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Road Asset Management and the Vehicles of the Future: An Overview, Opportunities, and Challenges

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Abstract

Connected and automated vehicles (CAVs) have the potential to significantly impact transportation systems in terms of mobility, the environment, safety, and the economy. These vehicles rely on a range of sensors and cameras to detect road signs and lane markings, as well as to scan their surroundings, and they are connected to other vehicles and infrastructures. Previous research has highlighted the need for transport asset management processes to manage the intrinsic aspects of CAVs more effectively, with a view to improving performance, resource utilization, and budget planning. However, little literature was found with a deep discussion of how CAVs will impact asset management. In this article we offer an initial discussion on the impacts of CAVs on road asset management. To do so, we first provide a short introduction to CAVs, followed by an overview of road asset management. We then comprehensively discuss many asset management aspects that are affected by CAVs. Finally, future research opportunities, challenges, and important subjects are outlined.

Keywords Road asset management · Connected vehicles · Automated vehicles · Autonomous vehicles · Intelligent transportation systems · Transport infrastructure

List of abbreviations

AASHTO	American Association of Highway and Transportation Officials
ADS	Automated Driving System
AI	Artificial Intelligence
AV	Automated Vehicle
BIM	Building Information Modelling
BSC	Balanced ScoreCard
CAR	Center for Automotive Research
CAV	Connected and Automated Vehicle
CITS	Cooperative Intelligent Transportation System
CV	Computer Vision
DE	Digital Engineering
DSRC	Dedicated Short-Range Communications
DSS	Decision Support Systems
GIS	Geographic Information System
GPS	Global Positioning System
HD	High-Definition
I2V	Infrastructure-to-Vehicle
ICT	Information and Communications Technology
ISO	International Organization for Standardization
ITS	Intelligent Transportation System
KPI	Key Performance Indicator
LiDAR	Light Detection and Ranging
LOS	Level of Service
OECD	Organization for Economic Cooperation and Development
ML	Machine Learning
NCHRP	National Cooperative Highway Research Program
NYSDOT	New York State Department of Transportation
PDCA	Plan-Do-Check-Act
PSC	Public Sector Consulting
RAM	road Asset Management
RSU	Roadside Unit
SAE	Society of Automobile Engineers
SAEV	Shared Autonomous Electric Vehicle
SAMP	Strategic Asset Management Plan
TQM	Total Quality Management
TAM	Transport Asset Management
UAV	Unmanned Aerial Vehicle

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UNECE	United Nations Economic Commission for Europe
USDOT	United States Department of Transportation
V2D	Vehicle-to-Device
V2G	Vehicle-to-Grid
V2I	vehicle-to-infrastructure
V2M	Vehicle-to-Motorcycle
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

1 Introduction

Automotive computation has been studied since the 1970s when engines could not meet strict new emission regulations [1]. Since then, vehicle sensors have been widespread and nowadays a normal vehicle can possess hundreds of sensors [2]. These sensors can provide valuable information to the driver, while protecting the passengers. These include collision sensors that automatically activate airbags, tighten seatbelts and, more recently, activate breaks, avoiding possible collision.

Currently, it is expected that vehicles can reach full driving automation (level 5 of SAE definition) in the near future. Additionally, other communication systems, such as vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-everything communication, are being developed, providing vehicles and roadside units information such as safety warnings and traffic information [3]. However, for them to be implemented and used, these technologies demand changes of infrastructure and road asset management. Furthermore, according to the European Commission [4], the transport sector cannot achieve higher levels of autonomous driving without an adequate physical road infrastructure.

Interest in this topic is rapidly evolving in academia, reflected in the number of papers published in recent years.

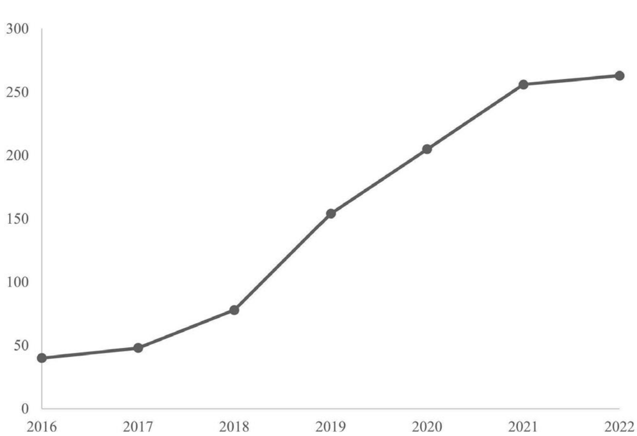


Fig. 1 Number of articles published since 2016

Scopus database showed that more than a thousand journal papers have been published in the field of infrastructure combined with automated vehicles (AVs) since 2015. In 2016, 40 papers were published, while more than 250 papers were published in 2022, showing the rising interest in the subject, as seen in Fig. 1.

Most current research in intelligent transportation systems has focused on the technology and systems of connected and automated vehicles (CAVs) [5], especially the technological challenges. Several studies are tackling problems such as lane change maneuver [6, 7], traffic and route planning [8–10], shared autonomous electric vehicle (SAEV) operations [11–14], object identification using artificial intelligence [15, 16], and even privacy and cyberattacks on automated vehicles [17, 18].

There are many challenges related to the connection and role of transportation agencies with CAV systems [19, 20]. These challenges need to be better researched according to existing literature. Key challenges include financing, staffing/workforce, understanding of possible impacts, deployment, maintenance, data generation and ownership, integration with existing infrastructure, and the transition and adoption process.

It is essential to address these challenges to meet the needs of the CAV environment. Nevertheless, more research is necessary on how to solve them effectively. Research found in the literature focusses more on issues related to vehicles and roadside units (vehicular communication systems), rather than other aspects, such as legislation and infrastructure. While several gaps have been identified, more detailed research on these topics is required. Additionally, to the best of the authors' knowledge, only very few works have been found on Web of Science, Scopus, and Google Scholar databases directly relating road asset management (RAM) with connected/automated vehicles, as outlined in Table 1.

Sinha et al. [21] start with a broad overview on the transport asset management, before heading into the challenges and opportunities, which include the advent of automated vehicles. Osichenko and Spielhofer [3] also present relevant topics and future challenges for the road asset management, including vehicles with advanced driver assistant systems, but do not explore in depth the implications of CAVs for asset management. Sobanjo [22] dedicates a section to asset management requirements for CAVs, but the work is mainly focused on the infrastructure requirements for CAVs.

While these works discuss CAVs and RAM to some degree, they do not link the topics together nor go deeply into the various aspects of asset management needs for CAVs. Therefore, the main novelty of this work is to provide a better understanding on how road asset management can be affected by the advent of CAVs. It presents an overview of CAVs and how they operate in Sect. 2, followed

Table 1 Approaches from the literature

Discussed topics		Literature found			
		Sinha et al. [21]	Osichenko and Spielhofer [3]	Sobanjo [22]	This study
CAV + RAM	CAV	X	X	X	X
	RAM	X	X	X	X
	Road Infrastructure		X	X	X
	Digital Infrastructure	X	X	X	X
	Policy		X		X
	Innovation				X
	Readiness of Agencies				X
	Challenges and Opportunities	X	X		X

by an overview of road asset management (Sect. 3), which is necessary to understand the connection between CAVs and their impact on asset management (discussed in detail in Sect. 4). Finally, conclusions and recommendations for future research are presented in Sect. 5.

2 Connected and Automated Vehicles Overview

To better understand how the vehicles of the future may impact road asset management, this section presents a concise overview of Connected and Automated Vehicles with a basic introduction to these vehicles and how they operate.

2.1 Introduction and Definitions

The terms "connected", "automated", and "autonomous" are often used interchangeably when referring to driving automation. Therefore, it is vital to distinguish between these terms from the outset. In control systems, autonomous means self-government, so autonomous controllers have the ability to perform without external intervention over a considerable period [23]. However, this meaning was broadened over time "to not only encompass decision making, but to represent the entire system functionality, thereby becoming synonymous with automated" [24].

The term "autonomous" is used more widely than "automated", even if "automated" is a more accurate term [25]. In the strict sense of the word, an autonomous vehicle would independently decide its destination and route, for example, regardless of the driver's/passenger's choice, while an automated vehicle would respect the received destination. The SAE J3016 standard [24] was updated in April 2021 to clarify the terms used in driving automation, and the term "autonomous" was then deprecated and is not recommended for describe driving automation.

Regarding Connected Vehicles (CVs), the United States Department of Transportation (USDOT) states that CV technology enables distinct types of vehicles to communicate with each other using wireless communication. The same type of communication can also be used to allow interaction with road infrastructure, such as traffic signals, work zones, and toll booths [26].

Both types of vehicles contain some driving automation system or technology, which is defined by SAE J3016 standard as "the hardware and software that are collectively capable of performing part or all of the dynamic driving task on a sustained basis" [24], on any level of automation. In this work the terms "autonomous vehicles" (AV) and "connected vehicles" (CV) will be extensively used to describe vehicles that do not need any human intervention for control, with (CV) or without (AV) connection to other vehicles and infrastructure. For the sake of abbreviation, the term "connected and autonomous vehicles" (CAV) will be used to refer to both types of vehicles.

According to PSC and CAR [27], three categories that can be used to classify approaches to CAV technology: intelligent transportation systems; automated vehicle systems; and connected vehicle systems. These categories are shown in more detail in Fig. 2.

In terms of transportation only, CAVs have the potential to change not only the way we conceive the concept of mobility, but to reduce transportation time and costs, and increase road capacity and fuel efficiency, thus also reducing emissions [22, 27, 28]. This work will further discuss the benefits of these vehicles and the sector's challenges.

2.2 Automated Vehicles Systems

According to Shladover [5] there have so far been four waves of Research and Development (R&D) on automated road vehicles, and we are currently living in the fourth one, which started in 2004 with the DARPA Grand Challenge and has been continued by Google, with its Waymo vehicles. Waymo, as other companies, is currently deploying automated level 4 technology, per SAE Levels of Automation. SAE and ISO [24] have determined six levels of driving automation in the J3016 standard, which is based on the functionality of the driving automation system feature. In summary, level 0 vehicles do not engage in any assistance related to the driving act itself and may help the driver to

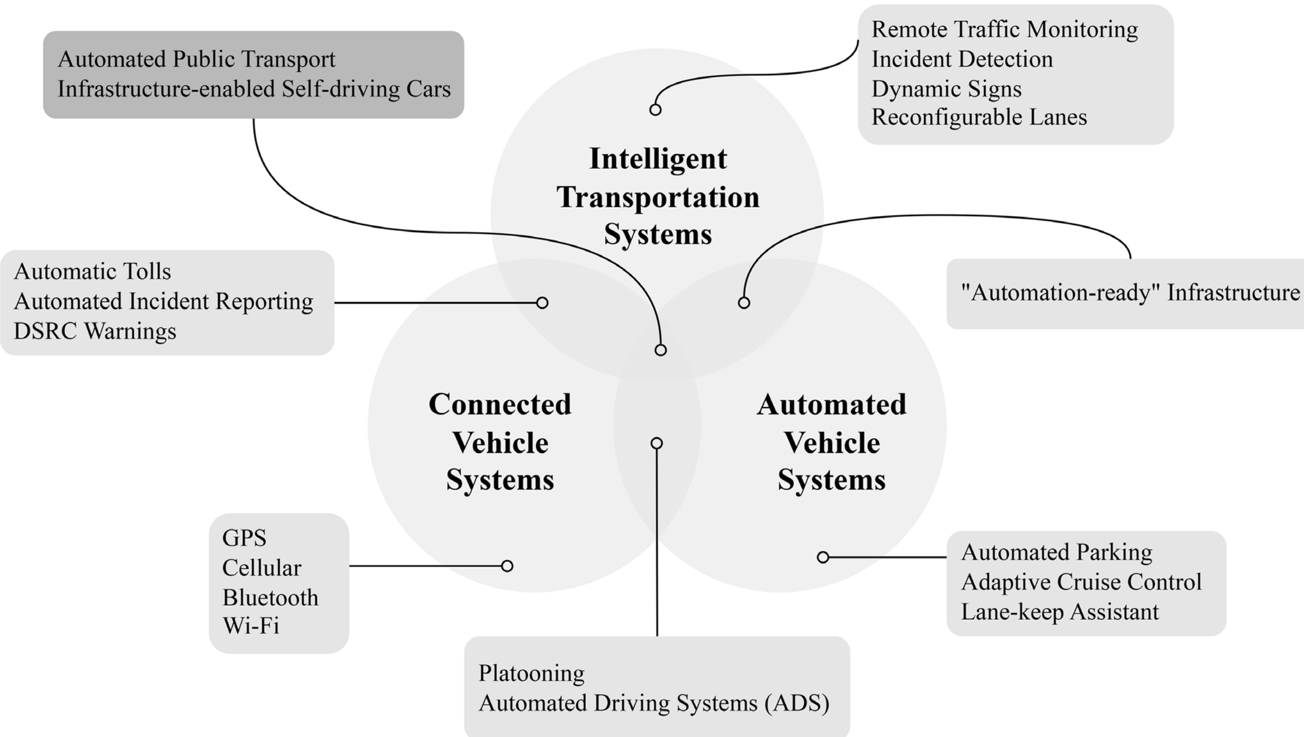


Fig. 2 Advanced transportation technologies. (adapted from [27])

Table 2 Levels of driving automation. (adapted from [24])

0	1	2	3	4	5
Driving when these features are engaged, even if feet are off the pedals and the driver is not steering			**Not** driving when these features are engaged, even if driver is seated in "driver's seat"		
Driver must supervise the features when needed to maintain safety			If feature request, driver must drive	The features do not require driving	
EXAMPLE FEATURES					
- automatic emergency breaking - blind spot warning - lane departure warning	- lane centering OR - adaptive cruise control	- lane centering AND - adaptive cruise control at the same time	- traffic jam chauffeur	- local driverless taxi - pedals/steering when may not be installed	- same as level 4, but can drive everywhere, in all conditions

avoid or mitigate potential collisions using various active safety systems, including warnings and emergency braking. On the other hand, level 5 vehicles are fully automated and do not require any intervention from the "driver", even being fully operational without a driver. A visual chart of driving automation levels can be found in Table 2, and more details about each level can be found in the J3016 standard.

As stated before and as seen in Fig. 2, an automated vehicle does not need to communicate with infrastructure or other vehicles, and AV manufacturers even claim that there is no need for infrastructure adaption [22] as it uses the vehicle's hardware to sense the environment around it and to take decisions. However, some of the benefits provided by CAVs, such as reduction of accidents and traffic, enhancement of fuel efficiency, and time travel improvement, are achieved when there is communication between vehicles and infrastructure [28]. Therefore, it is expected that AVs and CVs will operate together, and AVs will be able to communicate with other vehicles and infrastructure [22].

2.3 Connected Vehicles Systems

While AVs have been studied for more than 30 years, studies involving CV systems are relatively more recent, becoming more popular and accepted in the last two decades with the advance of the Vehicle-Infrastructure Integration initiative from the USDOT and the growing emphasis on "Cooperative Intelligent Transportation Systems (CITS)" in Europe [5].

These systems allow digital communication between the vehicle and the world (infrastructure, another vehicle, pedestrian, etc.). Some vehicles may only receive communication, others only send data, and others can receive and send digital data (not including sensor-based systems, such as LiDAR and radar, or analog systems like analog radio – AM/FM) [27]. Depending on the application requirements, several communication technologies can be used, such as dedicated short-range communications, cellular, and satellite, connecting vehicles to each other, but also to traffic signals, work zones, toll booths, school zones, and other types of infrastructure [26].

There are different types of vehicle communication, including: V2V (vehicle-to-vehicle); V2I (vehicle-to-infrastructure); I2V (infrastructure-to-vehicle); V2P (vehicle-to-pedestrian); V2M (vehicle-to-motorcycle); V2D (vehicle-to-device); V2G (vehicle-to-grid); V2N (vehicle-to-network); and V2X (vehicle-to-everything).

These types of communication are important elements of ITS and describe the relationship between different types of transport users and infrastructure [27]. Given that this work focuses on road asset management, it is important to mention the equipment required to allow this communication to happen.

Most applications require communication with low latency and high reliability so that specific wireless connections can be used, depending on the connection requirement [5]. Dedicated Short-Range Communications (DSRC) have been used mainly for this, since they were designed especially for automotive use and have the advantage of transmitting safe and fast messages. There are other types of wireless technologies, such as Wi-Fi, Bluetooth, cellular (such as the commonly named 5G), and even satellites, each with its advantages and disadvantages.

It is likely that transport agencies will be responsible for the installation and maintenance of devices that communicate through DSRC, especially RSUs. According to Perry et al. [29], "the purpose of the RSU is to facilitate communication between transportation infrastructure and vehicles and other mobile devices by exchanging data over DSRC in compliance with industry standards". Therefore, for example, the communication allowed by DSRC RSUs can be applied to traffic management, weather information, fleet management, and parking systems.

3 Road Asset Management

In this section we provide an inclusive discussion on road asset management, which is necessary to understand how it will be impacted by CAVs later. First, some concepts are introduced, followed by details of some aspects of asset management and what to expect in the future.

3.1 Definitions

An asset is any item, entity, or thing that has potential or actual value for an organization, while asset management is a systematic process of maintaining, upgrading, and operating assets, combining engineering, business, and economic principles. It can bring many benefits, such as higher financial performance, risk management, improvement of services, organizational sustainability, efficiency, and efficacy. To effectively manage the assets in an organization, a system is required to do so. An asset management system is a set of interrelated elements that must establish the asset management policy and objectives of that organization, while also accounting for the processes to achieve those objectives. This system comprises all processes, data, tools, and policies to manage assets effectively [30].

An asset management system can be a tool used to coordinate the interaction between assets and other functions of an organization. It requires accurate asset information and is more complex than a regular management information system [30]. The international standard ISO 55,001 provides more details about the fundamentals of asset management, which are grouped in the context of organization, leadership, planning, support, operation, performance evaluation, and improvement [31]. The relationship between these topics is shown in detail in Fig. 3. It is worth noting that they focus on aspects other than data or performance; organizational government is as important as information when implementing a robust asset management system, given it requires a mix of skills within an organization [32].

The organization should define internal and external questions that are relevant to its objectives and should be consistent with the organizational objectives. Top management should align the organizational objectives with the asset management policy and objectives, involving all leaders in all steps of the asset management system implementation. The principles that guide asset management should be documented in the Strategic Asset Management Plan (SAMP), which should be used to conduct the asset management objectives, describe the asset management system's role in meeting these objectives, and assist the system in developing its asset management plans. Collaboration with diverse parts of the organization is necessary to establish, implement, maintain, and improve the asset management system. The organization should also ensure that risks associated with any planned change that might impact the asset management objectives should be effectively managed [30, 31].

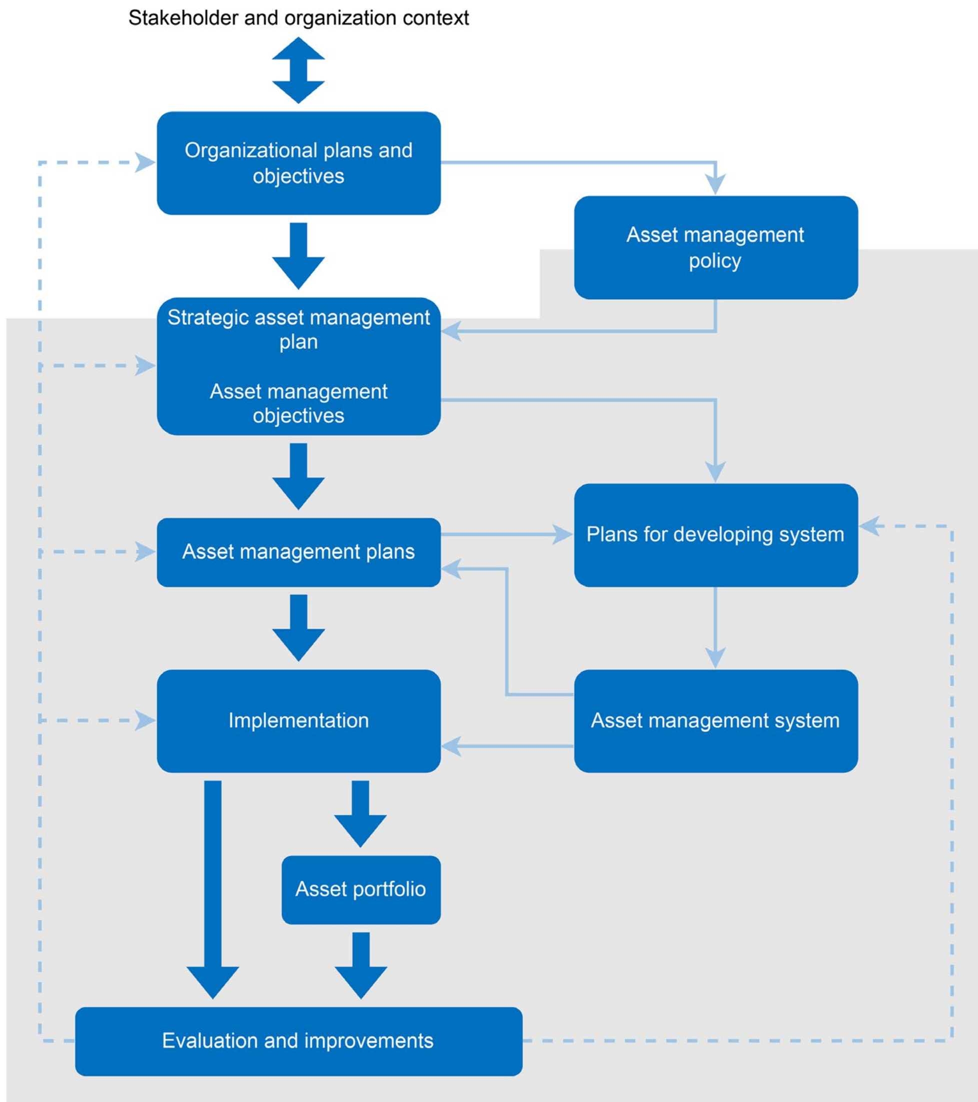


Fig. 3 Relationship between key elements of an asset management system. (adapted from [30]). Note: The grey highlighted box designates the boundary of the asset management system

Regarding outsourcing, the organization must guarantee that these outsourced activities are not removed from the asset management system, although this increases the complexity of the control. Asset management activities should be monitored and evaluated continuously to ensure continuous improvement in asset management. This process can be used to check any eventual problem, to see if the system is efficient in asset management, and to use the results in top management decision-making. Improvement opportunities can be identified with the performance monitoring of the asset management system and the asset itself. The usage of the asset management system should also be considered in emergencies and after such incidents, the events should be analyzed to prevent recurrence and improve the system. The standards ISO 55,000, 55,001, and 55,002 are well built to demonstrate how an organization can develop and implement an asset management system, so transport organizations can benefit from that [30, 31].

3.2 Introduction to Road Asset Management

Transport networks are a valuable infrastructure with high costs for both construction and maintenance. Typically, governments fund and maintain them due to their importance in daily life and their significant impact on the public. Optimized asset management is essential to reduce maintenance costs and save money. However, there are other motivations for using an asset management system in transportation, such as legislative requirements, coordination between different jurisdictions, and overlap with other infrastructures. Additionally, there are concerns about using multiple performance indicators, legal problems, and deciding the priority of infrastructure investment on the global budget [21, 33].

In road asset management, assets can be classified into [34]:

- Traffic service assets: all assets relevant to traffic systems, such as signals, marking, lighting, and safety devices;
- Road assets: all facilities and relevant information that belong to road systems, including earthworks, pavements, shoulders, and roadside areas;
- Property and data assets: road management facilities, road information storage and management systems;
- Other assets: other general road systems and information that cannot be grouped into any of the above categories.

Regarding the life cycle of transportation infrastructure, there are various phases involving its development, as described in Fig. 4: assessment; planning; design; construction; operations; monitoring; preservation; and end of life. At first, due to government plans or popular demand, the need for a transport infrastructure is identified. Then, experts evaluate the environmental, socio-economic, and technical feasibility of the construction. If approved, then the infrastructure is set to be designed and constructed, following the best practices. Afterwards, operation begins, which is the longest phase when the infrastructure is being used, while at the same time it is monitored and maintained. Lastly, the infrastructure is deactivated, following its planned life cycle or if an unplanned event occurs (such as a natural disaster) [21].

The New York State Department of Transportation (NYSDOT) established four major fronts for successful asset management: redefine organizational roles and responsibilities; develop a formal and disciplined core business process for program development; continue the development of critical transportation management systems; and design and implement a modern program and business system spearheaded by a state-of-the-art automated system [35]. The first step for successful asset management is reorganizing internal structure, defining each role well, and introducing

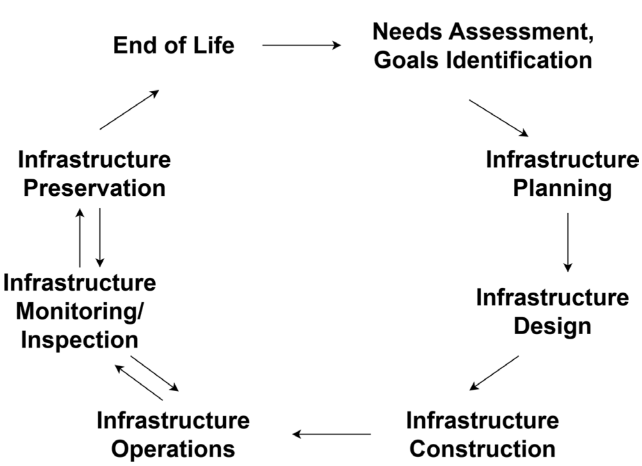


Fig. 4 Phases of transport infrastructure development. (adapted from [21])

the program update process. It is important to have well-maintained databases, appropriate tools to manage transportation assets, and to continuously use and improve existing systems to ensure optimal asset management. It is also important to design and perform the required assessments and implementation of measures, based on predictions supported by good data and models.

3.3 Development and Management Framework

The OECD [36] suggests an asset management development framework based on the Total Quality Management (TQM) concept of PDCA (Plan-Do-Check-Act) for continuous improvement. The PDCA was slightly changed to accommodate specific attributes of asset management but is still related to the original PDCA: Planning; Implementing (acquisition, operation, maintenance, rejuvenation, and rationalization); Reviewing; and Improving. The framework is divided into ten levels, indicating an organization's current asset management practice. Level 10, meaning that an organization excels at asset management, is demonstrated in Fig. 5.

Kellick [37] indicates similar factors that ensure a successful asset in an organization, while for infrastructure Younis and Knight [38] propose a similar management framework based mainly on the Balanced Scorecard (BSC). Overall, some aspects define the best practices on asset management: proactive instead of reactive; progressively include all asset types; focus the role of assets as part of a whole system; decisions are guided using cost-benefit-risk analysis; and merge asset management with global corporate management.

3.4 Common Transport Assets

To effectively manage a road asset system, as seen in previous sections, one of the aspects that stands out is the road authority's capacity to manage and integrate different data [39]. Osichenko and Spielhofer [3] propose the necessary information for a road asset management system: environmental data; socio-economic aspects; condition data; main road data; traffic data; weather data; accident data; and inventory data. As that is not an exhaustive list, it must be also noted that other aspects must be included in such system, like roadside units and road signage, for instance. Table 3 presents a diverse pool of information needed for appropriate decision-making regarding Transport Asset Management (TAM).

The NCHRP [40] discusses the importance of managing diverse types of road infrastructure, such as pavement markings, traffic signals, and lighting, instead of just pavements and bridges. They also emphasize the need to demonstrate

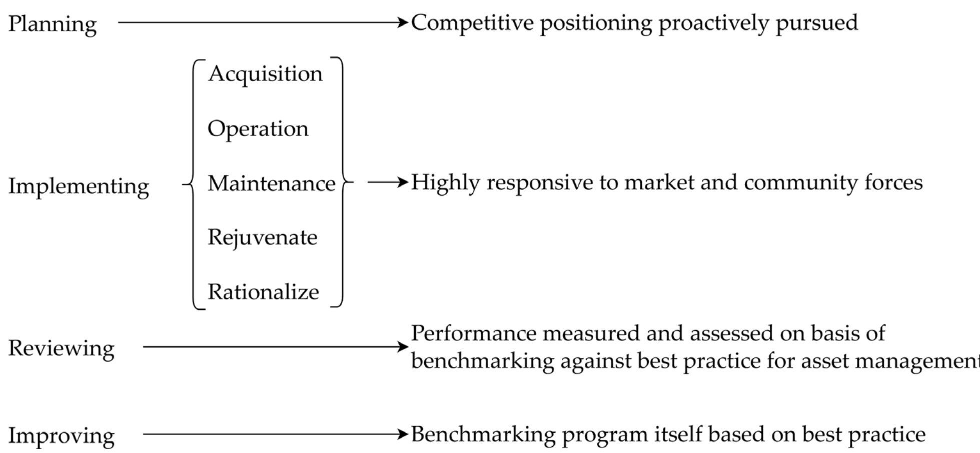


Fig. 5 Asset management development framework. (adapted from [36])

Table 3 Information needed for transport asset management. (adapted from [32, 39])

Type of information	Description
Asset inventory and design	Location, type, quantity, material, design details, pavement layers, bridge elements, and asset valuation information.
Asset condition and performance	Visual inspections, condition (roughness or cracking, e.g.), performance (e.g., remaining service life), and network level measures (percentage of pavement in good condition, e.g.).
Contextual	System or network characteristics, functional classification, highway geometric characteristics, traffic volumes, congestion and reliability, crash history, adjacent land uses, weather, and features of the natural environment.
Work	Date, cost, and scopes of work proposed, scheduled, and completed on assets (installation, replacement/reconstruction, rehabilitation, preservation, and maintenance).
Revenue and funding allocation	Historical and forecasted funds available for asset installation, replacement/reconstruction, rehabilitation, preservation, and maintenance.
Analysis	Forecasted condition and needs under varying funding or program scenarios, life treatment or life extension results, or project prioritization ratings or rankings.

to the public the benefits of these assets properly managed. The current practice used to manage these known assets can also be used on other types of assets, such as RSUs. However, caution should be taken when managing other assets that do not receive much attention, especially regarding the performance of the asset. Many assets do not have proper Key Performance Indicators (KPIs), and existing performance models must be improved with more data and study.

3.5 Collection Methods and Data Management

Effective asset management requires knowledge of all assets, but data collection can be expensive. Transport agencies rely on manual data collection and empirical methods to evaluate infrastructure conditions [39, 41, 42]. To improve these processes, innovative technology has been developed to automatize or improve the collection of typical data necessary for a RAM, such as smartphones, unmanned aerial vehicle (UAV), LiDAR, and embedded sensors (inside, on the surface or built with smart composites) [32, 42]. Artificial Intelligence (AI) techniques can be used to improve asset management and monitoring, such as Machine Learning (ML) and Computer Vision (CV) [43]. However, the collected data is not being used yet to unlock the full potential of Decision Support Systems (DSS). Future systems could benefit from smart data collection, resulting in a lower cost and resource usage, while maintaining/improving efficiency [42].

Asset management systems are used to document and track assets, with details of the infrastructure attributes. Agencies are required to have an asset inventory, and data collection, storage and maintenance is expensive [32, 44]. It is important to pay attention to data that comes directly from outside the organization, and to delegate departments to be responsible for data inherent to them [36]. Asset management systems are used to assist integration, using different data mining techniques to analyze possible data trends [45]. These systems should provide decision-support tools, such as life-cycle analysis, demand prediction, identification of optimal interventions, and benefit/cost analysis. There are different sorts of data analyses, some of which use a more general approach or some focus more on technical or financial aspects and will not be used in the same way at different levels of an organization.

There are several steps involved in collecting, processing, storing, managing, and analyzing data, which can be summarized as follows:

- Preliminary analysis that supports data collection;
- Identification of best practices for collecting data;
- Select the best team or contractor to collect data;
- Check if collected data integrate with existing agency data;
- Proper software and hardware to store and process data;
- Ensure that data is valid, consistent, and is of high-quality;
- Visualize and use that data to do proper analysis.

3.6 Asset Performance, Optimization, and Decision-Making

Regardless of the approach selected by the organization to manage assets, an asset management system must allow the organization to deliver expected value for customers, and that measurable metrics must be used to measure progress on established goals. The first step is to define what the transport agency wants to achieve, which is the link between the agency's goals and the needed investment/interventions. Performance targets are a common way to manage service levels, but the expected level of performance depends on the managed asset type. The defined indicators must be applied to a performance measurement framework that allows continuous improvement [32, 39].

The performance measurement framework should involve performance measures that can be used to guide the decision-making process and determine a minimum threshold for maintenance. It also permits the definition of budget plans and helps the accountability of the program and services delivered. OECD countries use some indicators to monitor the performance of road agencies [36], displayed below. Of the 14 indicators displayed, the last 5 are qualitative (marked with asterisks) and 9 are quantitative. Then, the quantitative indicators can be used for optimization.

- Road user costs;
- Level of satisfaction;
- User risk;
- Cost prediction;
- Overhead costs;
- Value of assets;
- Roughness;
- State of bridges;
- Satisfaction;
- Environmental policy *;
- Market research and customer feedback *;
- Long-term program *;
- Allocation of resources *;
- Quality management *.

For optimization, which is one of the most researched areas of asset management [21], transport agencies use historical data to develop performance models that can predict the future condition of a given asset and provide the best maintenance activity. Techniques such as regression, mathematical optimization, neural networks, and diverse ML and CV techniques are used to solve issues related to transport asset management. The decision-making process in transportation infrastructure is complex due to the several factors involved and limited resources, so a comprehensive decision-making framework should be adopted in an integrated system that includes all relevant factors [46, 47]. This framework should include processes such as condition assessment, analysis of deterioration and treatment efficiency, and forecasting and optimization models [39].

3.7 Current Implementation and Future Aspects

The previous sections summarize the steps for successful asset management in the road sector. Some specific guidelines and tools support full implementation by transport agencies, mainly based on ISO 55,000 (and variants), such as the ones from AASHTO [32], OECD [36], Austroads [48], and UNECE [39]. There are also some works stating the current state of transport agencies ([36, 40], for example), which in general show that while there are different levels of implementation by agencies, most of them follow some of those mentioned guidelines (especially the AASHTO guide). Moreover, there is a consensus on the components that should be included in an asset management system: asset inventory; maintenance methods; prediction models; life-cycle cost analysis; decision-aid tools; and asset management strategy [36]. However, once again, the details of each implementation vary considerably from agency to agency.

While there is the inherent challenge of managing assets, especially if a proper integration between the various areas within an organization (and their different data) is desired, new aspects must also be considered. Osichenko and Spielhofer [3] cite five main challenges for road asset management:

- Fast-growing road network and motorization rate;
- Connected and automated vehicles;
- Environmental and socio-economic aspects;
- New measurement systems;
- Climate change.

There is also a focus on new practices, such as Digital Engineering (DE), which is the convergence of emerging technologies such as Building Information Modelling (BIM), Geographic Information Systems (GIS), and other related systems towards better asset management [49, 50]. Other processes include 3D and 4D modeling, digital twin modeling, and big data [51, 52]. While these technologies can help asset management, there are plans to use digital twins to combine the management with traffic operations [53] or to improve road inspection [54]. The digitalization of roads and the development of smart cities can also be related to the use of embedded sensors, the internet of things, and virtual reality [55].

Finally, the advent of connected and automated vehicles will impact road asset management. These vehicles produce a large volume of data and require a seamless connection with other vehicles and the infrastructure itself. Although cellular networks such as 5G and 6G (still under development) will help the connection and data transfer between vehicles and everything, there are still lots of challenges and infrastructure requirements that must be resolved to enable the full potential of those vehicles.

4 Automated Vehicles and Asset Management

In the last century cars were directly responsible for the format of modern cities, while also impacting our everyday lives. Cars are responsible for lower city density, increasing traffic congestion and parking problems, and land waste for storing vehicles that are unused most of the time [56]. It is expected that the heavy usage of car sharing, CAVs, and architecture of the future will redesign cities towards a more human space.

Milakis et al. [57] propose a conceptualization of implications of CAVs in policies and societies, inspired by a ripple effect model developed previously by the same authors [58]. With this concept, the authors aim to model the sequential effects that the usage of CAVs might have on several aspects of our lives, directly affecting things such as travel costs and choices, and the more indirect impact on society of such things as health and social equity, as can be seen in Fig. 6.

We propose four areas that involve the link between road asset management and vehicle automation: physical infrastructure; communication and navigation; policy and

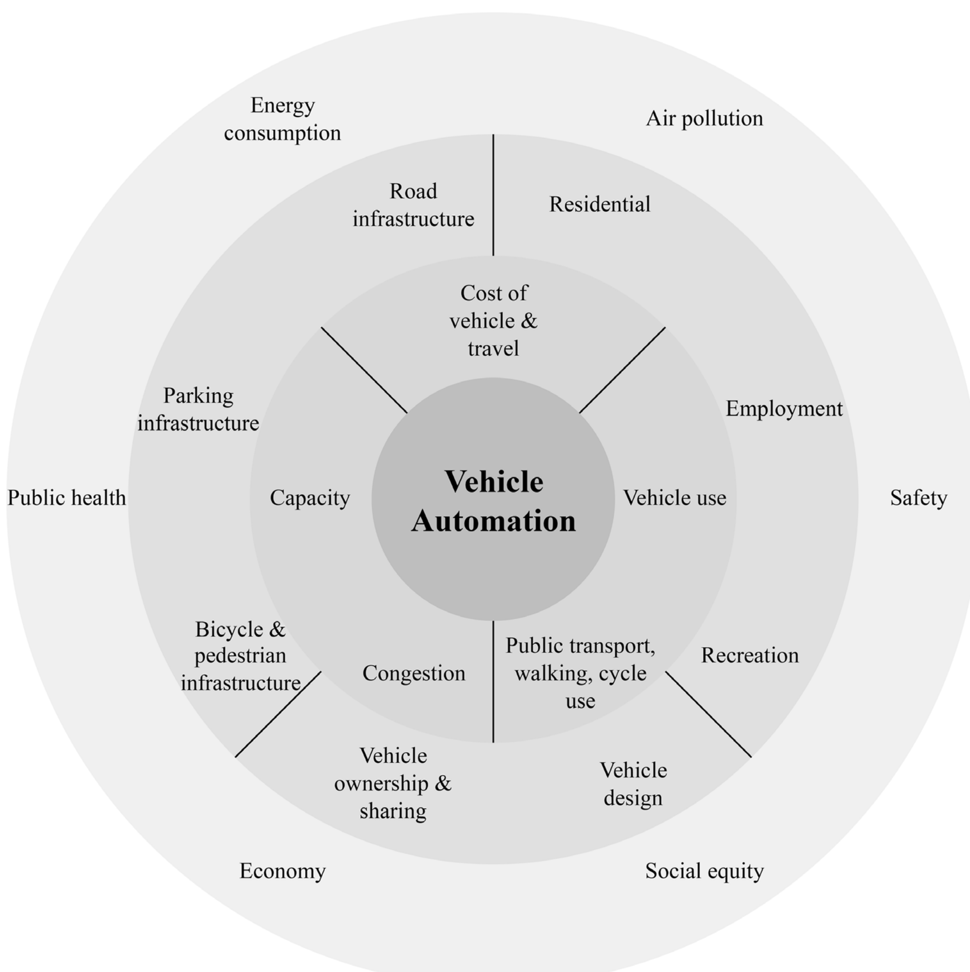


Fig. 6 The ripple effect of automated driving. (adapted from [58])

legislation; and innovation. Each area will be discussed in detail to explore how CAVs may interact with transport asset management, but it is important to point out here that there is some overlap between these areas, as seen in Fig. 7. Later, we examine how prepared transport agencies are, and the challenges and opportunities in this field.

4.1 Physical Infrastructure

In this section, we consider all aspects related to the physical characteristics of the road, including but not limited to the road design, paving (e.g.: road quality, markings, drainage), and signaling. At first, the way that CAVs interact with road infrastructure is supposed to be like human drivers. CAV companies are developing their vehicles to be used on regular roads, without requiring any dedicated carriageways. However, this may impact the technological progress, also affecting the penetration of CAVs in the market [59]. At the same time, road constructors may want to build future-proof roads (that could be called “CAV-ready roads”).

If positive, CAVs will heavily impact road design and road infrastructure. In the design process, several factors must be addressed, while the drivers react to the combination of them: design speed; traffic characteristics; number of lanes; Level of Service (LOS); sight distance; alignment, superelevation, and grades; cross section; lane width; and horizontal and vertical clearance [60]. All these characteristics may change and/or be optimized with the usage of CAVs; for example, given that CAVs react faster than humans, the breaking time reaction is lower for CAVs, meaning that stopping sight distance will be reduced, affecting the geometric design of the road.

Another aspect which has been studied is the deployment of these new vehicles. A solution constantly mentioned, for the mixed-use of regular and automated vehicles, is the usage of dedicated lanes for CAVs. For the operation of these lanes, the entry/exit design and the separation and signage of the dedicated lanes must be considered, accounting for traffic safety and efficiency [61].

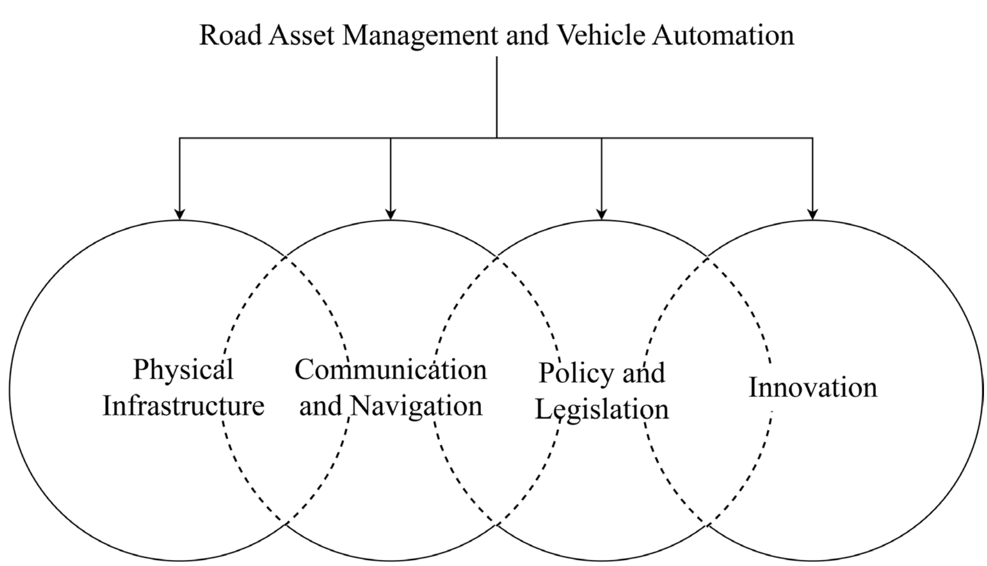
Moreover, new infrastructure is required for a proper operation of CAVs. Per SAE definition, vehicles with different levels of automation require different infrastructure. For instance, a level 5 vehicle requires speed limit beacons to regulate traffic flow and speed, magnetic nails or reflective striping for lane keeping, RSUs to guide merging and lane changing, and investment in infrastructure to enable platooning of vehicles [62].

Other infrastructure modifications are likely to occur, such as special ramps at highway-to-street interchanges. Nevertheless, the infrastructure modifications depend on CAVs rate of adoption. The lack of infrastructure may prevent a driver from purchasing a vehicle which is not fully automated, while the low adoption rate may also not justify investment from transport agencies in adapting infrastructure. It is suggested that infrastructure is modified incrementally, looking for user demand (in modern cities, for example) or deploying pilots projects in small areas [63].

Therefore, it is expected that the infrastructure changes will be deployed in stages, being dependent on the market penetration of CAVs. Signage, new lanes, and road design will be updated, impacting asset management, which must then account for these new items. For that, studies must be done to investigate the deterioration of CAVs assets and how performance models can predict their deterioration.

Regardless of deployment of new road design standards, current road maintenance can also be affected by CAVs. For instance, road surface quality and road marking quality are crucial factors for CAVs to function properly, since road markings act as rails for them (detected by cameras and sensors), while road quality can negatively impact their

Fig. 7 Connection between CAVs and road asset management



detection (potholes or bituminous lines can confuse the vehicle). Also, while for a human driver it is relatively simple to understand road markings, for CAVs they need to be very distinguishable (good quality paint with reflective properties and they must be clear and continuous) and kept simple. Current vehicles already possess some degree of technology that uses this information to keep them in lane. However, complex markings might be a problem for vehicles, resulting in lane departure or collision, for example. Some metrics for lane marking quality assessment include correctness, shape, and visibility, while for road quality there are already diverse indices such as IRI or PCI, among others.

Visibility is a critical aspect for CAVs, not only for lane markings, but also for other obstacles, signaling, traffic detection (other vehicles, cyclists, and pedestrians), and clear visibility (weather-wise). This involves detecting infrastructures and traffic using high-precision maps and sensors such as LiDAR, video cameras, radar sensors, and ultrasonic sensors mounted on wheels [64]. These sensors work together to help detect speed and distance of nearby objects for safe operation. The ability of automated vehicles to interpret signs, such as traffic lights, stop signs, speed limits, and lane markings accurately can prevent accidents and reduce road congestion. However, challenges still exist regarding sign detection accuracy in varying weather conditions or poor lighting situations. For example, LiDAR performance can be significantly reduced in bad weather, which can impact CAV functioning and safety. Additionally, signaling maintenance should receive high priority, given that while human drivers can understand scenarios where some signs are only partially visible or missing, CAVs might not infer the same information, leading to poor or dangerous driving.

It is not only bad signaling that can disrupt CAV driving, but the type of road can also affect it. The road environment complexity and road access are critical factors that can impact the performance of CAVs on the road [65]. Environmental complexity is related mainly to the road hierarchy (ranging from motorways to residential roads), since the level of difficulty of driving is expected to be lower on motorways than on local roads, while urban areas pose the greatest challenge. Navigation and interaction with other road users are considered the hardest issues to solve; narrow roads with no separation of user groups, community activity-supportive streets, vulnerable road user areas, high-public transport curbside activities, and rail and bus transit systems present significant difficulties [59].

As can be seen, the road access parameter, which is related on the types of road users (e.g.: pedestrians, cyclists, drivers), overlaps with the environmental complexity of the road. Roads where pedestrians and cyclists have high priority, such as living streets, can present unique challenges where conventional sensor systems may not be sufficient for effective navigation through crowded spaces. Similarly, residential streets often have more obstacles like parked cars or children playing nearby, requiring CAVs to navigate more carefully using their sensors' capabilities efficiently. Additionally, CAVs also have difficulties in tracking and avoiding pedestrian crossing a street where there are no crosswalks.

Therefore, with all this in mind, integrating CAVs into current road infrastructure may require some changes in road design, paving, signaling, and other aspects related to the physical characteristics of roads. CAVs interact with road infrastructure in a similar way to human drivers at present. However, dedicated lanes for CAVs have been proposed as a solution for mixed-use traffic. Maintenance of current road infrastructure can also be affected by CAVs due to requirements for high-quality painting with reflective properties and clear markings that are easily distinguishable by sensors, for example.

The complexity of the environment where CAVs operate presents challenges such as navigation issues when interacting with other users like pedestrians or cyclists who have priority in certain areas. Some of these challenges can be overcome with updated road design, advances in sensors technology, and improved communication.

4.2 Communication and Navigation

In this section we consider the characteristics linked to the digital infrastructure needed to ensure the proper functioning of CAVs, which are related to vehicle and infrastructure communication, and to navigation (GPS and maps). Some of these features could be included in the first section (physical infrastructure), but we have decided to group them here for a more focused look at them.

As stated before, the function of a RSU is to make communication possible between vehicles and infrastructure. Due to its nature, the RSU is an important component with the transport of the future, since it can be applied in many applications, such as accident, traffic, or weather warnings, automatic toll collection, and parking. However, as the success of CAV implementation is dependent on RSUs, deployment is challenging.

For example, when deploying a pilot, some measures should be taken, especially considering the installation of RSUs. There might be some restrictions in local law or space limitations for installing roadside equipment, so it is advised that work be carried in collaboration with local government to determine the feasibility in deploying tests [66]. Also, the availability of a robust network connection in order to properly connect RSUs and other equipment to the back-office facilities must be considered. For new road projects, provisions for conduit and fiber-optic installation should also be considered.

RSUs can be installed in poles located alongside roads, whether they are especially built or already existing, such as a traffic light arm or other signaling poles. They can be also installed inside a cabinet located on the side of a road. There are also elements of ITS embedded in pavements, such as induction loops, used to identify vehicle presence, especially when related to traffic signals or parking spaces.

Transport agencies, even of different sizes, appear to have similar infrastructural needs. According to a survey carried out by Barbaresso and Johnson [67], the main focus of CV program has been on V2V safety, but respondents are not sure about the role of infrastructure [22]. There are also concerns regarding the frequency of maintenance, the robustness and capabilities of remote diagnostics and resetting (when there is a failure), although by definition, both the hardware and software components of an RSU should be able to operate unattended in harsh outdoor environments for extended periods of time [29].

In the same survey, the issue of maintaining V2I infrastructure was addressed, mentioning the concerns not only about deployment and operational costs, but also long-term maintenance costs, especially given the lack of historical data and experience (from some agencies) on working with this type of infrastructure [22, 67]. Agencies that have experience in deploying pilot programs mentioned the infrastructural elements used in their tests, including 5.9 GHz DSRC RSUs, upgraded signal controller cabinets, backhaul communications and data management, and infrastructure-based messaging. Moreover, maintenance considerations for the deployment were separated into four areas: equipment operation and failure mitigation; state of health monitoring; security management; and data and network management [68].

Additionally, some lessons were learned from those pilot programs. It was observed that CAV infrastructure is going to be heavily associated with intersections and that RSUs receive special attention from agencies, regarding health monitoring and warranty period/repair/replacement. Also, it was identified that CAV infrastructure involves diverse elements and components to be installed or constructed with the infrastructure [68]. Sobanjo [22] adds that, given the diverse elements in CAV infrastructure, "deterioration models will need to consider failure times and use reliability-based concepts".

Even with RSUs helping with communication, a cellular network is also needed for other types of communication, transmitting route information and data. Since CAVs need low latency communication for real-time decision-making, 5G (the latest generation of mobile connectivity until now) is required. Also, CAVs generate a huge amount of data due to their sensors and cameras (around 4 TB of data per day), so data transfer rate is also important. 5G can supply that data transfer rate, making other types of data exchange possible, such as download/updating of High-Definition (HD) maps, software updates, video streams for remote assistance, or even media streaming for passengers while on board.

Communication capabilities can also improve location accuracy, which is crucial for a safe and efficient operation of a CAV. Since these vehicles rely on precise location data to navigate roads, avoid obstacles, and make decisions in real-time, even slight errors in location can lead to serious consequences such as collisions or wrong navigation. Precise location does not only affect navigation, but it is also related to vehicle performance since if it is not sure about its position, it can activate fallback safety measures (for example, stopping the vehicle entirely). This means that a vehicle cannot merely trust traditional positioning systems, such as GPS, due to its relatively low precision or susceptibility to external interference (e.g., weather, buildings). It must therefore be complemented by other technologies that can work together [59].

Embedded technologies such as LiDAR or cameras can assist vehicles with positional awareness on the road, while RSU triangulation techniques can improve geolocation accuracy in dense urban environments [69]. External information, coming from HD Maps, can also help that. The addition of the term "high-definition" refers to a highly detailed map with several features including lane geometry and markings, traffic signs, and road furniture, to within a few centimeters' accuracy, usually not found on regular maps. By integrating HD maps with sensor data from cameras, LiDAR and radar, a CAV can better determine its position relative to these features.

The importance of HD maps lies in their ability to provide an additional layer of redundancy to the onboard sensors used by AVs for navigation. In situations where environmental conditions are challenging or when objects like pedestrians or cyclists may not be easily detectable by onboard sensors alone due to occlusion or other factors, HD map data can help fill in the gaps in perception by providing context about what is happening beyond the range of immediate sensor coverage. Moreover, HD maps also enable more efficient route planning as they allow CAVs to anticipate upcoming changes in road conditions such as curves or intersections before approaching them. This can result in smoother driving behavior and reduced energy consumption which translates into longer operational range for electric CAVs, for example.

Maps providers, such as TomTom or HERE, can not only provide maps with high precision (regarding spatial positioning and completeness), but must likewise be concerned regarding time. Maps are always outdated, so the frequency of updates are also of the utmost importance. Since any map provider cannot guarantee that a map is 100% updated to match reality, CAVs must be prepared to deal with challenging conditions such as roadworks, which could alter the number of lanes available for driving in a given segment or modify the road markings readable by cameras. As said before, cellular data can be used to update maps, but can also give roadwork updates or on-the-fly traffic management via map providers or government information. V2I infrastructure (DSRC beacons for instance) can transmit updated roadwork layouts to a CAV to facilitate navigation within the works [65].

As can be seen, asset managers must deal with diverse infrastructure to ensure a proper flow of CAVs. This ranges from deploying RSUs, antennas, and DSRC beacons optimally, developing "invisible infrastructure" (like mapping or data management), or traditional infrastructure like fiber network to connect RSUs to back-office. This is challenging, given it includes different areas within government bodies, and raises issues with financing. Other issues like cybersecurity, privacy, and data governance also need attention. Some of these will be addressed in the following section.

4.3 Policy and Legislation

The integration of CAVs in the current transportation system creates several challenges for policymakers and managers, who are well aware of this. In a survey regarding how an agency should choose to invest time or resources for technical preparation for CAVs, the largest group of answers were related to legal, legislation, regulatory issues, and standards [70]. As this is a new area, agencies and government bodies need to be fast in regulating the deployment of CAVs and to provide a safe environment for companies to properly test and deploy the new vehicles.

Current laws assume a human is driving a machine, while the driver has the sole responsibility of the driving task. Within the CAV environment, the driving responsibility is passed to the machine, but sometimes where the vehicle is not capable of operating safely, this responsibility is passed to the human. A future-proof legislation should address that but should also be aware that CAVs and regular vehicles will co-exist for some period, so adaption and iteration is important, which is a challenge for legal departments [59].

Government bodies who are aware of those changes and are efficient about discussing and imposing new regulations are the candidates to be pioneers in deploying CAVs on a large-scale. Some countries such as Singapore, the United Kingdom, and Netherlands are ahead of the game and have drafted new standards, expanding their test areas and even setting up some driverless buses [71]. It is also important not only to update regulations, but also to publicly fund some pilots and improve institutional capacity. Policy makers need new skills, while there is a greater need than ever for coordination between different government bodies, such as transportation, justice, economy, and energy [59], as highlighted in Sect. 3.

Lastly, privacy concerns related to data collection practices associated with CAVs need attention from policymakers as they collect significant amounts of personal information. While automakers must ensure that their vehicles are equipped with advanced security features, capable of protecting against evolving threats posed by cybercriminals, legislation should also consider this. For example, a United Nations regulation from 2020 is already enforcing some measures against cyberattacks on CAVs [72].

4.4 Innovation

An updated policy shows that a given agency/government body is attempting to be ready for the mobility of the future. That not only displays a tendency to tackle challenging problems but signals to the market that the state/country is willing to test and adopt CAVs. However, this is not the only main factor, given that consumer acceptance is also a key factor in embracing new technology.

There are several factors that can be used to assess how well a place is prepared to accept CAVs, regardless of road infrastructure. KPMG [71] cites as relevant factors: industry partnerships and investments; patents; cybersecurity; cloud computing; artificial intelligence and Internet of Things; test areas; civil society technology use; consumer ICT adoption and digital skills; individual readiness; and online ride-hailing market penetration, among others. While at first glance one might imagine that a country that excels in some of these factors should excel in others, some of these factors can work counter-intuitively to the contrary. For example, India and Brazil have a relatively low public index of digital skills, yet at the same time, the penetration of the online ride-hailing market in these countries is remarkably high.

Consumer acceptance will also depend on other factors such as safety, reliability, and affordability. Manufacturers must ensure that their products are safe and reliable while being affordable for most consumers. Innovation is also an essential factor for the success of this technology since it enables carmakers to develop new features like self-driving capabilities or advanced sensors that improve user experience and safety on the roads. As such, policymakers must provide a favorable environment for innovation by investing in research and development initiatives aimed at enhancing CAV technologies. Moreover, collaboration between various stakeholders such as governments, carmakers, tech companies, and infrastructure providers is necessary to drive innovation forward while ensuring that consumer needs remain central throughout the process.

4.5 Readiness of Agencies and Governments

There are many uncertainties as to how CAVs will operate in the future and how they will integrate with existing vehicles, infrastructure, and space. It is expected that CAVs will significantly impact traffic, given that empty trips will occur (trips without a person inside the vehicle) and that demand might increase too (for example, travel for people who are ineligible to drive, such as the elderly). Traffic modelling tools, such as PTV Vissim and Visum, do not yet fully support simulation with CAVs [73], which may interfere with transport planning decisions. There are many other CAV issues and themes that concern agencies, such as safety, rideshare, land-use, parking, public transit, ownership, revenue, emissions, employment impacts, data-sharing, privacy, and regulation, for example [74].

Local authorities should anticipate technological changes and understand their roles with CAV systems. Literature states several challenges, such as understanding possible impacts, deployment, and integration with existing infrastructure, legislation, and transport policy, among others [19, 20]. CoExist [75] defines the concept of "automation-readiness" as the capability of making good decisions about the deployment of CAVs in a mixed road environment, which requires a strong understanding of CAV technology, its different uses and impacts on traffic, quality of life, and transport planning. The organization should also have a strategic approach in developing measures that ensure the proper deployment of CAVs, supporting mobility goals.

A survey of many transport agencies in the USA showed that a total of 41 already include AVs in their plans, while 12 have developed policies to guide the deployment and development of AVs [74]. These 12 agencies intended to promote innovation and ensure that the usage of these new vehicles addresses the problems of multimodal and public transportation, around congestion, equity, and other main issues. It was detected that many agencies are still being reactive rather than proactive, and that although they are aware of the advancing technology and the impacts it might have, the agencies are moving slowly towards creating policies to handle the deployment of CAVs. Another study of agencies in the 25 largest USA cities indicates similar insights, adding that most officials who were contacted felt unprepared to even respond to the survey regarding CAVs, and while most of them believe that AVs will be available for the public before the end of this decade, the local authorities are not yet clear about the share of responsibilities for implementing these changes [76].

4.6 Challenges and Opportunities

It is not only CAVs that will be challenging for transport managers, but there are other things too, such as road asset management related to infrastructure, the environment, and technology [21]. The impacts of climate change on infrastructure, namely more floods, longer droughts, freeze-thaw cycles more frequent, intense typhoons and hurricanes, and changes in wind (speed and profiles), compared to the current situation [77], could be severe, resulting in low cycle fatigue, accumulated damage, and faster surface deterioration [21]. These impacts will demand new design codes, affecting new and existing infrastructure, which in turn need to be more resilient and stable.

Managers of the future will also have to deal with the socio-economic and environmental impact of the vehicles. The motorization rate is increasing [3]; the advent of CAVs will likely impact the number of vehicles on street, while governments are enforcing the reduction of greenhouse emissions. The transport sector is one of the largest contributors of greenhouse emissions, accounting for around 14% of global emissions in 2018 [78], so reducing these emissions is essential if we are to meet climate goals. Some strategies include better vehicle efficiency, the usage of clean energy, and fuel taxes [3].

At the same time, the sustainable development of cities must be considered, and the deployment of CAVs (shared or not) can impact inequality within a city. For example, it is unclear how CAVs will impact the urban sprawl, which has direct effects on energy use, air and water quality, and the expansion of roads and other types of infrastructure [79]. Additionally, the implementation and the cost of CAVs may also be important criteria for how users will accept and react to CAVs [80].

The availability of big data will also impact road asset management. There will be a large amount of data produced by CAVs and this influx into asset management will bring some challenges, especially for a management heavily based on data, as better seen in Sect. 3. The conflation of new and old data, handling a continually increasing database, and the lack of tools to analyze this data quickly are problems that must be solved. AI techniques can be used to help manage the data and propose solutions. However, privacy concerns and computational and human resources are also challenges we need to consider [21]. Concurrently, this data usage is transforming road asset management, from a static environment to a dynamic one. Sensor data from smart pavements, GPS, imagery, weather, traffic, and accident data obtained and produced by CAVs can positively impact planning and operations. These data can improve monitoring of roads and asset management. HD Maps can be produced, road condition and assets can be evaluated in quasi real-time, emergency services can be improved, and decision-making will be better supported.

5 Summary and Conclusions

In this paper we present an overview of the impacts that CAVs will have on road asset management. To better understand this, an initial brief presentation of the vehicles of the future (automated and connected) is offered. Additionally, a comprehensive discussion on road asset management is presented. Finally, once all these concepts have been introduced, we thoroughly discuss some aspects that CAVs may have on road asset management.

It was observed that not many journal articles give an in-depth analysis on road asset management or investigate the effects of CAVs. The main novelty of this work is to discuss deeply these effects, while presenting an inclusive discussion on (road) asset management, based on the standards ISO 55,000, 55,001, and 55,002. While these standards are complete and well-built, our intention was to provide a concise overview for researchers who want to be introduced to this topic. On the other hand, there is an abundant amount of work on literature regarding CAVs, covering the intrinsic aspects of these vehicles. Therefore, a basic introduction to the details of the vehicles and how they operate is offered, to better understand the intersection between them and asset management.

It should be noted that CAVs will possibly change transport management. While some safety measures will theoretically be relaxed, since accidents due to human error should not happen, some aspects of the safety infrastructure will be deemed unnecessary. Nevertheless, the inclusion of sensors and other items will increase the need for asset management and ITS techniques. Big data and the high influx of information will bring some challenges on how to handle and use that information for asset management. Additionally, analytical techniques such as optimization, computer science, data science, and simulation can provide opportunities for asset management.

This paper has only been able to describe the most general aspects of asset management for vehicles of the future. However, there is still a need to better understand how the road infrastructure will be affected by CAVs, how the transport agencies can be prepared for their deployment, how the new infrastructure can be maintained, and if it is possible to draw a new methodology to manage the assets related to (and impacted by) CAVs, which can all be addressed in future research.

Even though this is only a preliminary study, it became evident that transport agencies will need to be assisted regarding asset management. Although many classical aspects and tools of asset management are still relevant, changes in our world bring new challenges, and those aspects should be considered in the asset management of the future.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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