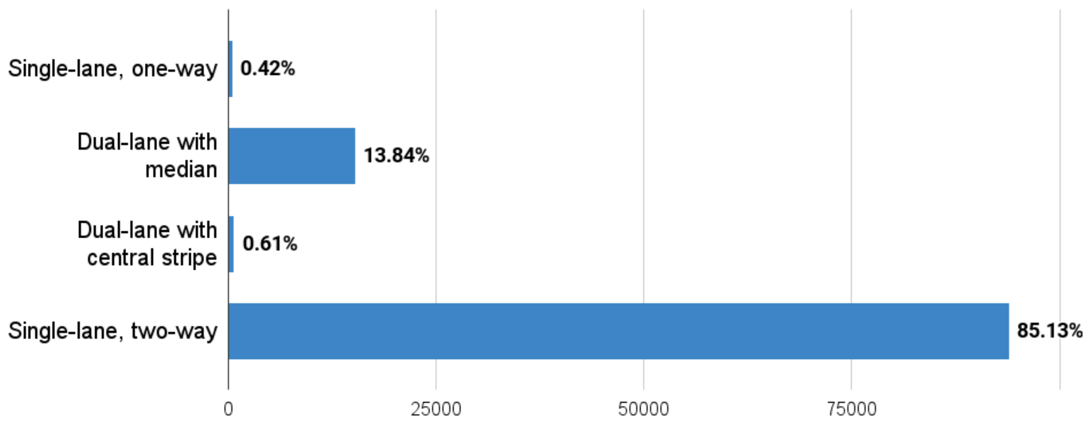
Source: TSC (2017).

Most Brazilian roadways were not initially planned to accommodate refuge areas. Moreover, the country's vast size poses challenges to strategically implementing refuge areas. A significant challenge is also the need for awareness and education among road users, as they must understand the presence and correct utilization of refuge areas. Complying with the guidelines for these areas will be essential to ensure they serve their intended purpose.

In addition, establishing exclusive lanes for AV operation could be a feasible option for certain road sections under specific conditions. For example, this approach may prove cost-effective on highways with multiple lanes, especially those with three lanes in each direction. In such cases, one lane could be allocated for AVs, another for conventional light vehicles, and a third for traditional heavy vehicles, including trucks. Conducting a comprehensive cost-benefit analysis is crucial for a more detailed assessment. Nonetheless, adopting this strategy would not only optimize financial investment but also reduce environmental impact, streamline implementation, and enhance the overall efficiency of road infrastructure utilization.

Despite the conceptual viability of this approach, careful consideration is essential to assess its potential effectiveness within the Brazilian context. CNT (2022a) does not explicitly delineate the percentage of Brazilian highways featuring three lanes in each direction; however, it underscores this characteristic in the context of duplicated highways. Approximately 14.4% of the surveyed highways exhibit duplicated lanes, while over 85% are single lanes (CNT, 2022a). A detailed breakdown of this information is provided in Figure 16. Nevertheless, highway segments boasting three or more lanes will likely be concentrated on routes critical for freight transport. This consideration is particularly pertinent as promoting platooning activity is a primary rationale for implementing exclusive lanes, potentially fulfilling this condition.

Figure 16 - Distribution of road types in Brazil per extension in kilometers



Source: Adapted from CNT (2022a).

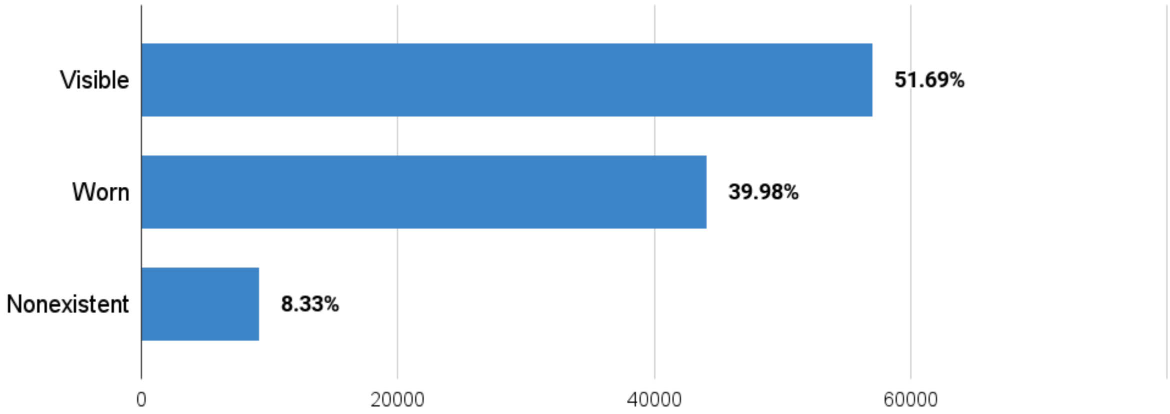
The adherence to standards for horizontal markings on rural highways is crucial for adapting Brazil's infrastructure to facilitate AV operations. Meeting the guidelines outlined in the Brazilian Traffic Signage Manual (MBST), especially in Volume IV - Horizontal Signage (CONTRAN, 2022), is crucial to ensure the safety of autonomous vehicle operations. Unlike geometric design criteria widely recognized for their significance, adherence to the MBST guidelines is almost indispensable. This manual establishes specific norms concerning the width and distance between signaling lines and using distinct colors for particular purposes.

The MBST is fundamental for standardizing road markings throughout Brazil. In contrast to other federal countries like the United States, where guidelines may vary between states, Brazil maintains remarkable uniformity in road markings due to this manual. However, this accomplishment presents another opportunity: exploring the potential for regional or even continental standardization of horizontal signage. This approach could prove especially beneficial among Mercosur countries, enhancing the facilitated circulation of vehicles across the region.

Regarding colors, if difficulties in the performance of yellow road markings compared to white ones are confirmed, it is advisable to explore strategies for enhancement. In this context, it is pertinent to consider the feasibility of training AV algorithms to more precisely identify yellow markings, which could be economically advantageous. Concerning the width of the markings, the guidelines outlined by the MBST already fulfill the minimum criteria for AVs. However, it would be beneficial for the MBST to incorporate guidelines related to minimum retroreflectivity standards to ensure legibility by AVs, as this is currently not addressed in the manual.

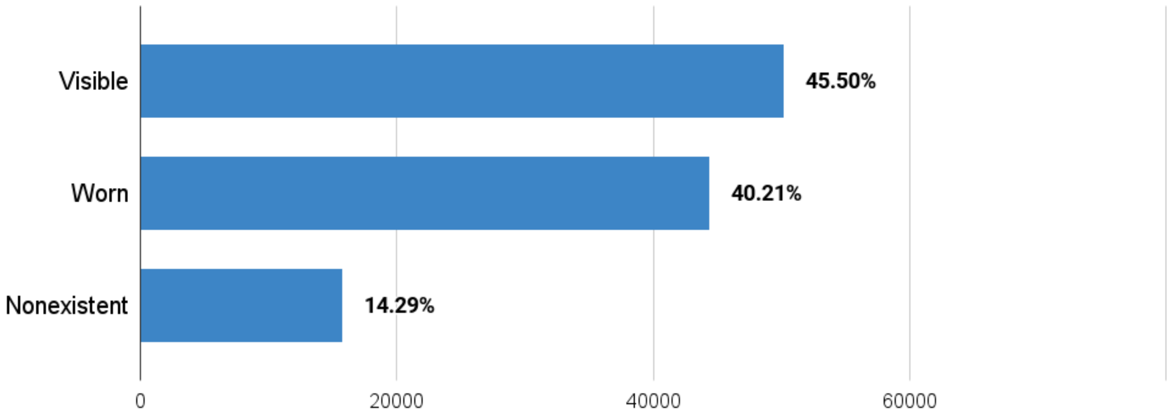
Nonetheless, despite the criteria set by the MBST for horizontal signage, practical adherence to these recommendations is often lacking. According to the CNT (2022a), center markings are absent in 8% of the surveyed road network, with 40% showing signs of wear. Similarly, edge markings are absent in 14.3% of the network, with wear conditions observed in 40.2%. Figures 17 and 18 illustrate these findings. Thus, maintaining horizontal signage conditions should be a pressing priority in Brazil.

Figure 17 - Conditions of center lanes in Brazil per extension in kilometers



Source: Adapted from CNT (2022a).

Figure 18 - Conditions of edge lanes in Brazil per extension in kilometers



Source: Adapted from CNT (2022a).

Also, in the Brazilian context, vertical traffic signage is regulated by the MBST across volumes I, II, and III (CONTRAN, 2022). This dissertation excludes the analysis of Volume V of the Manual, which covers traffic signalization, as it is presumably irrelevant to rural road networks. Instead, attention is directed towards Volume III, which deals with indication signage. This type of signage, laden with textual information, can present a noteworthy challenge for AVs navigating the national territory.

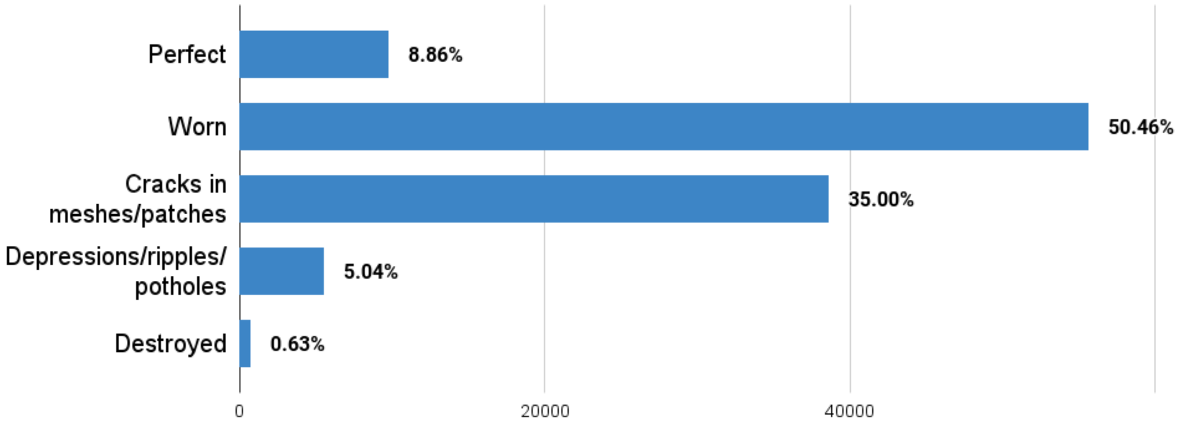
Issues of theft and vandalism of traffic signs also pose potential significant challenges for AVs in Brazil. Although national agencies' statistics do not provide specific numbers on this topic, it is widely acknowledged that such incidents are prevalent in Brazilian culture. To address these issues, implementing measures such as applying coatings and anti-graffiti paints on traffic signs has proven to be an effective strategy in preventing graffiti. Additionally, combating theft may be efficiently approached through the adoption of registration and tracking systems, along with the use of robust materials.

Moreover, the continental standardization of road signage is a medium-term strategy worth considering. This standardization should involve adopting uniform colors, symbols, and formats for all signs and implementing retroreflectivity standards to ensure visibility across various conditions. While language remains challenging, incorporating universal symbols and deploying bilingual signs when needed can address this issue. As a more advanced measure, contemplating using RFID technology in signs could eliminate such problems, thereby contributing to the safety and efficiency of AV operations.

As for the pavement, the analysis highlights the importance of directing efforts towards improving vehicle behavior, emphasizing uniform distribution control rather than considering modifications to the pavement structure, such as increasing thickness. However, uncertainties remain regarding how AVs will respond to the various issues present on road surfaces. Despite these uncertainties, improving road surface conditions is undeniably crucial for optimizing the safe operation of these vehicles.

As per CNT (2022a), a mere 8.9% of Brazil's road pavement is considered optimal. Contrastingly, a substantial 50.5% is in a worn-out state. Moreover, 5% of the pavement displays depressions, potholes, and ripples, while an additional 0.6% is completely deteriorated. Figure 19 illustrates a graphical representation of these findings. The survey highlights that 35% of the Brazilian road network exhibits cracks or patches. This issue can be particularly challenging for AVs as these imperfections may be misinterpreted as road markings.

Figure 19 - Condition of pavement surface in Brazil per extension in kilometers



Source: Adapted from CNT (2022a).

However, it is essential to exercise caution when analyzing the findings from CNT (2022a) and extrapolating from them to assess the suitability of a highway for AVs operation. This caution is warranted due to the potential inherent bias in such surveys, as their primary aim is to identify areas for improvement in Brazilian highways. Consequently, this perspective must be factored in when deliberating on the outcomes of this study. Acknowledging this bias can facilitate the development of more equitable and efficient policies and strategies for AV operation on Brazilian highways.

Adopting pragmatic approaches that optimize AV operations is opportune concerning structural components like bridges and tunnels. Suggesting a structural reassessment of bridges in the Brazilian context is impractical due to the high associated costs. Instead, a feasible option is to design AV platoon features to navigate existing bridges. If possible, any consideration of structural reassessment measures should be seen as a long-term strategy, focusing on critical cargo transportation routes. In certain situations, a more efficient approach could be to plan the movement of a platoon based on the structural characteristics of each bridge along a highway. In this scenario, as the platoon approaches a specific bridge, it would adapt its configuration in response to factors such as the number of trucks and the distance between them, taking into account the specifications of the bridge.

Furthermore, a practical and effective solution to mitigate the temporary blindness effect on AV cameras caused by the sudden change in lighting conditions is to install artificial lighting at the entrance and exit points of tunnels. Creating a transitional structure from the open road to the tunnel interior can also help in this regard in the medium term.

Regarding drainage, if the guidelines from the Highway Drainage Manual (DNIT, 2006) are adhered to, it should suffice. Currently, AVs may not necessitate substantial road changes in this aspect, as existing drainage systems are expected to manage rainy conditions, ensuring traffic safety effectively. Thus, drainage is not an immediate worry when adapting roads for AV operations. Instead, the focus should be on the visibility of horizontal signage, which must remain clear even in wet surface conditions.

Similar to drainage, there is limited literature on how lighting conditions specifically affect the operations of AVs. As previously discussed, adequate lighting plays a significant role in crucial functions like recognizing traffic signs and navigating tunnel entrances and exits. However, to provide more detailed recommendations, further comprehensive research is necessary to elucidate how factors such as color, intensity, and positioning of lighting sources impact AV operations on rural roads.

Work zones may pose the most significant challenge for AV operations and are indeed the primary obstacle to overcome regarding infrastructure criteria. Achieving full functionality in those environments is likely only possible with adequate digital infrastructure. In this scenario, sensors on barricades and cones would continuously monitor traffic conditions in real-time, facilitating direct communication with vehicles. This communication would provide crucial information such as the work zone's location, lane closure status, and real-time traffic speeds. Thus, the operation of Level 5 vehicles remains impractical until solutions are implemented in this regard since a human driver would always need to assume control in work zones.

As a more immediate measure, proposing the standardization of guidelines for road construction across countries and regions could be considered. This standardization should cover temporary road markings and equipment and include comprehensive information about the work, aiming to eliminate ambiguities. Therefore, the standardization of guidelines and the subsequent implementation of a digital infrastructure-based approach should contribute to adapting road work zones for the safe operation of AVs.

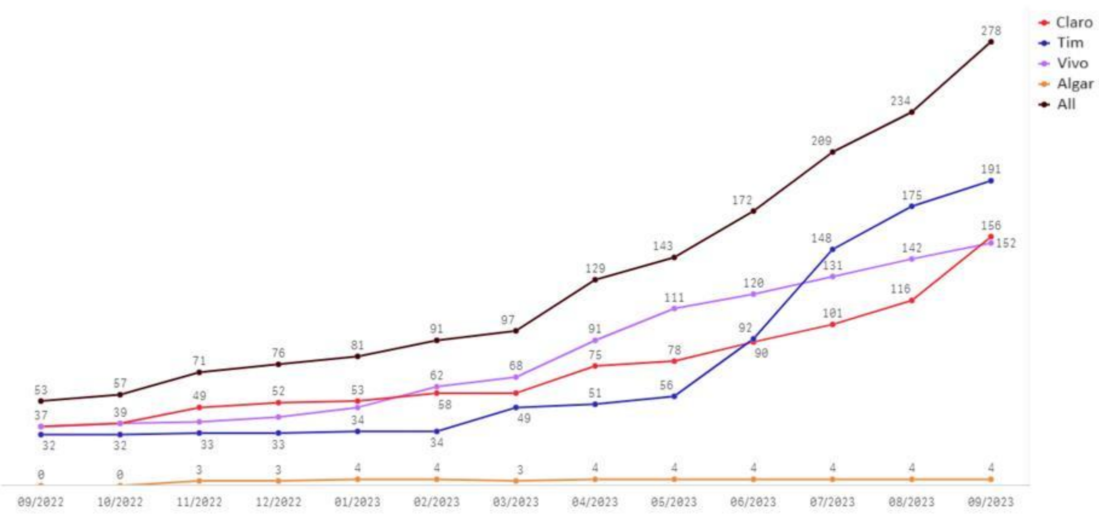
5.1.2 **Digital Infrastructure**

Regarding digital infrastructure, the analysis in this dissertation suggests that communication and digital mapping criteria are crucial for enhancing the safety of AVs. The importance of the first criterion becomes evident when AVs evolve beyond mere autonomy and operate as connected vehicles. In this circumstance, the so-called Connected Autonomous Vehicles (CAVs) will provide additional safety benefits through information redundancy.

However, a robust communication network is crucial to transition vehicles into CAVs. As discussed in this dissertation, mobile data networks are initially likely to support V2I communication, with V2V communication relying on DSRC, such as ITS-G5. Nevertheless, given the widespread availability and low latency of cellular networks, this technology is viable for the various forms of vehicle communication. Leveraging 5G technology, renowned for its minimal latency and high-speed data transfer capabilities, should be employed for this purpose.

5G network signal was introduced in Brazil in 2022, and as of September 2023, it was accessible in 278 cities, according to the National Telecommunications Agency (ANATEL, 2023a). The network has experienced substantial expansion. Figure 20 illustrates that in the same month in 2022, only about 53 cities had adopted this technology, indicating a fivefold increase in the number of covered cities within 12 months.

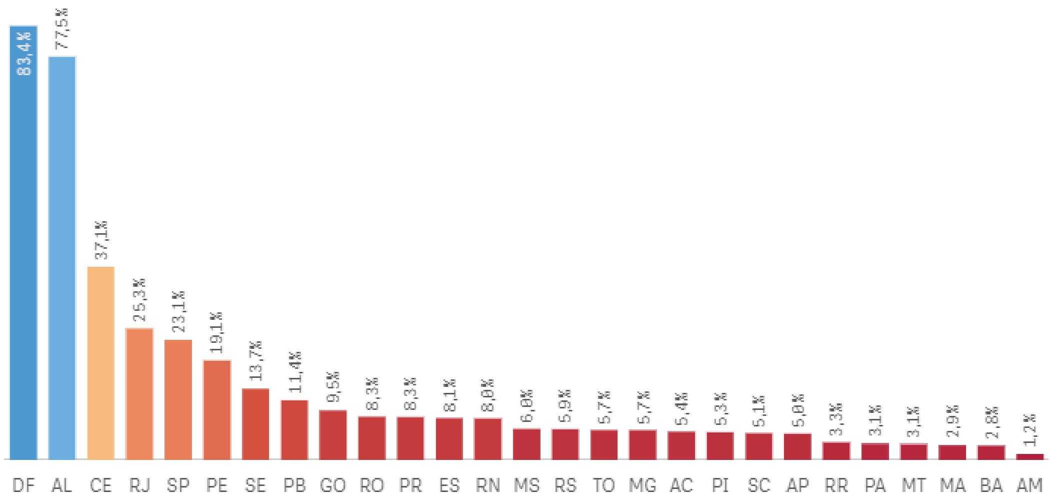
Figure 20 - Number of cities covered by 5G in Brazil by company



Source: Adapted from ANATEL (2023a).

However, in the context of AV traffic on rural highways, having 5G network coverage data specifically for the road network may be more relevant than analyzing coverage by cities. In this regard, ANATEL (2023b) provides data on the availability of 5G coverage for federal roadways. This analysis considers 121,780 kilometers of federal roadways registered in the National Road System of the National Department of Transport Infrastructure (DNIT). The percentage of road length covered by the 5G network in each state is displayed in Figure 21.

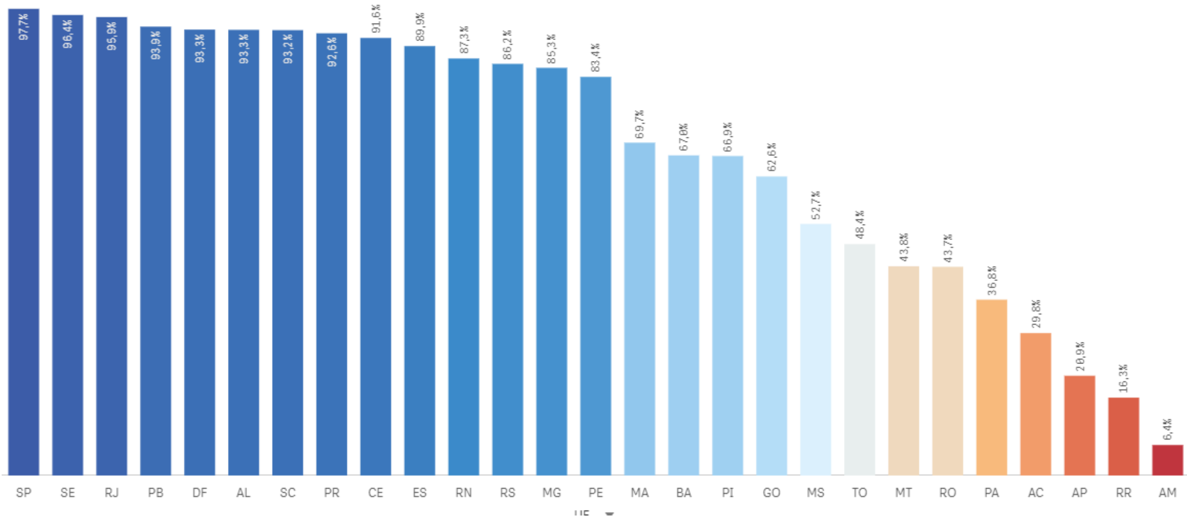
Figure 21 - Percentage of road length with 5G coverage by state



Source: ANATEL (2023b).

Figure 21 indicates that 5G coverage in Brazil is currently limited, particularly for CAV operations. However, this coverage is anticipated to gradually expand, following a pattern similar to the introduction of the previous technology, 4G. In 2012, 4G signals were introduced in Brazil, and ANATEL's data illustrates its extensive coverage on federal highways, as depicted per state in Figure 22.

Figure 22 - Percentage of road length with 4G coverage by state



Source: ANATEL (2023b).

Despite the impressive statistics on 4G coverage provided by ANATEL (2023b), particularly in Brazil's South and Southeast regions, the actual user experience, and consequently, that of CAVs, may not be as positive. This discrepancy arises from various factors that can compromise the efficiency of utilizing this communication network, such as:

- Signal quality, as interferences and natural obstacles can impede signal reception, even in areas officially designated as covered;
- Device and equipment conditions, as older or less advanced models may exhibit subpar performance in challenging coverage conditions;
- Service type, given that the percentage reported by ANATEL pertains to the combined coverage of all telecommunications providers;
- Subjective perception, as the coverage might be technically sufficient, but user expectations regarding performance may remain exceedingly high.

Thus, 4G coverage may be extensive in terms of geographical area, but individual user experiences can vary due to several factors affecting signal quality. The data released by ANATEL (2023b) also encompasses sections of federal highways passing through urban areas. Consequently, the comprehensiveness of 4G coverage is anticipated to be higher in cities. Considering these urban sections could result in an overall enhancement of 4G coverage along the highways.

On the other hand, it is also essential to shed light on the conditions of digital mapping of Brazilian highways, which is another aspect of digital infrastructure that will play a critical role in the operation of AVs. DNIT stands out as the primary source for publicly accessible georeferenced data on federal highways in Brazil. Supplementary data can be sourced from other entities, such as the Brazilian Institute of Geography and Statistics (IBGE) and certain state agencies, providing additional georeferenced information. However, the effectiveness of introducing AVs into the Brazilian road network hinges significantly on the accuracy of these digital maps.

To ensure a safer and more efficient functioning of AVs, high-precision mapping for federal highways with an accuracy level up to decimeters is crucial. This condition would enable AVs to precisely understand their position and adapt to road conditions with improved reliability. A promising approach to achieving this precision involves utilizing drones for high-resolution mapping. Drones can collect detailed geospatial data, including information about road lane geometry and specific features. Thus, integrating highly accurate digital maps with drone-derived data can provide AVs with a precise virtual depiction of the road environment, facilitating safe decision-making processes.

5.2 READINESS OF THE ROADS

The findings of this dissertation analysis have brought to light the extensive and comprehensive nature of the discourse surrounding the physical and digital infrastructure criteria pertinent to the operation of AVs. Nevertheless, limited efforts have been directed towards systematically classifying whether a road is prepared for the traffic of these vehicles. There is also a need to establish a timeframe for implementing identified improvements, which has also been underexplored.

In their study, Johnson and Rowland (2018) initially attempted to categorize the risks of insufficient physical infrastructure for AV operation. The study identified critical elements of such infrastructure, encompassing lane width, road markings, pavement quality, and bridge structure. Additionally, the study compiled a list of potential actions to alleviate risks resulting from the inadequacy of these elements. The authors' analyses, as presented in Table 5, provide insights into the weighted considerations associated with these actions.

Table 5 - Road asses and risk assessment (to be continued)

Element	Scenario Risk Level		Possible Actions
	Transition Phase Scenario	Full CAV Fleet Scenario	
Physical Signage	High risk, as both camera-based systems and humans will need to read and understand physical signage.	CAVs will obtain signage/advice from digital infrastructure, not signage; therefore, physical signage requirements will be significantly reduced.	**Signage Design Guidelines:** Aim to eliminate text-heavy designs and explore the integration of symbols from the Vienna Convention-based signs set. **Maintenance Regimes:** Review and enhance maintenance regimes for signage, especially reflectivity and readability **Signage Rollout Prioritization**: Give preference to signs that potentially adversely affect AV safety. **Pre-Road Opening Inspections:** Conduct thorough inspections before opening roads to AVs. **Machine Readable Codes**: Consider embedding machine-readable codes into current road signs.
Lane Width	Low risk; Likely to stay the same.	It will likely reduce lane width requirements, and land can be reallocated.	**Lane Width for AVs:** No immediate infrastructure changes are needed for lane width to accommodate a fully autonomous vehicle fleet. **Reallocating Space:** Consider prioritizing the reallocation of road space from vehicles through narrow lanes. **Transition Phase:** During the transition period, road design can adopt minimum lane widths per new standards. **Guidelines Update:** Regularly review and update road geometry guidelines for lane widths to align with an entire AV fleet's advanced sensing and control capabilities.
Road Markings	High risk due to safety concerns of poor/ inconsistent road markings.	Road markings are unlikely to be required for fully connected AV.	**Line Marking as Default:** Line marking should remain the primary method for lane use control in the near future. **Human and Camera-Based Systems:** Human drivers and camera-based driving systems may need to be phased out before line marking becomes obsolete for AVs.

Table 5 - Road asses and risk assessment (continued)

<table>
<tr><th rowspan="2">Element</th><th colspan="2">Scenario Risk Level</th><th rowspan="2">Possible Actions</th></tr>
<tr><th>Transition Phase Scenario</th><th>Full Connected AV Fleet Scenario</th></tr>
<tr><td>Pavement</td><td>Medium impact as pavement must be maintained for both connected AV and human drivers.</td><td>Medium impact as pavement requirements may change.</td><td>Technology vs. Infrastructure: Prioritize technology solutions to extend the life of existing or future road pavements over infrastructure upgrades.

Connected Fleet Lane Positioning: Implement technology to adjust vehicle tracking for uniform pavement wear and asset longevity.

Design for Concentrated Loads: Consider concentrated vehicle loads in designing and constructing new pavements.

AV Lane Restriction: Explore the possibility of designating specific lanes for autonomous heavy vehicles on freeways.

Road Material Innovation: Stay updated on road material technologies to adapt performance specifications to new materials.

GIS Data Utilization: Leverage existing GIS data to inform vehicle lane choices, extending pavement life.</td></tr>
<tr><td>Bridge Structure</td><td>High risk as bridge structures must be maintained for both connected AV and human drivers with differing loading.</td><td>High risk as loading may significantly change.</td><td>Infrastructure Changes: Consider changes like adding more lanes and altering loading for structures not initially designed for new traffic patterns, such as platooning.

Investment for Existing Infrastructure: Investment in additional structures or strengthening existing ones is typically needed when a clear need for the changes is identified, an expectation for existing infrastructure in the future.

Future-Ready Infrastructure: For upcoming infrastructure projects, plan for potential impacts on structures and design flexibility to accommodate future requirements.

Strengthening and Timing: Plan for how strengthening works can be implemented in the future, their design and construction, and when they will be required within the asset's design life.</td></tr>
</table>

Source: Adapted from Johnson and Rowland (2018).

Similarly, Huggins et al. (2017) outline highway modifications enabling AVs to operate within specific timeframes. These modifications are categorized as short-term, medium-term, or long-term, each with a designated duration. The short-term category spans 1-3 years, the medium-term category spans 3-5 years, and the long-term category encompasses five years or more. The authors' recommendations are tailored to suit Australia's needs. Table 6 displays the planned implementation timelines for physical infrastructure adaptations.

Table 6 - Proposed adjustments for road agencies about physical infrastructure (to be continued)

Issue	***Timing of Response***
Road Markings	
• Design: ○ Need for national and preferably international consistency; ○ Consistency for road works zones noted as particularly important.	**Short term:** Consider separate projects to document consistency in design approaches. **Medium term:** Consider additions to Standards and Guides to improve consistency. Standards may consider new use case-specific, e.g., roads with heavy vehicle platoon operation standards. **Long term:** Work with industry to develop design processes considering AV as core users and potentially consider the design of dedicated infrastructure.
• Asset management: ○ Maintenance hierarchy and intervention levels between jurisdictions and within jurisdictions vary, which results in varied outcomes; ○ Removal old-line markings at road works zones is particularly problematic for AV.	**Short term:** Document consistency in maintenance intervention levels and maintenance priority across jurisdictions. **Medium term:** Consider AV in the design of roadwork zones, including line removal and replacement. Consider a case for revising intervention levels/trigger points for line maintenance. **Long term:** See proactive maintenance processes considering AV as another key road user type. To improve operation, seek to gain information from multiple sources, including OEMs and System providers.
Road Signs (static)	
• Design ○ Need for national and preferably international consistency; ○ Consistency for road works zones noted as particularly important as temporary signs will often differ from the underlying map or digital representation; ○ Minimum standards need to be applied. Issues with adherence to standards, placement of signs, and lack of signs are known issues; ○ Speed limits used for a specific time of day and day of the week may be difficult to interpret; ○ Advisory speed signs are inconsistent and difficult for some AVs to interpret.	**Short term:** Consider undertaking a separate project to review the consistency of speed sign locations and non-compliance/exception to standards. Additional care is needed to ensure consistency of sign application in road work zones. **Medium term:** Consider additions needed to Standards and Guides to improve consistency. Consider use cases, e.g., roads that have heavy vehicle platoon operation. Consider AV in the design of road work zones. **Long term:** Consider the need for more or fewer signs to support future vehicle use cases (e.g., platooning) and the use of dedicated infrastructure. Seek greater international harmonization of standards and guidelines and vehicle use cases.

Table 6 - Proposed adjustments for road agencies about physical infrastructure (continued)

Issue	***Timing of Response***
Electronic signs, incl. Variable Message Signs (VMS)	
• Design and asset management o Some cameras cannot clearly read some Variable Speed Limit Signs (VSLS) o Noted that direct transmission of information from the sign to the vehicle (I2V) is possible.	**Short term:** Encourage discussion between VMS manufacturers, vehicle OEMs, and system suppliers to understand and document issues better. **Medium term:** Consider adding Standards and Guides to improve consistency and readability. **Long term:** Road operators work with the industry to develop design processes that consider AVs as core users and potentially consider the design of dedicated infrastructure.
Traffic systems Road vehicle and User Interaction and Geometric Design (lane width, gradient, curvature, intersection design)	
• Design and asset management o National and, where possible, international consistency is needed o Consider for specific use cases (e.g., platooning)	**Short term:** Consider immediate implications for design by undertaking detailed ConOps with road operators. Most significant are Platooning and Passenger Pick up and Drop off in urban environments. **Long term:** Consider access restriction and use of dedicated road space for AV-only facilities.
Structures pavements, bridges, tunnels, and barriers to protect critical infrastructure	
• Design and asset management o Requirement to change infrastructure as a result of AV introduction. Heavy vehicle platooning is the most prominent use case to be considered.	**Short term:** Consider potential increased loadings due to heavy vehicle platooning – impact on design and asset management. Pavement Design and Maintenance intervention levels for specific roads and structures may need to be revised. **Medium term:** Consider changes to Standards and Guidelines once new loadings are understood. Consider implications for emergency lanes and safe stopping places to bring vehicles to a safe resting state. **Long term:** Consider differing design and asset management needs using dedicated AV infrastructure.

Source: Adapted from Huggins et al. (2017).

Moreover, extending their analysis, Huggins et al. (2017) conducted a parallel examination of planned implementation timelines for elements pertaining to digital infrastructure. The outcomes of this analysis are presented in Table 7.

Table 7 - Proposed adjustments for road agencies about digital infrastructure

Issue	***Timing of Response***
Cellular communication coverage It is likely the minimum prerequisite for AV operation (for most use cases) — support coverage for all carriers.	**Short term:** Future expansion plans for cellular networks should consider the needs of the road network and AV use cases. **Medium term:** Consider an approach that ensures coverage is available from multiple suppliers
Other wireless communication The potential need for non-cellular V2I and I2V Communication	**Short term:** Consider the availability of devices in or on vehicles to deal with data will be the key element determining likely take-up. Consider the need for C-ITS infrastructure (DSRC) or Bluetooth and other direct forms of communication. Consider likely adoption, given potential penetration and benefits.
Positioning services • Need for positioning services with high accuracy and integrity to support AV operation; • Across the whole of the road network; • Consider particular positioning needs in tunnels and built-up areas (urban canyons).	**Short term:** Work with key government agencies to outline the need for future positioning services (which may include SBAS) Monitor international efforts to provide solutions to positioning needs for tunnels and built-up areas (urban canyons)

Source: Adapted from Huggins et al. (2017).

Although the study was conducted in 2017, there is no indication from the Australian reports that most recommendations proposed by Huggins and colleagues have been implemented. However, it is essential to note that this does not diminish the importance of the study's findings. It simply suggests that the projected timeline may not have been accurate.

Carreras et al. (2018) have introduced an alternative approach to categorizing the readiness of roads at different levels. However, this categorization primarily focuses on pertinent adjustments and digital elements, presenting them with limited detail. While the classification proposed by Carreras et al. (2018) provides a broad overview of digital infrastructure levels for AV traffic, it may lack the specificity needed for road operators to propose targeted improvement measures. The classification breakdown is provided in Table 8.

Table 8 - Levels of digital infrastructure for autonomous driving

	Level	Name	Description	Digital information provided to AVs: Digital map with static road signs	Digital information provided to AVs: VMS, warnings, incidents, weather	Digital information provided to AVs: Microscopic traffic situation	Digital information provided to AVs: Guidance: speed, gap, lane advice
Conventional infrastructure	**E**	Conventional infrastructure / no AV support	Conventional infrastructure without digital information. AVs need to recognize road geometry and road signs.				
Conventional infrastructure	**D**	Static digital information / Map support	Digital map data is available with static road signs. Map data could be complemented by physical reference points (landmarks signs). Traffic lights, short term road works and VMS need to be recognized by AVs.	X			
Digital infrastructure	**C**	Dynamic digital information	All dynamic and static infrastructure information is available in digital form and can be provided to AVs.	X	X		
Digital infrastructure	**B**	Cooperative perception	Infrastructure is capable of perceiving microscopic traffic situations and providing this data to AVs in real-time.	X	X	X	
Digital infrastructure	**A**	Cooperative driving	Based on the real-time information on vehicle movements, the infrastructure is able to guide AVs (groups of vehicles or single vehicles) in order to optimize the overall traffic flow.	X	X	X	X

Source: Carreras et al. (2018)

A more recent proposal for classifying the physical and digital infrastructure of roads for AVs has been introduced by the Colorado Department of Transportation (CDOT) and presented in the study by Poe et al. (2019). This proposal draws parallels with the SAE classification for automation levels and comprises six levels. Level 1 designates roads meeting the essential criteria for ensuring safe mobility, while level 6 pertains to roads capable of supporting the exclusive movement of vehicles with automation levels of 4 or higher. Table 9 displays the classification presented by Poe et al. (2019).

Table 9 - Road classification system proposed by CDOT

Level of classification	Description
Level 1	Unpaved and/or non-striped roads designed to a minimum standard level of safety and mobility.
Level 2	Paved roads designed to AASHTO's guidance and pavement marking standards and signing designed to meet MUTCD standards. There is no ITS equipment or infrastructure to collect CV data. Access to cellular data service may be available.
Level 3	ITS equipment operated by a traffic operation center (TOC) and/or one-way electronic data share between DOT/vehicle/user and/or mixed-use lanes.
Level 4	Roadway or specific lane(s) equipped with adaptive ITS equipment (i.e., smart signals hold for vehicles, highway lighting that turns on for vehicles), with TOC override only and/or two-way data share between DOT/vehicle/user and/or lanes designated for vehicle Levels 3 and 4 only.
Level 5	Roadway or specific lane(s) designed for vehicle Level 4 only, with additional features that may include inductive charging, advanced/enhanced data sharing, and more. Additionally, no roadside signs are needed because all roadway information is directed to vehicles' on-board systems.
Level 6	All lanes on a roadway designed for only vehicle Level 4 systems — no signs, signals, striping needed.

Source: Adapted from Poe et al. (2019).

The classification presented by Poe et al. (2019) offers clear and concise descriptions for each level of road infrastructure. However, the limited details may not be adequate for guiding specific road adaptations. This lack of comprehensive information underscores the need for a more detailed classification of road infrastructure levels tailored for AVs, as the analysis presented in this dissertation did not identify any suitable attempts to create one.

Hence, this study undertook a classification grounded in the outlined criteria within this dissertation. The proposed classification systematically assesses road preparedness, assigning levels ranging from 1 to 5 for individual criteria of physical infrastructure. These criteria encompass geometric design, road markings, traffic signs, pavement, structures, drainage, lighting, and work zones. Additionally, the classification encompasses digital infrastructure criteria, incorporating communication and digital mapping. The classification levels represent:

- **Level 1 - Not prepared:** Roadways are not adequately prepared for CAVs at this level. There is a lack of infrastructure and technology support for autonomous vehicles. AVs can still operate but may face significant challenges. Basic road infrastructure is either absent or insufficient for AV operations.

- **Level 2 - Slightly prepared:** Roadways at this level have made limited preparations to accommodate CAVs. Some essential infrastructure elements might be in place but are not fully optimized for autonomous vehicle use.
- **Level 3 - Moderately prepared:** Roadways at this level are moderately ready for CAVs. Their infrastructure improvements offer better support for autonomous vehicle operations.
- **Level 4 - Prepared:** Roadways are adequately prepared for CAVs at this level. The infrastructure and technology support for autonomous vehicles is well-established.
- **Level 5 - Fully prepared:** Roadways classified as fully prepared are extensively equipped for CAVs. They have implemented advanced infrastructure and technology solutions to maximize safety and efficiency for autonomous vehicles.

Based on the levels and criteria presented, Table 10 displays the classification proposed by this study.

Table 10 - Classification of road readiness for autonomous vehicles (to be continued)

<table>
<tr><th colspan="7">INDEX OF READINESS FOR AUTONOMOUS VEHICLES</th></tr>
<tr><td colspan="2" rowspan="2"></td><td>Level 1</td><td>Level 2</td><td>Level 3</td><td>Level 4</td><td>Level 5</td></tr>
<tr><td>Not prepared</td><td>Slightly Prepared</td><td>Moderately Prepared</td><td>Prepared</td><td>Fully Prepared</td></tr>
<tr><td rowspan="4">PHYSICAL INFRASTRUCTURE</td><td rowspan="2">Geometric Design</td><td>No shoulders or safe refuge areas</td><td>Shoulders are sparsely present but unpaved or of insufficient dimensions; there are no safe refuge areas.</td><td>Shoulders are primarily present, paved, properly designed, and adequately maintained; no safe refuge areas exist.</td><td>Shoulders are consistently present, paved, properly designed, and adequately maintained, even on bridges and overpasses; safe refuge areas may exist, but do not follow specific design guidelines.</td><td>Shoulders are consistently present, paved, properly designed, and adequately maintained, even on bridges and overpasses; safe refuge areas are present, with dimensions, spacing, and other conditions following proper guidelines.</td></tr>
<tr><td colspan="2">There are no dedicated lanes for autonomous vehicles.</td><td>Some lanes on certain sections of the roadway can serve as dedicated lanes on specific days and times.</td><td>Some lanes are consistently available as dedicated lanes on certain sections of the roadway.</td><td>Dedicated lanes are always available.</td></tr>
<tr><td>Road Markings</td><td>Road markings are absent or in poor condition.</td><td>Road markings are present but do not meet minimum retroreflectivity, contrast, or width criteria. They may not follow national standards.</td><td>Road markings are present, meet minimum criteria for retroreflectivity, contrast, or width, but may cause issues for autonomous vehicles under certain weather conditions. They may not follow national standards.</td><td>Road markings are consistently present, meet minimum criteria for retroreflectivity, contrast, or width, and are detectable under all weather conditions. They follow national standards.</td><td>Road markings are always present and intelligent, allowing for V2I (Vehicle-to-Infrastructure) communication. They follow national standards.</td></tr>
<tr><td>Traffic Signs</td><td>Traffic signs are absent, illegible, or obscured by vegetation.</td><td>Traffic signs are present and legible but do not meet minimum criteria for retroreflectivity. Electronic signs do not meet minimum update rate criteria. Signs may not follow national standards.</td><td>Traffic signs are present, legible, meet minimum criteria for retroreflectivity, and electronic signs have a minimum update rate of 200 Hz. They follow national standards.</td><td>Traffic signs are always visible and equipped with RFID technology. Electronic signs have a minimum update rate of 200 Hz. Signs follow national standards.</td><td>Traffic signs are always present and intelligent, allowing for V2I (Vehicle-to-Infrastructure) communication. They follow national standards.</td></tr>
</table>

Table 10 - Classification of Road Readiness for Autonomous Vehicles (to be continued)

<table>
<tr><th colspan="7">INDEX OF READINESS FOR AUTONOMOUS VEHICLES</th></tr>
<tr><th colspan="2" rowspan="2"></th><th>Level 1</th><th>Level 2</th><th>Level 3</th><th>Level 4</th><th>Level 5</th></tr>
<tr><th>Not prepared</th><th>Slightly Prepared</th><th>Moderately Prepared</th><th>Prepared</th><th>Fully Prepared</th></tr>
<tr><td rowspan="3">PHYSICAL INFRASTRUCTURE</td><td>Pavement</td><td>Unpaved road.</td><td>The road surface is in poor condition, with potholes, cracks, and unevenness, making it unsuitable for autonomous vehicle operation.</td><td>The road surface is in fair condition but may have some minor issues like cracks and surface irregularities that could affect autonomous vehicle performance.</td><td>The road surface is in good condition with minimal cracks or irregularities, suitable for autonomous vehicle operation under normal conditions.</td><td>The road surface is in excellent condition, well-maintained, and free from significant defects; it is also equipped with smart technology, such as sensors, to assist autonomous vehicles in navigation and maintenance.</td></tr>
<tr><td rowspan="2">Structures</td><td>No shoulders or protection grids on bridges; no adjustments in structure to allow platooning.</td><td>There are no shoulders or structural adjustments to allow platooning on bridges; protection grids are present.</td><td>No adjustments in structure to allow platooning on bridges; the presence of shoulders and protection grids.</td><td>Bridge structures are recalculated to allow small platoons, the presence of shoulders, and protection grids.</td><td>Bridge structures are recalculated to allow big platoons, the presence of shoulders, and protection grids.</td></tr>
<tr><td>Tunnels have inadequate lighting, leading to significant visibility challenges for autonomous vehicles. There are no adjustments to assist with changes in lighting. GPS signals are unreliable within tunnels, and there are no specific safety measures for fire incidents.</td><td>Tunnels have some lighting but may still result in temporary visibility issues for autonomous vehicles. There are limited adjustments to address lighting changes. GPS signals are unreliable within tunnels, and there are minimal safety measures for fire incidents.</td><td>Tunnels are well-lit, and there are adjustments to help vehicles adapt to changes in lighting, such as a transition structure. GPS reliability is improved with additional vehicle-based systems, but no advanced safety measures for fire incidents exist.</td><td colspan="2">Tunnels are well-lit with advanced lighting systems and effective vehicle-based adjustments for changing light conditions. GPS signals are supplemented with vehicle-based systems, ensuring better accuracy. Safety measures are in place for fire incidents.</td></tr>
</table>

Table 10 - Classification of road readiness for autonomous vehicles (to be continued)

INDEX OF READINESS FOR AUTONOMOUS VEHICLES						
		Level 1	Level 2	Level 3	Level 4	Level 5
		Not prepared	Slightly Prepared	Moderately Prepared	Prepared	Fully Prepared
PHYSICAL INFRASTRUCTURE	Drainage	Inadequate drainage systems result in water accumulation on the road surface, increasing the risk of hydroplaning and reduced traction. Autonomous vehicles may face difficulty detecting road markings and edges in wet conditions.	Drainage systems exist but may not be entirely effective, occasionally causing water accumulation on the road surface.	Drainage systems are generally effective, reducing the risk of water accumulation on the road surface. AVsom can handle wet conditions reasonably well.	Drainage systems are highly efficient, preventing water accumulation on the road surface. Autonomous vehicles perform well in wet conditions, with the ability to detect road markings and edges.	Drainage systems are excellent and also equipped with smart technology to provide autonomous vehicles with real-time information on road surface conditions. Autonomous vehicles perform exceptionally well in all weather conditions, and real-time digital mapping for surface friction is integrated.
	Lighting	Insufficient or inadequate lighting conditions, including low light and significant shadows, which severely hinder autonomous vehicles' ability to detect and recognize traffic signs.	Lighting conditions are somewhat inconsistent, with occasional issues such as low light and shadows affecting the recognition of traffic signs to some extent.	Lighting conditions are generally adequate, but there may be occasional inconsistencies in brightness and shadows. Autonomous vehicles can detect and recognize traffic signs reasonably well.	Consistent and effective lighting conditions that support the reliable detection and recognition of traffic signs by autonomous vehicles.	Lighting conditions also incorporate innovative technology to optimize lighting intensity and color and are well-located for the benefit of autonomous vehicles.
	Work Zones	Unpredictable work zones with rapid changes in infrastructure and traffic conditions, significantly affecting the safe operation of autonomous vehicles. AVs face significant challenges due to erratic road alterations, ambiguous lane markings, and a lack of standardized traffic management in these zones.		Work zones involve some alterations in road infrastructure and traffic organization. Efforts are made to standardize TCDs, but ambiguities may still arise.	Work zones are relatively straightforward, with minimal disruptions to road infrastructure and traffic patterns. Standardized TCDs are deployed to provide clear lane markings for autonomous vehicles.	Work zones are efficiently managed with advanced digital infrastructure, providing real-time communication and information to AVs. Standardization of work zone management is unambiguous and comprehensive.

Table 10 - Classification of road readiness for autonomous vehicles (continued)

INDEX OF READINESS FOR AUTONOMOUS VEHICLES						
		Level 1	Level 2	Level 3	Level 4	Level 5
		Not prepared	Slightly Prepared	Moderately Prepared	Prepared	Fully Prepared
DIGITAL INFRASTRUCTURE	Communication	No cellular network signal is available, making it impossible for VACs to communicate with each other or the infrastructure.	Some segments of the roadway have limited 3G/4G cellular network coverage. This enables basic communication for VACs, including V2V and V2I connections. However, the latency is moderate, and the data packet size is relatively small.	A significant portion of the roadway benefits from 4G/5G cellular network coverage. This provides robust communication capabilities for VACs, allowing for efficient V2V and V2I communication. The latency is low, and data packets can be of medium size. Facilities may also exist to support V2V communication via DSRC.	A reliable 5G cellular network covers the entire length of the roadway. This ensures low-latency communication for VACs, with the capacity to handle large data packets. Facilities are in place to facilitate V2V communication via DSRC.	The roadway boasts complete and dependable 5G network coverage. VACs benefit from exceptionally low latency and the ability to transmit large data packets. Special facilities support V2V communication via DSRC, and roadside units are connected with fiber optic cables to ensure high-speed communication along the entire roadway.
	Digital Mapping	Unmapped or highly inaccurate mapped roads.	Roadways are equipped with static maps that provide essential, permanent data such as road layouts and basic infrastructure. However, dynamic or real-time information is not included in these maps.	Roadways have an additional map layer that includes information about traffic signs and prominent landmarks, improving navigation and awareness for AVs.	Roadways have an extra map layer incorporating specific dynamic data like real-time traffic congestion. These maps have a high level of accuracy, typically in the decimeter range, ensuring precise navigation.	Roadways feature an additional map layer that provides various dynamic data, including information about VRUs and other nearby vehicles. These maps offer a high level of accuracy, typically in the centimeter range, enabling AVs to make informed decisions based on real-time information.

The proposed classification suggests that Brazilian roads would likely fall into levels 1 or 2 upon superficial analysis, as discussed in the previous chapter. However, room for improvement exists before AVs are introduced on Brazilian roads.

Designing a timeline with specific deadlines for infrastructure adjustments on Brazilian roads presents considerable challenges. Consequently, it is expected that this task should demonstrate dynamic behavior. The hurdles in providing an accurate forecast are notable, particularly considering that fully autonomous vehicles — level 5 automation — are not yet operational in the transportation system. Several factors could impede swift infrastructure adaptations, including:

- **Technological Development:** This stands out as the most significant factor. Rapid advancements in AV technology might outstrip the pace of infrastructure development, creating a potential mismatch.
- **Regulatory Challenges:** Delays may arise if the development and implementation of regulations governing AVs progress slowly. Addressing safety standards, liability issues, and operational guidelines in the regulatory framework is crucial.
- **Political Will**: The commitment of government agencies to invest in and prioritize AV infrastructure is paramount. Changes in political leadership or shifts in priorities could lead to delays.
- **Budgetary Constraints:** Securing adequate funding is essential for implementing infrastructure changes. Budget limitations or competing priorities may hinder allocating necessary resources for AV-related updates.
- **International Coordination:** Achieving global standards and coordination for AV infrastructure may prove challenging due to variations in regulations, technologies, and priorities among different countries.

Predicting timelines for adjustments in digital infrastructure poses more significant challenges than determining schedules for physical infrastructure adaptations. This heightened complexity arises from the swift evolution of communication and mapping technologies compared to physical elements like pavement and signage. For instance, anticipating the introduction of new generations of cellular networks in the upcoming decades and the subsequent transformative impacts is particularly challenging.

Additionally, the emergence of connected vehicles introduces concerns regarding data privacy. Data privacy and security issues may surface, especially given the extensive data collection required for AVs and their communication with infrastructure. Resolving these concerns is a time-consuming process that may delay the operationalization of these vehicles.

Notwithstanding these challenges, this study proposes a timeline for adjustments on rural Brazilian roads to enhance the efficiency of autonomous mobility in this context. The proposed timeline is based on Litman's predictions, as outlined in Table 2 in the second chapter of this dissertation. The analysis considers the following periods:

- **Phase 1:** Introduction of SAE level 4 vehicles on rural roads (c. 2030-2035);
- **Phase 2:** Approximately 20% of the fleet comprises autonomous vehicles, and connected vehicles emerge (c. 2050);
- **Phase 3:** Over 90% of the fleet consists of CAVs;
- **Phase 4 (hypothetical):** The fleet is composed solely of CAVs (over 2090).

Table 11 delineates the measures to be implemented in each phase for the criteria addressed in this study for physical infrastructure.

Table 11 - Suggestions for road operators about physical infrastructure (to be continued)

	ROAD READINESS INDEX FOR AUTONOMOUS VEHICLES FOR ROAD OPERATORS			
	Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads	**Phase 2: Approximately 20% of the Fleet are Autonomous Vehicles and Connected Vehicles Emerge**	**Phase 3: Over 90% of the Fleet are Connected and Autonomous Vehicles (CAVs)**	**Phase 4: Hypothetical - Fleet Composed Solely of CAVs**
	c. 2030-2035	**c. 2050**	**c. 2080**	**Later than 2090**
PHYSICAL INFRASTRUCTURE	GEOMETRIC DESIGN			
	• Evaluate the possibility of creating dedicated lanes on critical freight transportation routes; • Ensure shoulders are on all ODDs of vehicles.	• Define spacing for safe refuge areas, avoiding the use of shoulders for this purpose; • Ensure shoulders on all high-traffic highways; • Establish guidelines for the addition of dedicated lanes on high-traffic highways.	• Ensure shoulders on all highways for emergencies; • Implement safe refuge areas.	• Remove maximum tangent length criteria; • Relax sight distance and vertical curve length criteria; • Allow smaller lane width dimensions, considering the dimensions of AVs.
	ROAD MARKINGS			
	• Standardize markings in terms of color, luminance, and shape nationally; • Maintain adequate contrast (3:1); contrast stripes adjacent to road markings should have a width of 5 cm; • Adjust the width of all longitudinal markings to 15 cm; • Adjust the minimum retroreflectivity of all markings to 35 mcd/m²/lx.	• Standardize markings in terms of color, luminance, and shape, continentally; • Propose standard guidelines for the removal of previous markings; • Eliminate different shapes, such as those in zig-zag; • Install rumble strips in areas prone to heavy rains to facilitate the detection of markings.	• Consider the standardization of markings in terms of color, luminance, and shape globally.	• The dependence on road markings can be reduced if the digital infrastructure is fully operational to navigate CAVs.
	TRAFFIC SIGNS			
	• Standardize signs in terms of size, color, and shape on a national level; • Propose regular vegetation maintenance and targeted pruning; • Use anti-graffiti coatings; • Standardize a refresh rate exceeding 200 GHz in LED signs; • Ensure adequate spacing of signs when marginal roads or ramps are nearby.	• Standardize signs in terms of size, color, and shape on a continental level; • Eliminate text-based signs; • Determine efficient levels of retrorreflectivity; • Install motion sensors in traffic signs for deterring theft and rotation of traffic signs; • Apply remote sensing by drones to check visibility or occlusion.	• Standardize signs in terms of size, color, and shape on a global level; • Install RFID technology in all signs to enhance their tracking and management.	• Consider the dispensability of traffic signs as long as the digital infrastructure is fully operational to navigate CAVs.

Table 11 – Suggestions for road operators about physical infrastructure (to be continued)

	ROAD READINESS INDEX FOR AUTONOMOUS VEHICLES FOR ROAD OPERATORS			
	Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads	**Phase 2: Approximately 20% of the Fleet are Autonomous Vehicles and Connected Vehicles Emerge**	**Phase 3: Over 90% of the Fleet are Connected and Autonomous Vehicles (CAVs)**	**Phase 4: Hypothetical - Fleet Composed Solely of CAVs**
	c. 2030-2035	**c. 2050**	**c. 2080**	**Later than 2090**
PHYSICAL INFRASTRUCTURE	LIGHTING			
	• Propose regular and preventive maintenance of pavement conditions, including friction conditions.	• Consider increasing the thickness; • Implement road scanning technologies, such as terrestrial laser scanning and remote sensing by drones; • Use, whenever possible, more durable and wear-resistant materials, such as modified asphalt or high-strength concrete.	• Vary the lanes that are dedicated for platooning.	• Consider using materials with lower slip resistance in the surface layer.
	STRUCTURES			
	• Implement a transition structure at tunnel entrances and exits to improve the temporary visibility reduction issue for cameras; • Promote the use of appropriate materials and construction techniques for bridge supports; • Enhance ventilation and fire detection systems in tunnels; • Promote trilateration in tunnels to mitigate GPS signal loss issues.	-	• Propose structural reassessment of long-span bridges, especially on critical freight transport routes.	• Propose structural reassessment of all bridges.
	DRAINAGE			
	• Implement enhanced drainage systems to remove water from the paved surface rapidly.	• Develop road sensors capable of providing real-time information about the friction state of the surface, allowing AVs to detect and respond to inadequate drainage conditions.	-	-

Table 11 – Suggestions for road operators about physical infrastructure (continued)

	ROAD READINESS INDEX FOR AUTONOMOUS VEHICLES FOR ROAD OPERATORS			
	Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads	**Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads**	**Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads**	**Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads**
	c. 2030-2035	**c. 2050**	**c. 2080**	**Later than 2090**
PHYSICAL INFRASTRUCTURE	LIGHTING			
	• Identify critical areas such as tunnel entrances and exits, sharp curves, intersections, and animal crossing zones, and provide additional lighting to enhance nighttime visibility.	• Implement intelligent lighting systems that adjust dynamically based on traffic and ambient lighting conditions.	-	-
	WORK ZONES			
	• Ensure unambiguous road markings, especially in transitional areas between permanent and temporary lanes; • Develop guidelines for how work zone personnel interact with AVs, including hand signals, digital tools, or communication protocols.	• Standardize work zone guidelines, considering different countries and regions, to provide consistent information to AVs; • Install sensors on barricades and cones that monitor real-time traffic conditions.	• Establish a global standard for work zone management and data presentation to ensure safe operation for AVs.	• Implement a comprehensive and integrated digital infrastructure dedicated to work zones.

Source: Author (2023).

Similarly, Table 12 details the proposed actions to be undertaken in each phase concerning the criteria examined in this study with respect to digital infrastructure. Notably, the uncertainties in digital infrastructure adaptations are underscored over a more extended period. Continuous studies in this line are crucial to ensuring accurate predictions aligning with the development of AVs.

Table 12 - Suggestions for road operators about digital infrastructure

	ROAD READINESS INDEX FOR AUTONOMOUS VEHICLES FOR ROAD OPERATORS			
	Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads	**Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads**	**Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads**	**Phase 1: Introduction of SAE Level 4 Vehicles on Rural Roads**
	c. 2030-2035	**c. 2050**	**c. 2080**	**Later than 2090**
DIGITAL INFRASTRUCTURE	LIGHTING			
	• Focus on developing vehicle communication technologies, especially DSRC and cellular networks.	• Evaluate and establish communication infrastructure primarily for V2V communication, as AVs will predominantly communicate with each other in the early stages; • Focus on technologies similar to ITS-G5 for short-range V2V communication; • Expand and monitor the coverage of cellular networks to support V2I communication.	• Provide roadside units to facilitate V2I communication; • Ensure reliable V2X and V2I communication; • Explore using fiber-optic cables for high-speed communication, especially in areas with a high concentration of CAVs.	?
	MAPPING			
	• Invest in creating HD digital maps with an emphasis on accuracy and details; • Develop real-time map update systems to provide information on roadworks, temporary road closures, and weather conditions.	• Ensure a robust GNSS satellite infrastructure for accurate vehicle positioning; • Develop bidirectional digital maps that can receive information about incidents from the vehicle fleet and provide this information.	?	?

Source: Author (2023).

6 FINAL REMARKS

This study explored the impact of key road infrastructure criteria on the preparedness of rural roads for autonomous vehicle (AV) traffic. The examination specifically concentrated on assessing the readiness of Brazilian roads for adopting these vehicles. The analysis findings led to a suggested classification of roadways based on their physical and digital infrastructure criteria, evaluating their suitability for the safe and effective introduction of autonomous mobility.

The findings of this study underscored the critical need for immediate modifications to road design and maintenance aspects to accommodate AVs. Key insights from this dissertation emphasized the significant impact of signage and pavement conditions on AV operation within physical infrastructure. The importance of adhering to minimum specifications and standardizing criteria on an international scale is particularly highlighted. Furthermore, this study brought attention to the challenges faced by AVs in road work zones, emphasizing the necessity for a more precise delineation of safety guidelines specific to these areas.

In the realm of digital infrastructure, this study highlighted the importance of directing efforts toward establishing a robust communication network and enhancing digital mapping. This study did not directly tackle the topic of connected vehicles but contemplated a prospective scenario where vehicles interact with one another and the environment. In this context, investing in expanding and enhancing the 5G cellular network is crucial for communication. Regarding digital mapping, it was found that measures must be implemented to ensure its bidirectional functionality and high accuracy.

In conclusion, the infrastructure requirements emphasized in this study are relatively manageable. It is noteworthy that adjusting AVs to varying road conditions is a less challenging undertaking than overhauling the entire current road infrastructure. Nevertheless, this does not imply that the infrastructure should remain unaltered. Instead, targeted modifications can and should be implemented to enhance the efficiency of these vehicles. In this sense, it is crucial to assess whether the costs of these adjustments will be offset by the benefits of offering a form of mobility that operates without human intervention.

However, it is crucial to acknowledge the limitations inherent in this study. The analyses presented herein are primarily based on predictions and assumptions due to the early developmental stage of this technological innovation. Future dynamics may impact the infrastructure requirements in unforeseeable ways. As such, additional research is required to monitor and adapt road infrastructure in response to advancements in autonomous mobility.

Ongoing research must remain attentive in tracking the development of AVs to tackle emerging challenges effectively. Future studies should delve into optimizing traffic management systems tailored for these vehicles. Furthermore, a more in-depth investigation into the effects of autonomous transportation on urban mobility should be conducted, which goes beyond the scope of this dissertation.

In summary, this dissertation provided a comprehensive analysis of the interplay between AVs and road infrastructure, intending to guide planners, engineers, and policymakers in making informed decisions. The integration of autonomous mobility, coupled with the adaptation of infrastructure resources, has the potential to contribute to the establishment of a more efficient traffic environment.

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APPENDIX A – Records from the Qualitative Systematic Review

Table 1A - Records Included in the Qualitative Systematic Review (to be continued)

#	Author(s)	Year	Record Title	Type
1	Tengilimoglu O., Carsten O., Wadud Z.	2023	Infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders	J
2	Rana M.M., Hossain K.	2021	Connected and Autonomous Vehicles and Infrastructures: A Literature Review	J
3	Cucor B., Petrov T., Kamencay P., Pourhashem G., Dado M.	2022	Physical and Digital Infrastructure Readiness Index for Connected and Automated Vehicles	J
4	Wang P., McKeever B., Chan C.-Y.	2022	Automated Vehicles Industry Survey of Transportation Infrastructure Needs	J
5	Mihalj T., Li H., Babić D., Lex C., Jeudy M., Zovak G., Babić D., Eichberger A.	2022	Road Infrastructure Challenges Faced by Automated Driving: A Review	J
6	Sanusi F., Choi J., Kim Y.H., Moses R.	2022	Development of a Knowledge Base for Multiyear Infrastructure Planning for Connected and Automated Vehicles	J
7	Othman K.	2021	Impact of autonomous vehicles on the physical infrastructure: Changes and challenges	J
8	Guerrieri M., Mauro R., Pompigna A., Isaenko N.	2021	Road Design Criteria and Capacity Estimation Based on Autonomous Vehicles Performances. First Results from the European C-Roads Platform and A22 Motorway	J
9	Saeed T.U., Alabi B.N.T., Labi S.	2021	Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective	J
10	Najeh I., Bouillaut L., Daucher D., Redondin M.	2020	Maintenance strategy for the road infrastructure for the autonomous vehicle	P
11	Liu Y., Tight M., Sun Q., Kang R.	2019	A systematic review: Road infrastructure requirement for Connected and Autonomous Vehicles (CAVs)	J
12	Intini P., Colonna P., Berloco N., Ranieri V.	2019	Rethinking the main road design concepts for future Automated Vehicles Native Roads	J
13	Lu X., Madadi B., Farah H., Snelder M., Annema J.A., Arem B.V.	2019	Scenario-based infrastructure requirements for automated driving	P
14	Harrington R.J., Senatore C., Scanlon J.M., Yee R.M.	2018	The role of infrastructure in an automated vehicle future	J
15	Farah H., Erkens S.M.J.G., Alkim T., van Arem B.	2017	Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions	J
16	Nitsche P., Mocanu I., Reinthaler M.	2014	Requirements on tomorrow's road infrastructure for highly automated driving	P
17	Mocanu I., Nitsche P., Saleh P.	2015	Highly Automated Driving and its Requirements on Road Planning and Design	P
18	Xue S., Karl C., Irannezhad E.	2022	Minimum physical infrastructure standard for the operation of automated driving	R
19	Manivasakan, H; Kalra, R; O'Hern, S; Fang, YH; Xi, YF; Zheng, N	2021	Infrastructure requirement for autonomous vehicle integration for future urban and suburban roads-Current practice and a case study of Melbourne, Australia	J

Table 1A - Records Included in the Qualitative Systematic Review (continued)

#	Author(s)	Year	Record Title	Type
20	Ritter J., Kollmus B., Gasser T. M.	2020	Infrastructure modifications to support the introduction of the automated driving	P
21	Khoury J., Amine K., Saad R.A.	2019	An Initial Investigation of the Effects of a Fully Automated Vehicle Fleet on Geometric Design	J
22	Johnson, C.	2017	Readiness of the road network for connected and autonomous vehicle	R
23	Lyon B., Hudson N., Twycross M., Finn D., Porter S., Maklary Z., Waller T.	2017	Automated Vehicles: Do We Know Which Road to take?	R
24	Gopalakrishna D., Carlson P., Sweatman P., Raghunathan D., Brown L., Serulle N.	2021	Impacts of Automated Vehicles on Highway Infrastructure	R
25	Poe C. M., Seymour E. J., Kuciemba S., Row S.	2019	Connected Roadway Classification System Development	R
26	Carreras A., Daura X., Erhart J., Ruehrup S.	2018	Road infrastructure support levels for automated driving	P
27	Tengilimoglu O., Carsten O., Wadud Z.	2023	Implications of automated vehicles for physical road environment: A comprehensive review	J
28	Ye X., Wang X., Liu S., Tarko A. P.	2021	Feasibility study of highway alignment design controls for autonomous vehicles	J
29	Huggins R., Topp R., Gray L., Piper L., Jensen B., Isaac L., Polley S., Benjamin S., Somers A.	2017	Assessment of Key Road Operator Actions to Support Automated Vehicles	R
30	PIARC	2021	Automated Vehicles: Challenges and Opportunities for Road Operators and Road Authorities	R
31	Amelink A., Kulmala R. Jaaskelainen J., Sacs I., Narroway S., Niculescu M., Rey L., Alkim T.	2020	Road map and action plan to facilitate automated driving on TEN road network – version 2020	R
32	Transport Systems Catapult	2017	Future Proofing Infrastructure for Connected and Automated Vehicles	R
33	Ulrich S., Kulmala R., Appel K., Aiger W., Tenttinen M., Laitinen J.,	2020	Consequences of automation functions to infrastructure	R
34	Konstantinopoulou L., Ljubotina L.	2020	Other initiatives to meet the needs of automated cars	R
35	Johnson, B., Rowland, M	2018	Infrastructure Victoria: Automated and Zero Emission Vehicles	R

J = Journal article; P = Conference Proceedings; and R = Technical Report.

Source: Author (2023).