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Research paper

Digital twins-enabled game theoretical models and techniques for metaverse Connected and Autonomous Vehicles: A survey

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ABSTRACT

The popularity of information and communication technology in automobiles has led to the next generation of smart vehicles known as Connected and Autonomous Vehicles (CAVs). The advent of the CAVs has rapidly emerged as an essential component of Intelligent Transportation Systems (ITS) due to the usage of advanced technologies for autonomous navigation, sensing, and improved vehicle safety. Moreover, during this era, Metaverse, often known as an embodied version of the Internet, aims to create a fully immersive and self-sustaining virtual shared space where individuals can live and interact through digital avatars. Recent technological breakthroughs like Web 3.0, 6G networks, extended reality, artificial intelligence, edge computing, and blockchain propel the Metaverse from science fiction to a near-future reality. Moreover, an integral component enabling this transformation is Digital Twins (DTs), which play an essential role in establishing the communication link between the two realms. This article comprehensively analyzes a detailed assessment of the CAVs-assisted Digital Twin-enabled game theoretical models and techniques used in CAVs Metaverse. Moreover, we explore the decentralized and autonomous nature of blockchain technology, making it an ideal platform for CAVs for securing financial transactions in the Metaverse, fostering trust and authenticity. Finally, we discuss open issues and future research opportunities for Digital Twin-enabled CAV Metaverse systems.

1. Introduction

The term “Metaverse” refers to a computer-generated virtual realm that possesses an independent economy and has a consistent value system, which is connected to the physical world. It allows individual and software agents to interact with one another through 3D avatars within this digital space. The word was originally used in Neal Stephenson’s novel “Snow Crash” in 1992 (Dionisio et al., 2013), and it has since then been characterized from different perspectives, such as a shared virtual environment, an embodied Internet, a spatial Internet, and an omniverse. The phrase “Metaverse” alludes to a completely immersive, hyper spatiotemporal, and enormous virtual shared area in which users interact with one another via digital avatars (see Table 1). The Metaverse’s primary goal is to create a fully immersive, interconnected network of 3D virtual worlds and real-world locations that allow users to immerse themselves in realistic cyber experiences. Major technology giants have been investing billions of dollars in the development of this revolutionary concept, which has attracted significant attention from both industry and academia. The Gartner report (Gartner, 2022) predicts that by 2026, over 2 billion individuals are estimated to be engaged in social activities within the Metaverse for at least an hour each day. Another report by McKinsey & Company forecasts that the value of Metaverse will exceed $5 trillion by 2030 (Weking et al., 2023).

Augmented Reality (AR), Virtual Reality (VR), Extended Reality (XR), and Mixed Reality (MR) are the key technologies for interactions between virtual entities and avatars in the Metaverse. Moreover, Metaverse integrates a variety of other technologies to provide a seamless user experience, such as beyond 5G and 6G technologies to provide high-speed and Ultra-Reliable Low Latency Communications (URLLC) (Lee et al., 2021), Artificial Intelligence(AI) is used to create an intelligent Metaverse environment (Ning et al., 2023), in which Digital Twins are used to enable seamless mapping between the digital

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Table 1
List of acronyms.

Acronym	Description	Acronym	Description
3D	Three-Dimension	IPFS	Interplanetary File System
3GPP	Third Generation Partnership Project	LCD	Liquid Crystal Display
5G	Fifth Generation	LADAR	Light Detection and Ranging
6G	Sixth Generation	Li-Fi	Light Fidelity
6DOF	Six Degrees of Freedom	LIN	Local Interconnect Networks
AD	Autonomous Driving	LSTM	Long Short-Term Memory
ADAS	Advanced Driver Assistance Systems	mmWave	Millimeter wave
AI	Artificial Intelligence	MEC	Mobile Edge Computing
AIaaS	AI-as-a-Service	ML	Machine Learning
AMOLED	Active Matrix Organic Light Emitting Diode	MMOG	Massively Multiplayer Online Game
AORTA	Approximately Orchestrated Routing and Transportation Analyzer	NaaS	Network Slicing as a Service
ASIC	Application-specific Integrated Circuit	NFTs	Non-Fungible Tokens
AR	Augmented Reality	NOMA	Non-orthogonal Multiple Access
ARHUD	Augmented Reality Head-Up Display	OLED	Organic Light-Emitting Diode
AWS	Amazon Web Services	PaaS	Platform as a Service
BaaS	Blockchain-as-a-Service	QoS	Quality of Service
BS	Base Station	RADAR	Radio Detection and Ranging
BCI	Brain-Computer Interface	RANs	Radio Access Networks
CaaS	Component as a Service	RL	Reinforcement Learning
CAVs	Connected and Autonomous Vehicles	RSUs	Roadside Units
CAN	Controller Area Networks	SaaS	Software-as-a-Service
CIoT	Cloud with Internet-of-Things	SDN	Software-Defined Networking
CNN	Convolutional Neural Networks	SDRANs	Software Defined Radio Access Networks
COLLADA	Collaborative Design Activity	SINR	Signal-to-Interference Noise Ratio
CV	Computer Vision	SONAR	Sound Navigation and Ranging
DBaaS	Database-as-a-Service	SUMO	Simulation of Urban Mobility
D2D	Device-to-Device	TaaS	Technology-as-a-Service
DAO	Decentralized Autonomous Organization	ThZ	Terahertz
DL	Deep Learning	TPU	Tensor Processing Unit
DoS	Denial-of-Service	URLLC	Ultra Reliable Low Latency Communications
DSRC	Dedicated Short Range Communications	UAV	Unmanned Aerial Vehicle
DT	Digital Twin	USPTO	United States Patent and Trademark Office
eMMB	Enhanced Mobile Broadband	VANET	Vehicular Ad-hoc Network
ECaaS	Edge Computing-as-a-Service	VLC	Visible Light Communication
ECUs	Electronic and Control Units	VRML	Virtual Reality Modeling Language
ERC	Ethereum Request for Comments	VR	Virtual Reality
FPV	First Person View	V2V	Vehicle-to-Vehicle
FL	Federated Learning	V2I	Vehicle-to-Infrastructure
FoV	Field of View	V2X	Vehicle-to-Everything
GCP	Google Cloud Platform	WWW	World Wide Web
GPS	Global Positioning System	X3D	Extensible 3D
GPU	Graphical Processing Unit	XaaS	Everything-as-a-Service
GT	Game Theory	XR	Extended Reality
HCI	Human Computer Interaction		
HMDs	Head Mounted Displays		
IaaS	Infrastructure-as-a-Service		
IMU	Inertial Measurement Unit		
IRS	Intelligent Reflecting Surfaces		
ITS	Intelligent Transportation Systems		
IoT	Internet of Things		

and physical worlds (Lv et al., 2022), and blockchain technologies are used for asset management within the Metaverse (Ali et al., 2022; Xu et al., 2022a).

The concept of Metaverse has applications in CAVs, which have been a long-standing engineering goal in the automotive industry (Zhou et al., 2022). The term CAVs are intertwined with two technologies, connected vehicles, and autonomous vehicles, which are revolutionizing the automotive industry by offering the potential to replace human drivers for some or all driving operations (Hussain and Zeadally, 2018). Connected vehicles have the capability to exchange information about oncoming traffic, blind spots, obstacles, accident warnings, and traffic congestion with other connected devices, vehicles, and road infrastructure within their communication range. Autonomous vehicles, on the other hand, utilize automated technologies to conduct the task of driving without human assistance (BAE systems, 2021), thus reducing the likelihood of traffic accidents and minimizing congestion on the roadways (Wang et al., 2019).

With the latest advancements in technologies, the idea that roads may one day be full of self-driving vehicles and connected devices seems to be feasible. A recent news article reports that the government intends to develop infrastructure and landing facilities for drones and helipads on national highways. This initiative aims to enhance emergency medical services by deploying 600 new flying objects to assist people in medical emergencies. Thus, in the coming years, the automotive industry and transportation systems will likely undergo a dramatic change to increase user accessibility, safety, and efficiency.

Although connected vehicles offer potential benefits, concerns regarding security and privacy have emerged for vehicle manufacturers. The increasing level of connectivity and automation has made CAVs more susceptible to attacks from both inside and outside of vehicles (Aliwa et al., 2021). Attackers may compromise the vehicle's sensory systems to manipulate its behavior or disrupt wireless signals, leading to Denial-of-Service (DoS) attacks (Gupta et al., 2020). They can spoof emergency vehicle warning signs to deceive the vehicle sensor. Moreover, downloading music on the car stereo may contain malware codes that could infiltrate the vehicle's entertainment system and disrupt other crucial systems, such as the engine or brakes (Sun et al., 2021b). Moreover, compromising physical objects like road signs

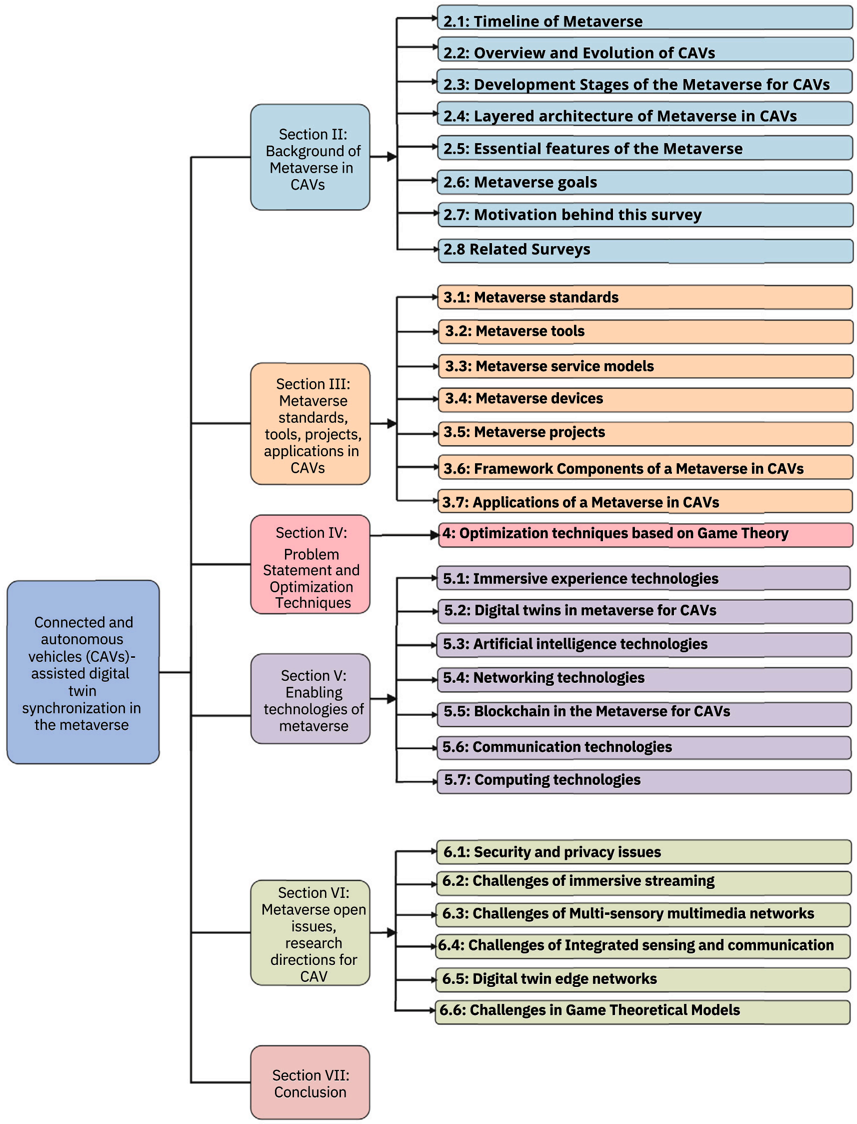

Fig. 1. Taxonomy of the CAVs-assisted Digital Twin synchronization in the Metaverse.

can mislead the vehicle, as demonstrated by the attack on the Test Mobileye EyeQ 3 camera (O'Neillarchive, 2020).

According to a recent report, the infotainment systems of two widely recognized connected cars manufactured by Ford and Volkswagen in Europe has indicated potential vulnerability to cyberattacks (Team, 2020). This highlights the necessity for enhanced security measures, making it essential to address potential cyber-security risks and vulnerabilities to facilitate the widespread deployment of CAVs in intelligent transportation systems (Hahn et al., 2019; Cui et al., 2019; Lamssaggad et al., 2021). A list of acronyms used in this paper is summarized in Table 1, and Fig. 1 depicts the taxonomy of CAVs-assisted Digital Twin in the Metaverse.

1.1. Paper contributions

The list of contributions of the paper are summarized below.

- This paper presents a thorough literature survey that evaluates the CAVs-assisted Digital Twin-enabled game theory concepts and techniques employed within the CAVs Metaverse. First, we presented the Metaverse's history, including the timeline revolution from 1994 to 2023, the evolution of CAVs and their development stages, the layered architecture of the Metaverse in CAVs, and vital features and objectives.
- Furthermore, we explore the Metaverse standards, tools, and devices used in real-world applications, along with active initiatives, framework components, Metaverse optimization methodologies, and CAV applications.
- The paper then discusses the real-world challenges that CAVs encounter, such as lane-change decision-making, traffic flow optimization, cross-intersection coordination to minimize accidents, and resource management. Then, as a solution, we provide Game Theory-based optimization strategies for CAVs and integration of the different enabling technologies that meet these issues by modeling interactions between multiple agents, including vehicles, infrastructure, and pedestrians.
- We explore the decentralized, and autonomous nature of blockchain technology, making it an ideal platform for CAVs for securing the financial transactions in the Metaverse, fostering trust and authenticity. Finally, we discuss open issues and future research opportunities for Digital Twin-enabled CAVs Metaverse systems.

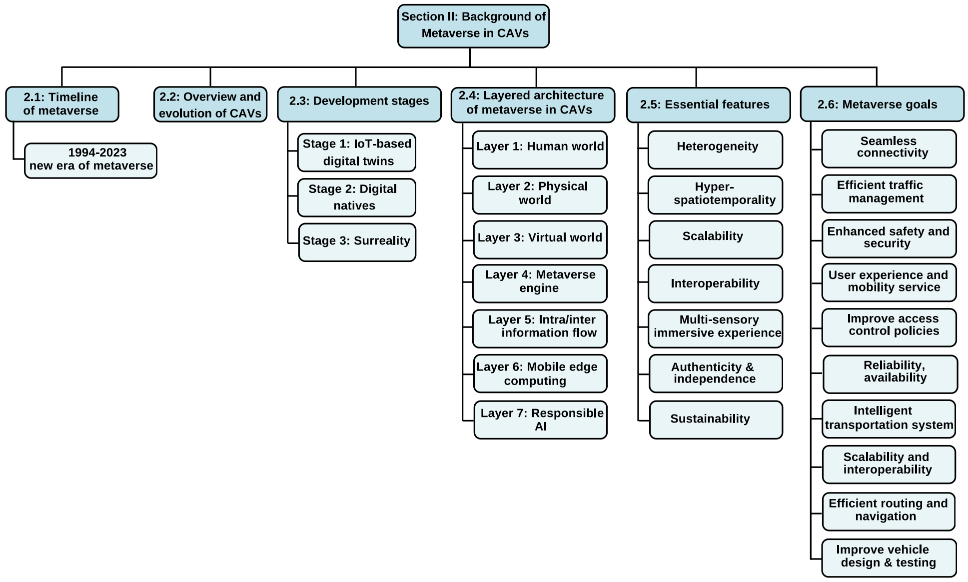

Fig. 2. Background of a Metaverse in CAVs.

1.2. Paper organization

The paper is structured as follows: Section 2 examines the history of Metaverse in CAVs. Section 3 investigates Metaverse standards, tools, ongoing initiatives, and their applications in CAVs. Section 4 goes over the problem statement and optimization approaches for addressing the real-world problems of Metaverse in CAVs. Then, in Section 5, we see how the various enabling technologies can be integrated into autonomous vehicles. Section 6 then examines unresolved issues and research directions for CAVs, followed by Section 7, which concludes the work.

2. Background of Metaverse in CAVs

This section covers the timeline of Metaverse, development stages, layered architecture of Metaverse in CAVs, essential features, alongwith the Metaverse goals. Furthermore, in Fig. 2 we have depicted the taxonomy of a Metaverse's background in CAVs.

2.1. Timeline of Metaverse

A wide range of technological advancements have influenced the evolution of the Metaverse, including the birth of the Internet and its first mention in the literature, the creation of the first virtual world project known as Second Life, the evolution of Extended Reality (XR) technologies, and the emergence of cryptocurrency and blockchain (Huynh-The et al., 2023b). Fig. 3 depicts the evolution of the Metaverse from 1994 to 2023, highlighting the significant shifts that have shaped the new era of this technology.

1994–1999: World Wide Web (WWW) and Mixed Reality (MR)

The WWW emerged in 1989 but gained substantial momentum in the mid-1990s, providing a global platform for information sharing and laying the foundation for the Metaverse (Stephenson, 2003; Duan et al., 2021). Over time, additional concepts such as lifelogging, mirror worlds, virtual collective spaces, an embodied Internet, and the omniverse have contributed to the idea of a computer-generated universe. In 1995, Active Worlds introduced an online virtual reality platform with a functional web browser, allowing users to create personalized avatars and interact with others in a shared virtual space (Duan et al., 2021). Active Worlds was an early pioneer of user-generated content platforms, offering users the ability to shape their virtual experiences (Dionisio et al., 2013).

1999–2002: Internet of things (IoT)

From 1992 to 2002, the emergence of the Internet of Things (IoT) brought about a revolutionary change in which physical devices, sensors, and objects could establish connections and exchange data with various systems over the Internet (Sun et al., 2022a). The evolution of the Internet of Things encouraged the incorporation of real-world objects into the Metaverse, enabling seamless communication between virtual and actual entities.

2002–2006: Birth of Digital Twin

Michael Grieves (Huynh-The et al., 2023b) presented Digital Twins as an experimental technique in 2002 at the University of Michigan, titled "Conceptual Ideal for Product Lifecycle Management". As a result, the concept of Digital Twins has become a crucial component in the construction of the Metaverse, a completely immersive and interconnected virtual environment. Philip Rosedale founded Linden Labs in 2003 and developed Second Life, a Massively Multiplayer Online Game (MMOG) that allows players to construct a 3-D virtual world in which they may create and control digital avatars and engage socially inside a virtual environment. The second life platform was seen as an early forerunner of the Metaverse and an important example of a virtual world that allowed for social interactions.

2006: Roblox

Roblox is a massively multiplayer online game platform that was developed in 2006 by Roblox Cooperation (Duan et al., 2021). This platform allowed users to build their own space by providing numerous resources such as pre-built models, tools, and scripting language for users to develop and share their own games through Roblox Studio (Ning et al., 2023; Lin et al., 2022). Roblox has quickly gained popularity among the young audience due to its ease of use and interactive gaming experience (Xu et al., 2022a).

2009–2014: Emergence of digital currency, blockchain technology, and modern headsets

The period from 2009 to 2014 marked a pivotal phase in the evolution of the Metaverse, driven by the advent of Bitcoin, blockchain technology, and modern VR headsets. Bitcoin is introduced in 2008 by Satoshi Nakamoto and implemented in 2009, established a decentralized digital currency enabling peer-to-peer transactions without a central authority (Nakamoto, 2008; Sun et al., 2022a). Blockchain

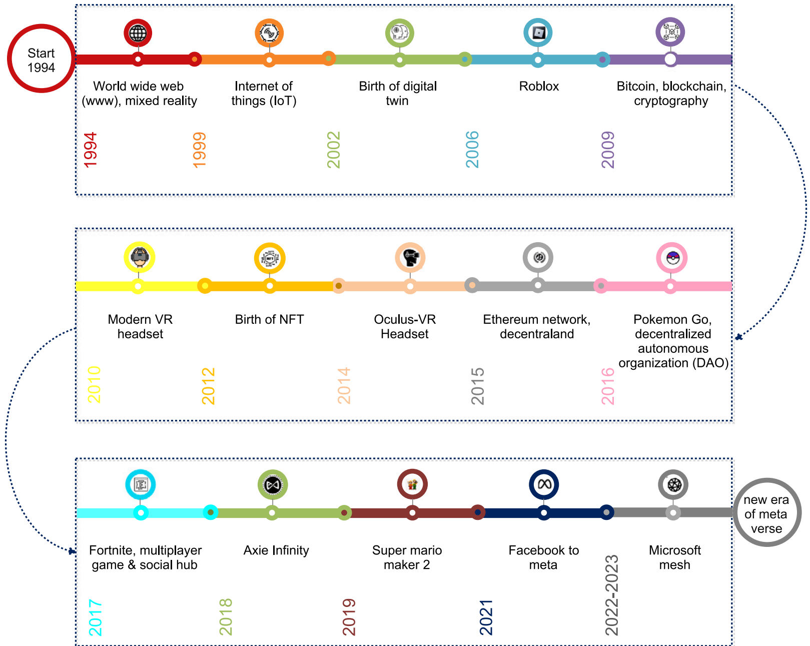

Fig. 3. Timeline revolution in the Metaverse.

technology, a distributed ledger characterized by enhanced security and tamper resistance serves as the foundation for digital transactions.

This era also saw the rise of modern VR headsets such as the HTC Vive and Oculus Rift, offering immersive experiences, and the emergence of Non-Fungible Tokens (NFTs), enabling ownership of unique digital assets. Together, these innovations laid the foundation for the emergence of Metaverse technologies and virtual environments that will continue to shape our future.

2015–2016: The advent of Ethereum, Decentraland, Pokemon Go

From the year 2015 to 2016, the Metaverse experienced several significant developments, including Ethereum, a decentralized blockchain-based platform that was introduced in 2015, enabling developers to build decentralized applications and smart contracts, improving network speed, efficiency, and security (Duan et al., 2021). That same year was the launch of Decentraland, a virtual world built on the Ethereum blockchain, allowing users to buy virtual land and create personalized spaces. Governed by a Decentralized Autonomous Organization (DAO), Decentraland uses NFTs and the MANA cryptocurrency for transactions (Siniarski et al., 2022; Gadekallu et al., 2022). Furthermore in 2016, Pokémon Go revolutionized mobile gaming and elevated the immersion and engagement of the gaming experience (Xu et al., 2022a). Niantic Labs created and published Pokemon Go, a GPS location-based game, encouraged players to explore their surroundings to capture and interact with virtual Pokémon (Duan et al., 2021). Thus, by overlaying digital elements onto real environments, this game provided an immersive and engaging gaming experience.

2017–2020: The Power of Play- How Fortnite, Axie Infinity, and Super Mario Maker 2 propelled the Metaverse into mainstream popularity?

Following the success of Pokemon Go, Epic Games developed Fortnite in 2017, a multiplayer game with three modes i.e. Fornite Battle Royale, Fornite: Save the World, and Fornite Creative, offering players a virtual space to socialize and express themselves. In 2018, a non-fungible token-based "play to earn" game called Axie Infinity was created by Sky Mavis, inspired by the Pokemon series (Gadekallu et al., 2022), allowing players to raise and trade virtual creatures called Axies (Ali et al., 2022). Super Mario Maker 2 in 2019 further expanded user engagement by enabling players to design, share, and play custom levels online (Xu et al., 2022a). Thus, these games led to an unprecedented surge in the Metaverse's popularity by showcasing its potential for social interactions, decentralized ecosystem, and user-generated content.

2021–2022: The Metaverse's ascension with Facebook's rebranding to Meta and the launch of Microsoft's Mesh.

In 2021, two pivotal events occurred that marked the ascension of the Metaverse. In Oct 2021, Facebook rebranded as Meta, a move that reflected growing ambitions to transcend beyond social media, web3, and into the Metaverse (Ning et al., 2023). As part of this effort, the company invests $10 billion aimed at fostering virtual connections, socialization, and business opportunities. Shortly after, Microsoft introduced a new platform called Microsoft Mesh, a mixed-reality platform designed for virtual collaborations, allowing teams to collaborate virtually from different geographic locations. As a result of these initiatives, the Metaverse is emerging as a new frontier in the digital workplace, reshaping how we interact, work, and transact business online.

2023 and beyond- The new era of the Metaverse

With the continuing growth of technology, we may expect the Metaverse to evolve and provide more seamless and immersive experiences. Even new technological advances in blockchain and cryptocurrency will play an important part in moulding the future of the Metaverse. Thus, in the future years, we may expect the Metaverse to become a fundamental part of our digital lives, with substantial ramifications for how we socialize and work with others (Ning et al., 2023).

2.2. Overview and evolution of CAVs

Connected and autonomous vehicles (CAVs) are vehicles that combine connectivity and automated driving technologies to assist or replace humans in the task of driving, enabling them to interact with networks, infrastructure, and other vehicles independently. With the integration of advanced sensor technology, onboard and remote processing capabilities, GPS, and telecommunications systems, CAVs enhance

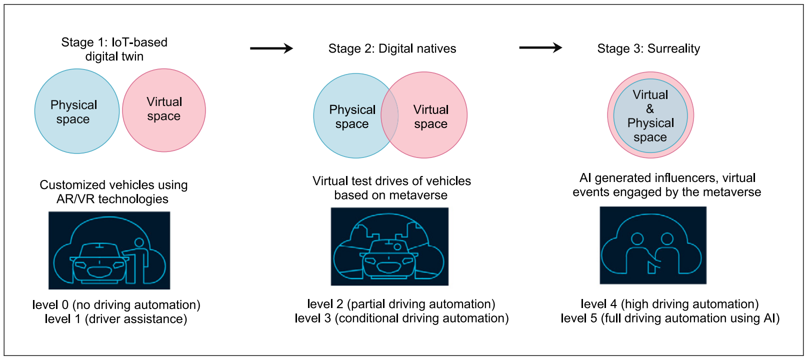

Fig. 4. Development stages of the Metaverse with respect to CAVs.

transportation efficiency, reduce accidents, improve safety, and provide environmentally friendly mobility solutions (Hussain and Zeadally, 2018).

The concept of autonomous driving emerged with the invention of remote-controlled devices, referred to as "phantom autos" in the 1920s. The field of autonomous vehicles gained momentum in the 1980s with projects like Carnegie Mellon's Autonomous Land Vehicle (ALV), developed at NavLab (Kanade et al., 1986) and Mercedes-Benz's "Prometheus Project", which designed the first lane-tracking robotic car (Behringer and Muller, 1998). In 2004, the DARPA Grand Challenge (DGC) propelled navigation and sensory technology advancements (Behringer et al., 2004). Furthermore, technologies such as Vehicular Ad hoc Networks (VANET) and Dedicated Short-Range Communication (DSRC) standards emerged, enabling Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication (Kenney, 2011). With advancements in artificial intelligence, sensor technology such as LIDAR, radar, and cameras alongside communication systems (VANET, 5G) to operate in complex environments, and high-speed communication from 2010 to the present, CAVs are now equipped with advanced driver-assistance systems (ADAS) that allow for high levels of autonomy, real-time decision-making, and enhanced safety (Damaj et al., 2022).

The advanced computing platforms, such as NVIDIA's Drive PX2, support the extensive GPU processing needs of these autonomous systems (Lopez, 2016). The collaborations between tech companies and automakers, including partnerships between Google, Tesla, Microsoft, Volvo, and Toyota, drive innovation and lead the way in driverless car technology. Recent projects such as Volkswagen's V-charge and PSA Group's "eyes-off" tests in Europe highlight progress toward widespread deployment (Group, 2016). These enhancements will support real-time decision-making while integrating next-generation technologies such as AI, Digital Twins, and mobile edge computing, which will pave the way for CAVs in intelligent transportation systems.

2.3. Development stages of the Metaverse for CAVs

The development stages of the Metaverse for the CAVs represent the evolution and progression of this immersive virtual world. These stages serve as a visual representation of how the Metaverse undergoes transformation and expansion over time, as depicted in Fig. 4. In this part, we provide a complete description of the three stages of Metaverse evolution in the context of CAVs.

Stage 1: IoT-based digital-twin

Stage 1 of the Metaverse development focuses on the creation of Digital Twins, which are virtual representations of physical vehicles. These Digital Twins enable customized experiences through the use of Augmented Reality (AR) and Virtual Reality (VR) technologies, facilitating simulation and testing in a virtual environment. This stage encompasses both Level 0 and Level 1 vehicle autonomy (Bojic, 2022; Xu et al., 2022a). At Level 0, there is no driving automation, and the driver retains complete control of vehicle operations including steering, accelerating, braking, stability control, blind-spot warning, lane-keeping assistance, and automatic emergency warnings, to provide alerts and support in specific situations. These features only alert/support the driver under certain situations but do not drive the vehicles (Maurer et al., 2016).

Level 1 introduces the lowest level of automation with Advanced Driver Assistance Systems (ADAS) technology (Okuda et al., 2014) such as adaptive cruise control and lane-centering assistance, which aids the driver with steering, braking, or accelerating assistance. An ADAS system also incorporates features like rear-view cameras and lane departure alerts, requiring driver to remain vigilant and prepared to take control of the vehicle whenever necessary (Omeiza et al., 2022). The digital twin approach eliminates the need for physical prototypes, allowing for iterative design improvements efficiently.

Stage 2: Digital natives

In this stage, the Metaverse progresses to digital natives which mainly focuses on native content creation. The digital natives represented by avatars can produce innovations and valuable insights exclusive to the virtual realm (Wang et al., 2022; Bojic, 2022). This phase recognizes the virtual space to attain equal significance as its physical counterparts, thereby creating more intersections between these two realms. During this stage, the Metaverse progresses to virtual test drives within the digital environment, corresponding to Level 2 and Level 3 autonomous driving capabilities.

At Level 2, vehicles exhibit partial automation and incorporate multiple assisted driving technologies that work together simultaneously. These technologies allow the vehicle to handle both steering and acceleration/deceleration, though human supervision remains essential. Tesla's Autopilot is an example of Level 2 automation, comprising a suite of advanced driver-assistance system features (BAE systems, 2021; Yaqoob et al., 2019). Level 3 introduces conditional automation, where the vehicles have the ability to make decisions without human intervention, leveraging sensors like LiDAR (Gruyer et al., 2017; Bhat et al., 2018). While the vehicle controls operations, human intervention is still required during emergencies or system failures (Xu et al., 2023).

Stage 3: Surreality

In the final stage, the Metaverse reaches a condition of surreality, corresponding with the highest levels of autonomous driving and AI-driven interactions. At Level 4, vehicles possess the capability to operate in self-driving mode in most conditions and programmed to stop in the event of an emergency or system failure (Yuan et al., 2018). Level 5 signifies the utmost level of automation under all conditions without any human intervention (Yaqoob et al., 2020). In this stage, the Metaverse will integrate Artificial Intelligence (AI) and machine learning to enable vehicles to navigate roads autonomously, respond to real-time road and traffic changes, and make safe driving decisions independently (Namatherdhala et al., 2022; Shalev-Shwartz et al., 2016; Grigorescu et al., 2020). This not only improves driving comfort, but also efficiency and convenience.

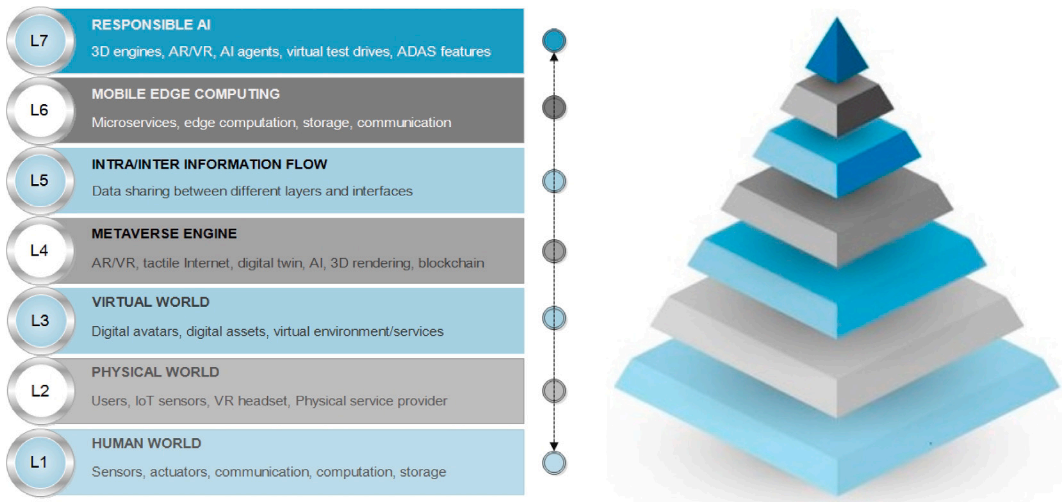

Fig. 5. (a) Layered architecture of Metaverse in CAVs, (b) Automation pyramid of transition shift in CAVs from Industry 3.0 to Industry 4.0.

2.4. Layered architecture of Metaverse in CAVs

We present a layered architecture of Metaverse for CAVs, based on the framework introduced by Xu et al. (2022a) and Wang et al. (2023b), which incorporates the integration of these three realms as illustrated in Fig. 5(a). Similarly, the automation pyramid, shown in Fig. 5(b) is a reference model for addressing the issues that CAVs are facing as a result of the paradigm transition from Industry 3.0 to Industry 4.0. Sensors, actuators, and VR headset units are used in level 1 and level 2 to control the manufacturing processes. Then, in order to meet the necessary quality standards in level 3, the physical world's activities are monitored, supervised, and controlled. The industrial control operations and management responsibilities for dynamic work scheduling, data collection, dissemination, and optimization comprise the next level of the automation pyramid, which is level 4. Resource planning, information exchange, data-driven analysis, and process optimization through decision support systems are all included in Level 5. Then, at level 6, local/remote cloud–edge computation is carried out by means of embedded hardware and software systems at the edge layer, integrating the real and virtual worlds. Lastly, data visualization is carried out at level 7 so that real-time control can operate in the cloud and be shared across all levels instead of just one. The layered architecture consists of seven layers, which are discussed below.

1. Human world: This layer represents the physical presence of human users, their interactions, and activities essential for societal functioning (Lim et al., 2022; Heller and Goodman, 2016). It provides the Metaverse with infrastructure for computation, storage, communication, and sensing, enabling seamless interaction between the physical and digital realms (Genay et al., 2021). Sensors gather real-world data, including environmental and road conditions, vital for the operation of connected autonomous vehicles (CAVs) in virtual spaces. Actuators control physical devices, simulating realistic vehicle behaviors to enhance immersive simulations. The communication framework integrates diverse networks, including satellite, cellular, and Unmanned Aerial Vehicle (UAV) systems, ensuring connectivity and data flow within the Metaverse.

2. Physical world: This layer gathers data about vehicles, road conditions, traffic patterns, and environmental factors using IoT sensors, cameras, and GPS systems. It involves stakeholders such as users, automobile manufacturers, fleet operators, and infrastructure providers, which influence the CAVs interactions in the virtual realm. The key stakeholders are:

- ***Users:*** Users of CAVs are the drivers, passengers, and fleet managers, that interact in the virtual environments as avatars in the Metaverse through the AR/VR devices such as Head-Mounted Displays (HMDs), AR goggles, Human-Computer Interaction (HCI) systems.
- ***IoT sensors:*** IoT sensors deployed in the physical world collect real-time data about vehicles, traffic, and environmental conditions to update the virtual world, ensuring a seamless, immersive experience in the Metaverse.
- ***Physical service provider:*** They are responsible for operating and managing the physical infrastructure that supports the Metaverse engine, including communication and computing resources at the network's edge, enabling efficient CAV connectivity and processing.

3. Virtual world: The virtual layer of the Metaverse designed for connected autonomous vehicles (CAVs) encompasses elements, including the virtual environment, services, digital assets, and avatars. Within this virtual world, digital avatars represent users, operators, and fleet managers, serving as virtual identities or avatars for interaction and communication using Extended Reality (XR) and Human-Computer Interaction (HCI) technologies. Digital assets encompass CAV-related components, including their design, features, onboard hardware, and communication systems, enhancing the virtual representation of CAVs.

4. Metaverse engine: The Metaverse engine serves as the foundation for the integration of AR/VR, tactile Internet, Digital Twin, AI, 3D rendering, and blockchain technologies in the realm of CAVs (Wang et al., 2023b). It acts as the central processing unit, receiving real-world vehicular data and utilizing these technologies to generate, maintain, and update the virtual world. Through the use of Digital Twin technology, the Metaverse engine generates virtual replicas of CAVs and their surrounding environments (Ali et al., 2024). These Digital Twins accurately mirror the physical characteristics and behaviors of the actual vehicles, enabling realistic simulations, testing, and analysis within the Metaverse. XR and HCI techniques enable immersive interactions, allowing users to manage digital avatars and interact with virtual CAVs in the metaverse (Lim et al., 2022). The Metaverse engine employs AI-based algorithms which enhance decision-making, personalize avatars, and enrich the Metaverse experience by enabling virtual CAVs to respond intelligently to diverse scenarios (Wang et al., 2023a).

5. Intra/Inter information flow: This layer manages information exchange across Metaverse layers for CAVs, encompassing both intra-flow and inter-flow. In the human world, social networks enable interaction, while in the physical world, IoT sensors, actuators, and cameras capture environmental data. This data is processed and transmitted to the virtual world via communication frameworks. The Metaverse engine then integrates AI, Digital Twins, 3D rendering, and tactile Internet to create virtual representations that mirror the physical world. These digital creations are shared across sub-Metaverses, enabling realistic simulations and seamless interactions (Ning et al., 2023).

6. Mobile Edge Computing (MEC): The traditional cloud can effectively handle large-scale data maintenance over long periods but it can face limitations while offering offloading services for real-time user interactions due to latency and network congestion. Thus, MEC is a distributed computing infrastructure, designed to enable real-time processing of large amounts of data at the edge of the network i.e., closer to end-users and their devices (Zhou et al., 2022). It facilitates efficient data processing and storage, reducing latency and enhancing real-time decision-making like navigation direction, facilitating object detection for Augmented Reality Head-Up Display (ARHUD) in ADAS (Advanced Driver Assistance Systems) (Zhou et al., 2020), efficient traffic monitoring, and task scheduling for CAVs in the metaverse.

7. Responsible AI: This layer focuses on ensuring ethical, safe, and reliable behavior of CAVs within the Metaverse (Li et al., 2022). It involves developing AI models that adhere to fairness, transparency, and accountability. AI agents simulate realistic driving scenarios and interactions, allowing CAVs to undergo virtual test drives to assess their performance, safety, and regulatory compliance. The integration of 3D engines and AR/VR technologies enables immersive visualization and interaction with virtual CAVs models, enhancing understanding and engagement. Responsible AI in the Metaverse for CAVs also encompasses ADAS features, which supports various tasks, such as lane-keeping, adaptive cruise control, collision avoidance, and pedestrian detection (Hussain and Zeadally, 2018; Zheng et al., 2015), ensuring safer and more efficient CAV operations in the Metaverse.

2.5. Essential features of the Metaverse

Metaverse is a fully-immersive, scalable, persistent, and interoperable platform integrating the physical and virtual worlds in real-time (Thomason, 2021). This section presents the seven essential features of the Metaverse which are summarized in Table 2. The prominent features of the Metaverse with respect to CAVs are discussed as follows.

(1) Heterogenity: The heterogeneity within the Metaverse encompasses diverse virtual spaces, varied device interfaces, a mix of data types including both structured and unstructured information, a multitude of communication modes such as cellular and satellite, and the inherent diversity of human psychology (Wang et al., 2022).

(2) Hyper spatiotemporality: Hyper spatiotemporality in the Metaverse refers to the remarkable ability it offers users to transcend the limitations of time and space, enabling seamless and immersive navigation through virtual environments (Ning et al., 2023).

(3) Scalability: The scalability of the Metaverse pertains to its ability to efficiently handle and support a substantial number of concurrent users/avatar interactions, and end devices while maintaining the system efficiency and user experience (Dionisio et al., 2013).

(4) Interoperability: Interoperability within the Metaverse represents the capability of systems and platforms to seamlessly access and exchange digital information and assets among various integrated virtual subworlds. This enables users to freely navigate across different virtual worlds or sub-Metaverses without disrupting their immersive experience. For example, a user can create content within a game like Minecraft and seamlessly transfer that content to another game or platform, such as Roblox, while maintaining their identity and preserving their overall experience (Lee et al., 2021).

(5) Multi-sensory immersive experience: In the Metaverse, a multi-sensory immersive experience refers to a computer-generated virtual setting that is realistic enough for users to feel emotionally and psychologically absorbed. Users can interact with virtual entities and real-world projections with the use of technologies such as sensors, VR, AR, or IoT, substantially stimulating their multiple senses (Han et al., 2010). The Metaverse will allow users to have real-world-like realistic, immersive, and multimodal experiences, similar to the embodied Internet as envisioned by Mark Zuckerberg (Ali et al., 2022; Bojic, 2022).

(6) Authenticity and independence: The Metaverse encompasses both digital replicas of the physical world and virtual world creations, forming a parallel space that maintains a strong connection to external reality while remaining highly autonomous (Li et al., 2022). Within the Metaverse, participants have the ability to engage in activities that closely mirror the authenticity of the physical world, but also transcend the limitations of physical space.

(7) Sustainability: Sustainability in the Metaverse is characterized by a consistent value system and a closed economic loop infrastructure, ensuring high independence (Wang et al., 2022). To maintain persistence and eliminate single points of failure, the Metaverse must be built on a decentralized framework. It should continuously foster digital content creation, driving innovation (Dionisio et al., 2013), and adopt green technology, including NFTs and blockchain, to enable secure and transparent data management while promoting digital literacy.

2.6. Metaverse goals

This section outlines the Metaverse goals for connected and autonomous vehicles, as summarized in Table 3. These goals are discussed as follows.

G_1**- Seamless connectivity:** The Metaverse enables seamless connectivity for CAVs, facilitating constant communication between vehicles, infrastructure, and entities. It is anticipated that current communication systems such as LTE, 4G, and 5G could be incapable of meeting Metaverse demand for CAVs (Zhou et al., 2022). Connectivity for CAVs can be enhanced with 6G technologies, including Visible light communication (VLC) and Terahertz (THz) wireless communication, Intelligent Reflecting Surfaces (IRS), Non-orthogonal Multiple Access (NOMA), and Millimeter wave (mmWave) (Li et al., 2022; Siniarski et al., 2022).

G_2**- Efficient traffic management:** Applying machine learning such as federated learning for efficiently training meta-space CAVs models, reinforcement learning for resource allocation, and generative AI for simulating traffic data can help identify patterns, anomalies, and correlations in transportation data (Khan et al., 2022b; Xu et al., 2023). These techniques can provide valuable insights for optimizing traffic management, predicting traffic conditions, and improving transportation operations.

G_3**- Enhanced safety and security:** Safety is a primary goal for CAVs in the Metaverse, which is ensured by employing cybersecurity measures to enhance the safety features of CAVs. This includes implementing secure communication protocols, encryption, and authentication systems to prevent unauthorized access and data breaches.

G_4**- User experience and mobility service:** The Metaverse aims to enhance CAV user experience and mobility services by integrating augmented, virtual reality experiences, Digital Twins, on-demand mobility, real-time traffic updates, and in-vehicle entertainment and productivity. For example, AR interfaces can make hidden information visible to drivers, while Digital Twins can be used to provide a simulation platform with an immersive realistic experience for safe virtual driver training (Hussain and Zeadally, 2018).

G_5**- Improve access control policies:** The Metaverse improves access control in CAVs by implementing advanced technologies digital identity

Table 2
Features of Metaverse.

Features	Requirements	Platform	Vehicle computing hardware	Use cases
Heterogeneity	Centralized computing Vehicle-to-cloud communication Vehicle-to-vehicle communication Vehicle-to-infrastructure communication Vehicle-to-pedestrian communication.	Unreal engine, Unity.	On-board navigator, LiDAR, cameras (Gruyer et al., 2017).	Interactive in-vehicle gaming, personalized ADAS with XR, and virtual test drives.
Hyper-spatiotemporality	Cloud computing, low-latency communication, 5G/6G networks.	Google Earth, HERE.	On-board navigator, Stereo camera, IMU, Radar (Broggi et al., 2013).	On-ramp merges, immersive navigation, teleportation.
Scalability	Hybrid cloud (V2V VANET cloud combined with edge cloud) (Arthurs et al., 2021), Vehicle-to-cloud communication.	Microsoft azure, Amazon web services(AWS).	In-vehicle GPU, In-vehicle TPU.	Fleet vehicle optimization.
Interoperability	Interoperable protocols, cloud/edge computing, semantic computing.	OpenStreetMap, Mapbox.	Radar, auditory sensors, tactile sensors, olfactory sensors.	Cross-platform massively multiplayer online games, collaborative traffic management, cross-platform route synchronization.
Multi-sensory immersive experience	High synchronization, low latency, huge data monitoring, Real-time 3D rendering engine, real-time computing, Quality of Service(QoS).	Oculus Rift, HTC Vive, Microsoft HoloLens.	Holographic display, wearable XR device.	Immersive navigation, personalized ADAS with XR, VR driver training, and remote vehicle monitoring.
Authenticity and independence	Decentralized computing, secure peer-to-peer communication, security and privacy (Yaqoob et al., 2019).	Blockchain.	Video cameras, LiDAR, Radar, In-vehicle GPU, In-vehicle TPU.	Automated driving, mapping, and localization.
Sustainability	Energy-efficient computing (Yaqoob et al., 2019), eco-friendly communication.	GreenCloud, renewable energy sources (Zhang et al., 2023), collaborative mobility platforms.	Environmental sensors.	Eco-friendly routes (Tian et al., 2018), real-time electric vehicle charging, real-time environmental impact monitoring.

management systems, user profiles, and preferences, to establish and manage the identities of individuals and entities accessing CAVs.

G_6- **Reliability, availability:** The Metaverse achieves reliability and availability in CAVs through a combination of technologies and strategies. By distributing computational tasks across multiple nodes using blockchain-based edge computing infrastructure, the Metaverse can ensure that CAVs functions can be performed locally and efficiently. This reduces reliance on centralized systems and improves the reliability and availability of computing resources (Ahsani et al., 2023).

G_7- **Intelligent transportation system:** The autonomous driving system, the intelligent collection system, and the intelligent mining system are all part of the intelligent systems in CAVs. A quick, high-precision perception, localization, planning, decision-making, high-precision map construction, and updating are necessary, whether the mining system is physical or virtual. These can be realized by implementing Computer Vision (CV) to build and update high-precision maps, and NLP-based methods can be used to improve vehicle object communications (Liu et al., 2023a).

G_8- **Scalability and interoperability:** These are crucial factors for the successful integration of CAVs within the Metaverse ecosystem.

G_9- **Efficient routing and navigation:** In the Metaverse environment, AR, and MR, can be used to improve the vehicle navigation and user experience. For instance, industries such as Civil Maps (Li et al., 2022), and WayRay have applied AR/MR to understand the navigation operation of autonomous driving vehicles. Tactile live maps (car localization-5 cm, 10–100 μs end-to-end latency) and AR, MR can be used to improve the navigation system of the autonomous vehicle system.

G_{10}- **Improve vehicle design and testing:** CAV operators and maintenance personnel can engage in virtual training simulations that replicate real-world scenarios. This allows them to gain experience and develop skills in a safe and controlled environment. Training in Digital Twins helps prepare individuals to handle complex situations and make informed decisions when operating CAVs (Han et al., 2022a).

2.7. Motivation behind this survey

CAVs use an amalgamation of advanced technology with smart sensors and complex algorithms to identify and respond to their surrounding ecosystem, which includes LIDAR, a Global Positioning System (GPS), computer vision, radar sensors plus cameras to be connected, ADAS, Autonomous Driving (AD), and so on. Emerging technologies such as the integrity of AI and machine learning algorithms, smart sensors and robotics, computer vision, AR/VR, and Cloud with Internet-of-Things (CIoT) are fostering innovation in CAV technology to improve road safety.

The Quectel report (Casetti, 2023) forecasts a compound annual growth rate of 27.75% over the next five years, from 2019 to 2024. According to the forecast, more than 11.2 million connected automobiles would be equipped with Vehicle-to-Everything (V2X) systems by 2024. According to the Intel report (BAE systems, 2021), there is some complexity in CAVs because modern vehicles have hundreds of Electronic and Control Units (ECUs) and thousands of lines of code, which will increase in the future. According to Intel, the first CAVs will analyze about 4000 GB of data every day, with cameras measuring over 20–40 MB/s, RADAR measuring over 10–100 kB/s, SONAR measuring over 10–100 kB/s, GPS measuring 50 kB/s, and LIDAR measuring 10–70 MB/s for a single autonomous vehicle.

However, the number of vulnerabilities caused by the exponential rise of modern vehicles with IoT ecosystems poses a significant risk of safety-critical difficulties with CAVs. The security researchers discovered that the attacker mostly targeted the following security threats: (i) remotely operate a car by hacking the vehicle from the manufacturing site to compromise firmware authenticity, (ii) disable the vehicle, (iii) remotely unlock a vehicle/theft, (iv) establish a safety condition, (v) track or monitor the vehicle, (vi) use the vehicle as a weapon, (vii) ransomware attack, (viii) illegal commodities distribution, and (ix) attack vectors to acquire control of the CAVs.

Motivated by the potential consequences of security threats in the field of CAVs technology, this survey covers all aspects of CAVs security challenges and how we can use Metaverse and Digital Twin technology based on blockchain and game theoretical approaches to address this issue.

Table 3
Metaverse goals for connected and autonomous vehicles.

ID	Goals	Technical requirements of CAVs	Feasible solutions
G_1	Seamless connectivity	High-capacity data transmission network.	Investigating emerging 6G technologies such as VLC, Terahertz, IRS, NOMA, and mmWave for V2V and V2I networks (Li et al., 2022; Siniarski et al., 2022).
G_2	Efficient traffic management	Collection of real-time traffic data (traffic flow, road conditions, incidents, etc.) and proactive management of it.	CAVs can anticipate and proactively respond to potential traffic events by employing machine learning, and AI algorithms such as federated, reinforcement, and generative AI to provide valuable insights for optimizing traffic management, predicting traffic conditions, and improving transportation operations (Khan et al., 2022b).
G_3	Enhance safety and security	Ensure network security of vehicles, infrastructure, and other entities, risk of tampering during information sharing.	Blockchain-based data sharing and digital signature authentication protocol to verify the integrity of CAVs and their software components (Huynh-The et al., 2023a).
G_4	User Experience and mobility services	Requirement to facilitate the integration of mobility services, and personalize the CAVs experience.	Adopting VR, AR, ADAS, and edge computing-based storage and offloading schemes can enhance the user and mobility service experience of CAVs network (Khan et al., 2022a).
G_5	Improve access control policies	Governance of access rights and permissions of individuals and entities in CAVs, maintains user profiles and preferences.	Digital identity management scheme to establish access control between CAVs and authorized entities.
G_6	Reliability, availability	Single point of failure, efficient processing, reliability, and consistency of transactions performed.	Blockchain-based multi-access edge computing CAVs networks can be used to improve reliability and availability (Ahsani et al., 2023).
G_7	Intelligent virtual system	High-precision perception, localization, planning, decision-making, context awareness, the map construction system is required.	Methods based on computer vision (CV) can be used to build and update high-precision maps, and NLP-based methods can be used to realize entities communication in CAVs (Liu et al., 2023a).
G_8	Scalability and interoperability	Compatibility and interoperability between the virtual and physical worlds of CAVs, efficient storage, and retrieval of data.	Leveraging interplanetary file system (IPFS) based data storage solutions can contribute to scalability in Metaverse-connected autonomous vehicles (Peng et al., 2023).
G_9	Efficient routing and navigation	Detection of vehicle surroundings, real-time sensory traffic conditions data, and road closures.	Tactile live maps (that provide car localization of 5 cm, end-to-end latency of 10–100 μs), and AR, MR can be used to improve the navigation system of the autonomous vehicle system (Riegler et al., 2021).
G_{10}	Improve vehicle design and testing	Digital model of CAVs is required that enables observation of vehicles, pedestrians, roads, and traffic signals.	Empowering Digital Twins (DTs) to support synchronization between virtual and physical space of vehicles, e.g., virtual driver training (Han et al., 2022a).

2.8. Related surveys

This section provides a comparative analysis of existing surveys on Metaverse applications in Connected and Autonomous Vehicles (CAVs), with an emphasis on the role of Digital Twin (DT). Table 4 summarizes the scope and coverage of key parameters across existing studies, highlighting the gaps in current literature and the contribution of our survey. We have identified nine parameters, denoted as P_1 to P_9, which represent critical aspects in integrating the Metaverse technologies in CAVs. Parameter P_1 represents the foundational Metaverse architecture for CAVs, while P_2 covers the objectives specific to Metaverse for CAVs. The standards, tools, and models that enable Metaverse functionality are discussed by P_3. Furthermore, P_4 focuses on Metaverse devices and projects related to CAVs, while P_5 discusses advanced optimization techniques, including game theory approaches for CAVs. Parameters P_6 and P_7 provide deeper insights into applied technologies within the Metaverse for CAVs. The applications of the Metaverse in CAVs are discussed in P_6, and P_7 discusses the vital role of Digital Twins (DT) for CAVs in achieving real-time data synchronization and simulation for enhanced CAV performance and safety. Additionally, P_8 covers blockchain integration for CAVs in the Metaverse, and finally, P_9 discusses the open issues and future directions within the Metaverse for CAVs, with the objective to highlight the potential research gaps and emerging challenges.

The analysis of existing surveys reveals that, while each contributes valuable insights, significant gaps that are crucial for a comprehensive understanding of the field remain unaddressed. Recent studies such as Dionisio et al. (2013) introduced foundational concepts of virtual 3D worlds and the Metaverse frameworks, but they lack specifics on CAV applications, leaving a gap in real-world applicability for autonomous systems. Zhang et al. (2017) and Hussain and Zeadally

Table 4
Comparison and gaps in the existing surveys in Metaverse for CAVs.

Authors	Year	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
Dionisio et al. (2013)	2013	✓	✗	✗	✗	✓	✗	✓	✗	✓
Zhang et al. (2017)	2017	✗	✗	✗	✗	✓	✗	✗	✓	✗
Hussain and Zeadally (2018)	2018	✗	✗	✗	✗	✗	✓	✗	✗	✗
Tian et al. (2018)	2018	✓	✗	✗	✗	✗	✓	✓	✗	✗
Lee et al. (2021)	2021	✓	✗	✓	✗	✗	✓	✓	✓	✓
Arthurs et al. (2021)	2021	✓	✗	✗	✗	✗	✓	✓	✗	✗
Sun et al. (2022a)	2022	✓	✗	✗	✗	✗	✓	✓	✓	✓
Zeng et al. (2022)	2022	✗	✗	✗	✗	✓	✓	✗	✗	✗
Xu et al. (2022a)	2022	✓	✗	✗	✓	✓	✓	✗	✓	✓
Gadekallu et al. (2022)	2022	✗	✗	✗	✓	✗	✓	✓	✓	✓
Ali et al. (2022)	2022	✓	✗	✓	✓	✗	✗	✓	✓	✓
Wang et al. (2022)	2022	✓	✗	✓	✗	✗	✓	✓	✓	✓
Zhou et al. (2022)	2022	✓	✗	✗	✗	✗	✓	✓	✗	✗
Ning et al. (2023)	2023	✗	✗	✓	✓	✗	✓	✓	✓	✓
Xu et al. (2023)	2023	✓	✗	✗	✗	✓	✓	✓	✗	✓
Ahsani et al. (2023)	2023	✓	✗	✓	✗	✗	✓	✓	✓	✓
Wang et al. (2023b)	2023	✓	✗	✓	✗	✗	✓	✓	✓	✓
Our survey	2023	✓	✓	✓	✓	✓	✓	✓	✓	✓

P_1– Metaverse architecture in CAVs, P_2– Metaverse goals in CAVs, P_3– Metaverse standards, tools, models, P_4– Metaverse devices and projects, P_5– Optimization techniques using game theory in CAVs, P_6– Applications of Metaverse in CAVs, P_7– : Digital Twins in Metaverse for CAVs, P_8– Blockchain for CAVs in Metaverse, P_9– Metaverse open issues, future directions in CAVs.

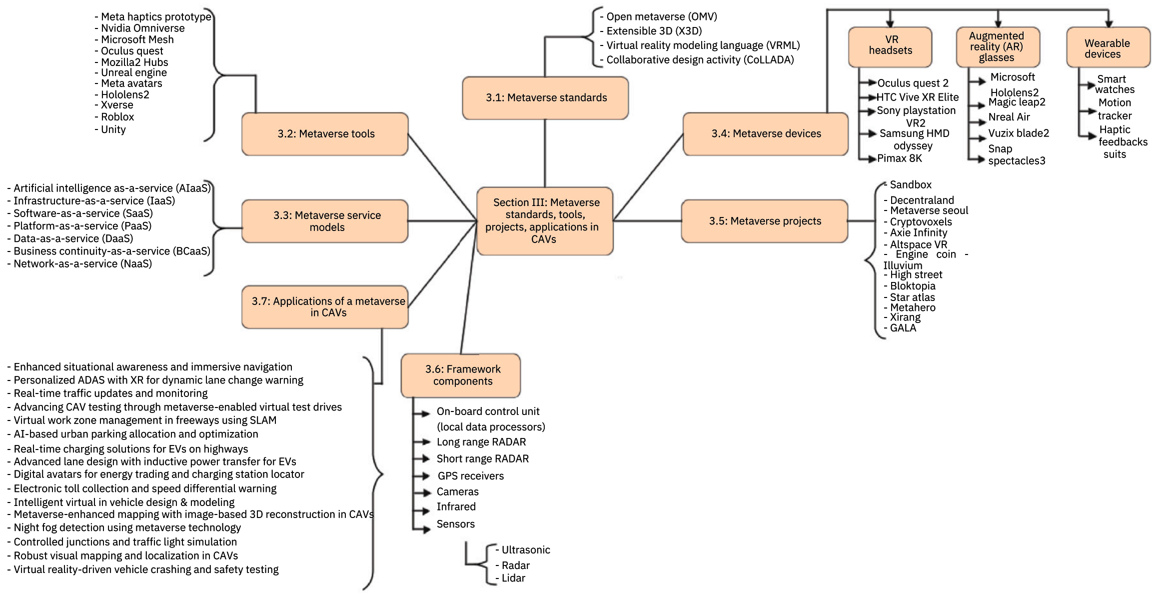

Fig. 6. Taxonomy of Metaverse standards, tools, projects, optimization techniques, and applications in CAVs.

(2018) provide frameworks for contract theory, wireless communications and autonomous vehicle challenges, respectively, yet they do not extend these concepts to the unique needs of CAVs in a Metaverse environment. Similarly, Tian et al. (2018) focus on the performance evaluation framework for CAVs but overlooks critical Metaverse components such as blockchain and Digital Twins (DTs). Recent studies, such as Lee et al. (2021) and Arthurs et al. (2021), examine edge computing and connectivity, essential for CAVs, but they did not delve into discussing optimization methods like game theory and providing a cohesive framework for the integration of Metaverse technologies.

More recent surveys offer insights into specific components but do not address a holistic approach to Metaverse-CAV integration. Sun et al. (2022a) and Zeng et al. (2022) explore applications like federated learning in autonomous controllers but lack analysis on secure data handling via blockchain or optimization techniques. Xu et al. (2022a) and Gadekallu et al. (2022) examine blockchain and DT applications but overlook a comprehensive integration of these technologies in CAVs. Ali et al. (2022) and Wang et al. (2022) address Metaverse fundamentals, security, and privacy but do not cover how these aspects intersect with CAV-specific challenges. Recent studies such as Ning et al. (2023) and Ahsani et al. (2023), and Wang et al. (2023b) have begun to explore future directions and advanced technologies like AI and edge computing; however, they lack a comprehensive framework that unifies architecture, optimization, and real-time data needs for CAVs. Our survey contributes by addressing these gaps by providing an integrated framework that covers all critical parameters: Metaverse architecture, goals, standards, devices, game-theoretic optimization, applications, Digital Twins, blockchain, and future directions, setting a comprehensive foundation for future research in the CAV-Metaverse field.

2.9. Survey structure

Following is the structure of this survey article: Section 2, present Metaverse standards, tools, projects, and applications of Metaverse in CAVs. In Section 3, we described the Metaverse enabling technologies related to CAVs. Section 4 discusses Metaverse open issues and future research directions. Finally, in Section 5, paper is concluded.

3. Metaverse standards, tools, projects, and applications in CAVs

This section covers the Metaverse standards, tools, devices used in real-world applications, running projects, framework components, optimization techniques in collaboration with the Metaverse, and applications with respect to CAVs. The taxonomy of Section 2 is presented in Fig. 6. The explanation of each sub-section is listed below.

3.1. Metaverse standards

Technologies such as augmented reality, virtual reality, AI, and IoT are emerged as foundational components of the Metaverse and have contributed to creating immersive interactive experiences for virtual worlds, games, and social networks. However, interoperability between these interconnected Metaverse services can only be provided through standards, which allows users to move seamlessly from one service to another as shown in Fig. 7.

Open Metaverse (OMV): This standard fosters the development of interoperability to enable industries to create an open, interoperable, and inclusive Metaverse. This would bridge the gap between applications to scale beyond a series of disconnected silos and to evolve a platform that is open to accelerate the development and deployment phase (Havele et al., 2022).

Extensible 3D (X3D): X3D standard was developed by Web3D Consortium which is used for publishing, viewing, printing, and archiving interactive 3D models on the Web (Havele et al., 2022). X3D supports a rich set of features such as high-quality graphics, a lightweight 3D runtime engine, modern animation, cross-platform, and more that make it suitable to use in engineering scientific visualization, AR/VR/MR, and Metaverse applications. The latest version of the extensible 3D standard is X3D®4 (X3D4) which will catalyze new value for Metaverse-industry partners.

Virtual reality modeling language (VRML): VRML is an open standard tool for representing 3-dimensional (3D) animations, graphical

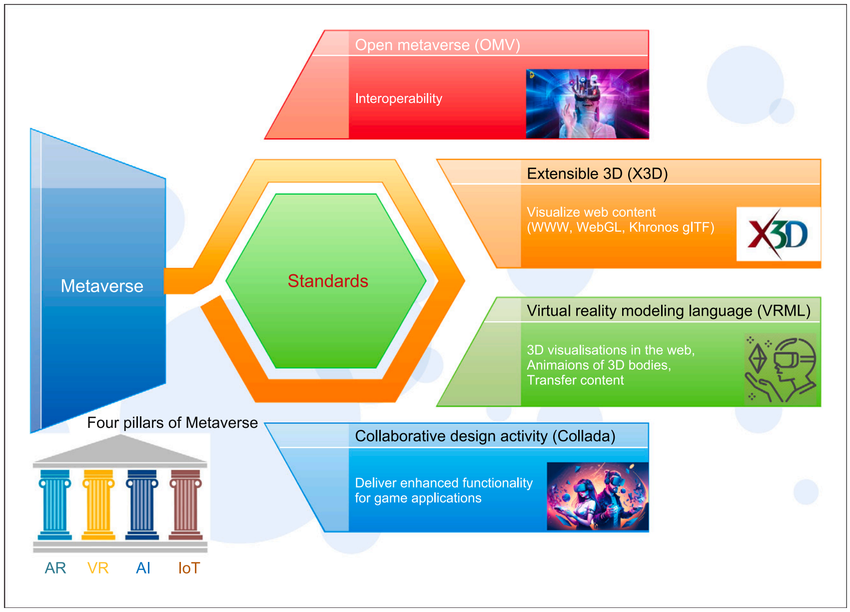

Fig. 7. Metaverse standards.

web-based models, interactive vector graphics, and objects (Oberhauser, 2021). It was primarily designed for virtual reality applications, particularly for the world wide web. Currently, VRML has been superseded by X3D

Collaborative design activity (COLLADA): This is an open standard XML-based file format for exchanging digital assets between various software applications and platforms. COLLADA has been used in the past for critical applications of Metaverse e.g.; interoperability and seamless exchange of 3D models, animations, and textures in virtual reality, gaming, and computer graphics. It provides a common format for representing 3D models, animations, and textures allowing different software applications and platforms to work together seamlessly, enabling creators to share content without losing fidelity or essential details (Wicaksana and Hartawan, 2023).

3.2. Metaverse tools

A variety of tools support the development and interaction within the Metaverse, each providing unique features designed for specific applications. For example, the Meta Haptics gloves prototype enables a realistic tactile experience through air pockets, suitable for VR-based enterprise applications (Xu et al., 2022a). Nvidia Omniverse, a comprehensive suite of cloud-based services, allows for 3D simulation and real-time collaboration across Digital Twin and gaming applications. Similarly, Roblox is an online game creation platform where users can develop and publish games for the community. Upon signing up, users receive an avatar they can personalize by collecting items during activities or using the in-game currency, Robux (Ning et al., 2023). Furthermore, Microsoft Mesh facilitates mixed-reality (MR) experiences, allowing users to join virtual meetings as digital avatars, with synchronized gestures and expressions across devices (Ali et al., 2022). Meta's Oculus Quest 2 and Mozilla Hubs provide versatile VR environments for gaming and collaborative settings, while tools like Unreal Engine and Unity offer platforms for immersive content creation, from gaming to Digital Twin applications for CAVs (Xu et al., 2022a).

In addition, digital avatars in platforms like Meta avatars, Hololens2 by Microsoft, and the blockchain-based Xverse enable various applications from virtual meetings to NFT trading. These tools collectively contribute to the Metaverse ecosystem, enhancing user interactivity, content creation, and real-time simulation. A summary of these tools, including their features, applications, and main purposes, is presented in Table 5.

3.3. Metaverse service models

The idea of the "as-a-service (aaS)" model was introduced by the United States Patent and Trademark Office (USPTO) in 1985 and gained popularity throughout the cloud computing era. The term "as a Service" typically refers to the delivery of a particular service or functionality over the Internet or a network, providing it on-demand to users. Examples of popular "as-a-service (aaS)" models in the cloud computing environment include Software-as-a-Service (SaaS), Platform-as-a-Service (PaaS), and Infrastructure-as-a-Service (IaaS). Accordingly, the Metaverse can benefit from the "as-a-service (aaS)" model. MaaS can simply be described as an enterprise solution where companies or platforms provide infrastructure, tools, and services to facilitate the creation, deployment, and management of Metaverse environments. Everything in the Metaverse can be thought of as a delivery model that can be generated or modified as function modules, like Everything-as-a-Service (XaaS) in cloud computing systems. Instead of traditional purchases or license models that necessitate prohibitive capital expenditure, users in MaaS only pay for the MaaS models (e.g., computing, communications, and data resources) that are used. Thus, the MaaS model will open a new marketplace where small to mid-sized industries can also gain profit from the Metaverse technology without getting into the technical, management, and implementation complexity of the Metaverse (Wei et al., 2023).

Metaverse services are classified into two types based on their service requirements: Component-as-a-Service (CaaS) and Technology-as-a-Service (TaaS). CaaS refers mostly to as-a-service models that provide multidimensional resources such as software-as-a-service (SaaS), PaaS, SaaS and Database-as-a-Service (DaaS). TaaS refers mostly to as-a-service models that utilize multidimensional resources, such as AI-as-a-Service (AIaaS), Blockchain-as-a-Service (BaaS), Edge Computing-as-a-Service (ECaaS), and 3D-as-a-Service (3DaaS) (Lyu et al., 2024). Table 6 shows a further split of CaaS and TaaS.

3.4. Metaverse devices

In this section, we will discuss the different types of devices that are currently being used in the development of the Metaverse. These devices can be categorized into three main types: VR headsets, Augmented Reality (AR) glasses, and wearable devices. The features of each of these devices are summarized in Tables 7 and 8 and the description is given below.

Table 5
List of Metaverse tools and their features.

Name	Developer	Features and benefits	Applications	Main purpose
Haptics gloves prototype (Xu et al., 2022a)	Meta in 2021.	Recreates the full sensation of touch, wired glove or data glove, science fiction staple.	Video games, wristband.	Transferring information, exerting force, moving, and getting feedback from the environment, decrease the input lag for video games.
Omniverse (Xu et al., 2022a)	Nvidia in 2022.	3D simulation and effects, supports animation, 3D rendering, materials and lighting.	Samsung's Digital Twin store, CAVs, Gaming.	Enables users to navigate, edit, and render Pixar USD content while providing capabilities including animation clips, skeleton animation, animation caches, and form blending.
Mesh (Ali et al., 2022)	Microsoft in 2021.	Personalize emotive avatars, organize areas for synchronous and asynchronous communication, content annotated with ink.	Participate in virtual meetings, and bring in 3D files from OneDrive.	Enables developers to create MR apps for Microsoft, host them there, and manage them there in the Azure cloud.
Oculus quest 2 (Xu et al., 2022a)	Meta in 2020 and Quest 3 in 2023.	Hand controllers with virtual reality device.	Fetel heart VR for sonographers, Rezzila training application adopted by Manchester football club, gaming, CAV infotainment.	High-resolution graphic encounters that are quite immersive.
Hubs (Ali et al., 2022)	Mozilla in 2018.	Design of a 3D environment, enter a VR meeting, secure cloud environment.	Editing photographs.	Highly realistic 2D image conversion for a customized avatar.
Unreal engine (Xu et al., 2022a)	Epic Games in 1998.	Photorealistic rendering, lifelike animation, simulation and effects.	Gaming, AI-driven CAVs using ADAS in BMW.	Simulation software that build virtual models for CAV to analyze the behavior of the vehicle.
Digital avatars (Xu et al., 2022a)	Meta in 2022.	Creation of authentic avatars.	Gaming, virtual car test drive.	Own VR experience.
Hololens2 (Xu et al., 2022a)	Microsoft in 2019.	Uses energy-efficient video camera in CAVs, hand controllers with mixed reality device.	Holographic pedestrian warning.	Use advanced sensors to display information of CAV on the dashboard, and simulate the virtual environment.
Xverse (Ali et al., 2022)	Ken Liao in 2021.	Blockchain-based virtual ecosystem.	NFTs trading.	Web3 Bitcoin wallet, connect to decentralized application.
Roblox (Xu et al., 2022a)	David Baszucki and Erik Cassel in 2006.	Useful for content creators.	Online gaming.	Virtual 3D gaming.
Unity (Xu et al., 2022a)	Unity technologies in 2005.	Creating real-time 2D/3D content.	Dress-X of H&M collaboration, Hyundai's meta-factory in Singapore.	Allows users to enter a 3D environment as an avatar by scanning the QR code on their web3 wallet.

3.4.1. VR headsets

VR headset is a head-mounted device that allows users to interact with simulated environments by providing a virtual reality experience. It enables users to feel fully immersed in a virtual world and provides a First-person view (FPV).

Oculus quest 2: The Oculus Quest 2 is a VR headset developed by Meta. It can be connected to a desktop computer using either USB or Wi-Fi in order to run compatible VR applications (Xu et al., 2022a).

HTC Vive XR Elite: The HTC Vive XR Elite is a lightweight and immersive virtual reality headset that gives a realistic experience to users. It provides a high-resolution display, hand-tracking capabilities, and room-scale movement tracking to allow users to move freely in virtual environments.

Sony playstation VR2: It aims to elevate user immersion through various features, including tactile feedback, adaptive triggers, and finger touch detection. These elements work together to create a more engaging and interactive gaming experience.

Samsung HMD odyssey: The HMD Odyssey is a Windows Mixed Reality headset that provides an immersive virtual experience. It does not require external headphones due to its integrated audio technology and enables users to explore the virtual world by connecting the device to a compatible PC.

Pimax 8K: Pimax 8K is a high-resolution head-mounted display that provides an 8k visual experience with a wide Field of view (FoV). It aims to replicate natural vision and elevate the sense of vision in virtual reality to the next level.

3.4.2. Augmented Reality (AR) glasses

Augmented reality glasses are AR devices that capture and process the real-world environment of a user, and augment it with virtual elements (Ro et al., 2018).

Microsoft Hololens 2: It is an augmented reality headset developed by Microsoft to offer an enhanced AR experience with improved immersive ness and ergonomic design.

Magic leap 2: These glasses are more comfortable to wear and offer a larger field of view (FoV). These glasses include a dimming feature to be used in brightly lit environments.

Nreal Air: Nreal Air is lightweight AR glass with low Blue Light emission, flicker-Free visuals, and an Eye Comfort display that amplifies your mobile, PC, and gaming experience.

Vuzix blade 2: The Vuzix Blade 2 AR glasses utilize advanced waveguide optics to provide a hands-free mobile computing and connectivity experience.

Snap spectacles 3: Snap Spectacles 3 utilizes the images captured by its dual cameras to create a geometric map of its surrounding environment for accurate spatial understanding and AR experiences.

Table 6
Metaverse service models.

Category	Service models	Functions and services offered	Popular vendors for MaaS	Metaverse applications scenario
CaaS	IaaS	Provides hardware platform e.g., virtual machines, storage, and networking capabilities, and databases.	Amazon Web Services (AWS), Microsoft Azure, Google Cloud Platform (GCP).	IaaS facilitate the resource requirements of the Metaverse in applications like rendering high-quality graphics, CAVs simulations, 3D modeling, virtual reality etc.
	PaaS	Provides platform to build, deploy, and manage Metaverse applications.	High Fidelity, Somnium Space.	PaaS enables integration of various Metaverse applications, such as virtual world creation, avatar customization, social interactions, and real-time communication.
	SaaS	SaaS provides ready-to-use software such as 3D modeling software, animation tools, texture editors, etc.	Unity Technologies, Epic Games.	SaaS simplify the adoption and usage of a Metaverse in applications like virtual marketplaces, vehicle Control, and monitoring, virtual learning and training, virtual tourism.
	DaaS	Create modify device patterns for efficient data collection and interaction protocol. For example, sensors, graphics processing units.	HP (DaaS), Dell (Dell Technologies DaaS).	AR/VR devices to optimize user engagement, sensor service models (e.g., Nexxiot's sensors) support continuous data collection in Digital Twin environment.
TaaS	AIaaS	Predict and update physical world status in intelligent and autonomous fashion.	Amazon Machine Learning, Microsoft Azure Cognitive Services, Google Cloud Machine Learning.	AI-based route optimization, decision-making, traffic flow, virtual training, and many more.
	BaaS	Empower orchestration and management of Metaverse network service.	Lovelace World-(2021), Propel MaaS.	Blockchain-based Metaverse solutions like digital asset ownership and trading, decentralized exchange, vehicle identity, and authentication, etc.
	ECaaS	Provide data processing capability that reduces latency and improves the quality of service for Metaverse users.	Amazon AWS Outposts, Microsoft Azure Stack Edge, Google Edge TPU.	Latency-sensitive applications like automotive vehicles, virtual gaming, AR/VR video shooting, smart hospital, etc.
	3DaaS	Enables real-time capturing and rendering of 3D representation.	Touchcast, MetaverseBooks, Somnium Space, Roblox Corporation.	3D object detection for autonomous driving, design of 3D digital avatars, 3D VR games, etc.

3.4.3. *Wearable devices*

Wearable devices in the Metaverse encompass technologies that users can physically wear to enhance immersion and interaction by engaging multiple senses. These devices are designed to provide users a more immersive and multisensory experience.

Smart Watches: Smart Watches are wearable device with a touch-screen interface, advanced features, and wireless connectivity capabilities. They collect sensor data, control devices such as wireless headsets, and serves as a portable interface for users to interact in the virtual space. It has the capability to display messages, alerts, and notifications from the Metaverse platform, providing convenient access to information during virtual experiences.

Motion trackers: It capture real-time movements and gestures of objects and users using sensors in the physical world, which is then analyzed and synchronized with the avatar movement in virtual environments. These devices enable avatars to replicate real-world movements and providing users with immersive and realistic experiences.

Haptic feedbacks suits: Haptic feedback suits, also known as a tactile suits, haptic vest, or VR suit, is a wearable device that capture motion and biometrics while providing touch and vibration feedback (Dionisio et al., 2013). They bridge the physical and virtual worlds by detecting body movements, gestures, and physiological states, and reconstructing these sensations in the virtual space. These suits enhance user interaction by delivering simulated tactile experiences, enriching immersion in virtual environments (Laycock and Day, 2003; Sun et al., 2022b).

3.5. *Metaverse projects*

For the adoption of the Metaverse to provide end-to-end security in the virtual world, Metaverse project initiatives have adopted blockchain-based decentralized environments for immersive gaming experiences. The list of Metaverse projects are as follows: Sandbox (SAND), Decentraland (MANA), Metaverse Seoul, Cryptovoxels, Axie Infinity (AXS), Altspace VR, Engine Coin (ENJ), Illuvium (ILV), High Street, Bloktopia (BLOK), Star Atlas, Metahero, Xirang, GALA gaming Metaverse, etc. These initiatives projects are cryptocurrency that uses Ethereum blockchain-enabled platforms to build applications and a Metaverse that delivers a variety of blockchain-based applications, and services ranging from real-world sensors to CAVs sensors which allow vehicles to communicate without sharing personal information. The features of all the Metaverse projects are summarized in Table 9.

3.6. *Framework components of a Metaverse in CAVs*

In this part, we discuss the key high-level functional components of connected autonomous vehicles as shown in the framework of a Metaverse based on the virtual test drive of CAVs. The utilization of a Metaverse-enabled platform, the Mahindra XUV400verse, which offers various features to enhance the customer experience is presented in Fig. 8.

On-board control unit: An On-Board Unit (OBU) is an electronic device installed in vehicles to record traffic data and facilitate communication using the Dedicated short-range communication (DSRC) standard protocol to communicate with other vehicles within its communication range (Sun et al., 2021b). The OBU enables the exchange of critical information such as speed limits, collision alerts, and blind spot warnings, promoting safer driving practices (Yang et al., 2014). Equipped with processors and sensors, the OBU displays data on the vehicle dashboard and employs AI/ML algorithms at the backend to analyze data, predict outcomes, and support intelligent decision-making.

Long range RADAR: These radars are capable of detecting and recognizing objects in the range of up to 250 m from the sensor with a narrow field of view (FoV). For virtual test driving in the Metaverse, these radars are utilized for a range of applications, such as traffic sign recognition, lane departure warning, cross-traffic alert, and parking assistance (Dickmann et al., 2016; Bilik et al., 2019).

Short-range RADAR: Short-range radars are typically deployed for surround view, blind spot detection, rear collision warning, and park

Table 7
Comparison of key characteristics of VR and AR devices.

Device Type	Category	Oculus quest 2	HTC Vive XR Elite	PlayStation VR2	Samsung HMD odyssey	Pimax 8K
						
VR headsets	Company name	Facebook(Meta)	HTC	Sony	Samsung	Pimax
	Initial cost	$399	$1099	$550	$499	$1,299
	Platform	Oculus, SteamVR	Viveport	PlayStation	Windows Mixed Reality	SteamVR
	Resolution	1832x1920	3840x1920	2000x2040	1440x1600	3160x2160
	Refresh rate	120Hz	90Hz	120Hz	90Hz	90Hz
	Display type	LCD	LCD	OLED	AMOLED	LCD
	Field of view	89°	110°	110°	110°	200°
	Weight	503g	625g	560g	645g	472g
	Features	Hand tracking, 6DOF tracking, touch controllers, integrated audio.	Room-scale tracking, 4 wide FoV tracking cameras, depth sensing precision, high-resolution RGB color camera.	Adaptive triggers, Haptic feedback, precision control, finger touch detection.	Integrated AKG headphones, built-in microphone.	Ultra-wide field of view, ergonomic design, 3D spatial audio, 6DoF positional tracking.
AR glasses		Microsoft Hololens2	Magic leap 2	Nreal Air	Vuzix blade 2	Snap spectacles3
						
	Company name	Microsoft	Magic Leap	Nreal	Vuzix	Snap
	Initial cost	$3500	$3299	$400	$1299	$380
	Platform	Windows Mixed Reality	Open XR	Android	Vuzix	Lens Studio
	Resolution	1440x936	1440x1760	1920x1080	480x480	1642x1642
	Refresh rate	60Hz	120Hz	60Hz	N/A	120Hz
	Display type	2xLBS binocular	2xLCoS binocular	2xMicro OLED binocular	Monocular display	Transparent display
	Field of view	52°diagonal	70°diagonal	46°diagonal	20°diagonal	105°diagonal
	Operating system	Windows Holographic	Magic Leap OS	Android Go 10	Vuzix, Android	Android
	Ports	USB Type-C	USB Type-C	USB Type-C	USB 2.0 Micro-B	USB Type-C
	Weight	556g	260g	79 g	93g	56.5g
	Features	AI coprocessor, built-in spatial sound, gesture commands, eye tracking.	Higher accuracy 6DoF optical tracking, Haptic feedback, Built-in stereo speakers, wider FoV.	Integrated stereo speakers, 3DoF Non-positional tracking.	3DoF head tracking, autofocus HD camera, noise-cancellation mics.	3D effects, AR filters, video recording.

Table 8
Comparison of key characteristics of wearable devices for Metaverse in CAVs.

Device type	Smart watches	Motion trackers	Haptic feedback suits
Features	ECG, GPS, water resistance, notifications.	Full-body motion capture, gesture recognition.	Haptic feedback, adjustable intensity, full-body coverage.
Battery life	24–72 h	Up to 12 h	4–8 h
Sensors	Heart rate monitor, accelerometer, GPS.	Accelerometer, gyroscope, magnetometer.	Multiple pressure and vibration sensors.
Connectivity	Bluetooth, Wi-Fi	Bluetooth	Bluetooth, wired
Weight	30–60 g	100–200 g (for body sensors)	1–2 kg
Brands	Apple (Apple Watch), Samsung (Galaxy Watch), Garmin (Forerunner), Fitbit (Versa)	Vicon (Vicon Motion), Xsens (MVN Awinda), Noitom (Perception Neuron)	bHaptics (TactSuit), Teslasuit, Hardlight VR, HaptX

assistance within a range of up to 50 m from the sensors. These sensors typically have a large field of view (FoV) and high resolution to effectively detect objects in close-proximity situations (Bilik et al., 2019; Dickmann et al., 2014).

Ultrasonic sensor: The ultrasonic sensor utilizes high-frequency ultrasonic impulses to measure the distance between the vehicle and its target by emitting pulses and detecting reflections from nearby objects. In the Metaverse, the ultrasonic sensors simulate obstacles detection, such as pedestrians, or hazards on the roads, to enhance virtual test drives. Features such as adaptive cruise control leverage these sensors to manage steering and harmonizes the speed of vehicles to optimize road safety and enhance the overall driving experience.

LIDAR: Light detection and ranging (LIDAR) sensors are used to detect objects and estimate the distance by emitting laser light. In the Metaverse, they enables advanced 3D reconstruction for situational awareness, supporting 360-degree visualization, object tracking, collision avoidance, and emergency braking for CAVs, which are essential

Table 9
List of Metaverse projects and their characteristics for gaming applications.

Metaverse projects	Developer	Blockchain platform	Characteristics	Compatible wallets	Integrated products
Sandbox (Huynh-The et al., 2023a)	Arthur Madrid, Sebastien Borget in 2012.	Non-fungible tokens (NFTs) on Ethereum.	Allow players to design, publish, and earn money from their own video games and experiences.	MetaMask, WalletConnect, Coinbase.	VoxEdit, Marketplace, Game Maker.
Decentraland (Huynh-The et al., 2023a)	Esteban Ordano, Ariel Meilich in 2017.	Ethereum smart contract using MANA cryptocurrency.	Virtual real estate platform where users can buy or sell avatar wearables, avatar emotes, lands.	MANA wallet, MetaMask, Coinbase wallet, WalletConnect.	Layered protocols: consensus, land content, real-time layers.
Metaverse Seoul (Xu et al., 2022a)	Seoul Metropolitan Government in 2022.	ZepetoX tokens based on the Solana blockchain.	Seoul becomes the first Metaverse smart city by providing a virtual access to local services.	CoinDesk, Bithumb, UPbit, Korbit.	VR, AR, and Hologram technologies.
Cryptovoxels (Duan et al., 2021)	Nolan Consulting in 2018.	Utilizing the ERC-721 token on the Ethereum blockchain.	Virtual world offers features like creating avatars, NFT-enabled shops, virtual land, and player interaction.	Metamask, Coinbase, Torus Wallet, Wallet Connect.	VR headsets such as HTC Vive, and Oculus Quest.
Axie Infinity (Huynh-The et al., 2023a)	Sky Mavis in 2018.	Ethereum-based Ronin sidechain.	It is a virtual creature that players can collect, breed, grow, and battle that can freely exchange lands.	Binance, Huobi Global, Coinbase, FTX.	Tokens used are Axie Infinity Shards (AXS), and Smooth Love Potions (SLP).
Altspace VR (Xu et al., 2022a)	Microsoft in 2015.	Ethereum blockchain.	Virtual social environments for players to communicate with friends and coworkers through 3D avatars.	Metamask.	Platform for connecting people.
Engine Coin (Kaur and Gupta, 2021; Shafiq, 2022)	Maxim Blagov, Witek Radomski in 2009.	ERC-20 standard on Ethereum.	A virtual good that may be owned virtually and traded between gamers using smart wallets.	Coinbase, Binance, Gemini	Coin exchange rate is $2.71, smart contracts, tokens.
Illuvium (Huynh-The et al., 2023a; Staff, 2022)	Kieran Warwick, Aaron Warwick in 2020.	ERC-20 Immutable X ethereum blockchain.	Desktop-based video game app. Classes: Empath, Fighter, Guardian, Rogue.	Coinbase, KuCoin, OKX.	Platform: decentralized finance (DeFi).
High Street (Huynh-The et al., 2023b)	Jenny Guo in 2021.	ERC-20 standard token based on the Ethereum.	Hexagon-shaped virtual plots for players to provide in-game infrastructures for clubs, stores.	Binance, Coinbase.	Unified MMORPG game, VR technology.
Bloktopia (Torky et al., 2023)	Ross Tavakoli, Paddy Carroll in 2021.	ERC-20 on Polygon based on Ethereum.	Reblok- virtual real estate, staking pools- pool resources.	OKEx, KuCoin, QuickSwap.	Deploy Reblok, VR property.
Star Atlas (Huynh-The et al., 2023b)	Sperasoft, Automata S.A. in 2021.	Solana blockchain.	Players in an online game create avatars, play, and win prizes in a 3D virtual world.	Phantom, sollet wallet.	Unreal Engine 5, real-time gameplay.
Metahero (Wong, 2022)	WOLF in 2018.	Binance Smart Chain.	Platform for 3D scanning and modeling.	KuCoin.	Hyper-realistic digital avatars.
Xirang (Xu et al., 2022a)	Baidu in 2023.	Ethereum blockchain.	AI capabilities like intelligent vision, voice, NLP, real-time audio/video.	It does not support cryptocurrencies.	Supports VR goggles, Unity, Unreal, Cocos.
GALA (Wang et al., 2022)	Eric Schiermeyer in 2019.	ERC-20, BEP-20 utility token.	Offers play-to-earn (P2E) games.	MetaMask, Coinbase.	Nodes: founder, game, players.

for ensuring safety during virtual test drives (Zhou et al., 2022; Li and Ibanez-Guzman, 2020).

GPS receivers: The Global Positioning System (GPS) in the Metaverse enables users to access accurate location-based services which range from centimeter to meter-level accuracy. GPS plays a vital role in the navigation and localization of vehicles in the Metaverse with predefined road maps. Fig. 8 illustrates a Metaverse-enabled virtual test-driving scenario with XUV400 where GPS is depicted on the dashboard, providing a live navigation map for user assistance (Sun et al., 2021b).

Camera: The cameras are mounted on the front, rear, right and left sides of the CAV to provide a 360° view. These cameras employ super-wide lenses with both wide and narrow fields of view to capture a panoramic view. These cameras enable real-time obstacle detection, lane departure checking, parking assistance, and tracking of relevant information. Thus, the CAV within the Metaverse can effectively recognize objects, control vehicle motion, and create 3D representations of virtual scenes.

Infrared: Infrared sensors empower CAV to navigate and perceive the environment in night or low-light conditions by capturing the infrared radiations emitted by objects. This improves the vehicle's ability to detect obstacles and ensures a safe driving experience (Rosique et al., 2019). By integrating infrared sensors, Metaverse-enabled virtual test driving enables users and testers to assess the effectiveness of the CAV's infrared-based perception system. This will enable us to validate the accuracy of these systems in virtual simulation under different lightening conditions.

3.7. Applications of a Metaverse in CAVs

We present a representative list of applications of the Metaverse in CAVs in Table 10. Here, we provide a brief description of these applications:

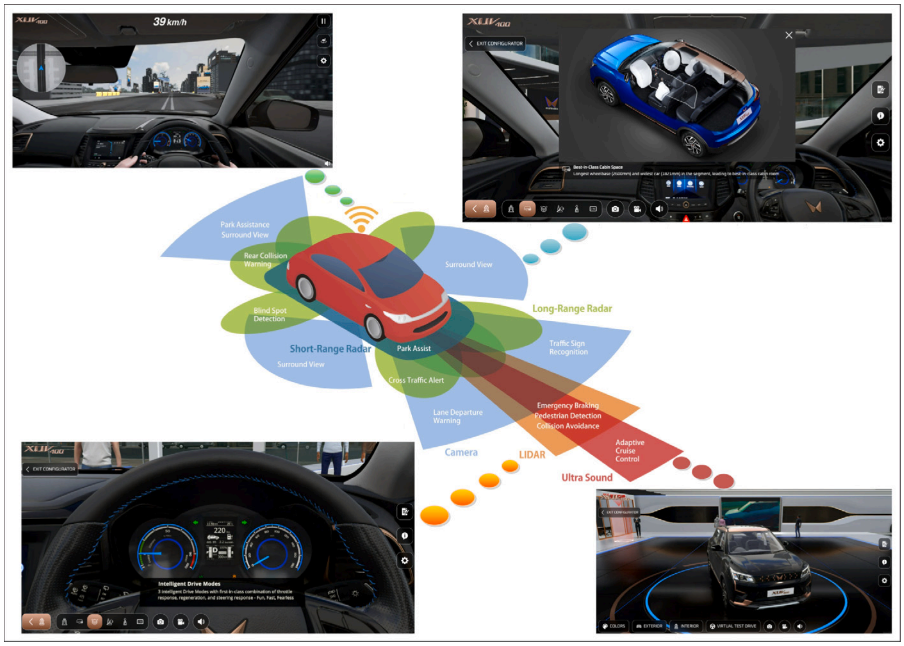

Fig. 8. Components of a Metaverse based on the virtual test drive of CAV.

3.7.1. *Enhanced situational awareness and immersive navigation*

This application leverages the Metaverse to enhance situational awareness of CAVs by sharing real-time information such as traffic conditions, road information, and weather updates between V2V and between V2I communication. The immersive navigation provides the drivers with real-time updates and navigation routes to make informed decisions and provide a personalized navigation experience (Tian et al., 2018; Dwivedi et al., 2022).

3.7.2. *Personalized ADAS with XR for dynamic lane change warning*

This application integrates Extended Reality (XR) technologies to provide real-time visual feedback and alerts for CAV users. It incorporates a V2V-based lane change warning system that evaluates the safe distance between the CAV and its surrounding vehicles in both the original and the desired lane (Tian et al., 2018). By enabling coordinated and safe lane changes, it improves traffic flow and minimizes the negative effects of uncoordinated maneuvers (Schubert et al., 2010).

3.7.3. *Real-time traffic updates and monitoring*

CAVs receive real-time updates on traffic conditions such as traffic flow, congestion, weather updates, road hazards, accidents, etc (Zhou et al., 2022). These updates enable CAVs to make well-informed decisions and optimize their routes, resulting in safer and more efficient journeys.

3.7.4. *Advancing CAV testing through Metaverse-enabled virtual test drives*

Metaverse-enabled virtual test drives offer CAVs the opportunity for virtual testing that closely emulates real-world conditions. This simulated environment allows for controlled evaluations of CAV performance, features, and behavior across various scenarios and conditions (Dwivedi et al., 2022). It minimizes reliance on physical prototypes, offering a cost-effective solution for testing CAVs and their functionalities.

3.7.5. *Virtual work zone management in freeways using SLAM*

SLAM techniques are integrated into the Metaverse to create virtual maps of work zone areas, including lane closures, diversions, speed limitations, and temporary changes in road conditions. These virtual maps are integrated into the CAV navigation system to provide real-time awareness of work zones for CAV users (Tian et al., 2018).

3.7.6. *AI-based urban parking allocation and optimization*

Artificial intelligence algorithms are utilized to efficiently allocate and optimize parking spots in urban areas. This leads to improved traffic flow, reduced fuel consumption, and enhanced user convenience by minimizing the search time (Beheshti and Sukthankar, 2015).

3.7.7. *Real-time charging solutions for EVs on highways*

Real-time charging solutions for EVs are deployed to meet the charging requirements of electric vehicles during their journeys. The Metaverse incorporates charging infrastructure to facilitate EV battery recharging and offers real-time information on charging stations, including their availability, to the users.

3.7.8. *Advanced lane design with inductive power transfer for EVs*

The Metaverse is employed to design dedicated lanes equipped with an inductive power transfer system. These specialized lanes are connected to a power source that converts electricity into a power beam, which is transmitted to the electric vehicle. The EV is equipped with a power beam receiver that converts the power beam back into electrical power, charging the vehicle's battery (Sumi et al., 2018).

3.7.9. *Digital avatars for energy trading and charging station locator*

Digital avatars serve as user representations within the Metaverse environment, enabling decentralized energy trading among EV users. They provide a platform for users to engage in peer-to-peer energy trade, alleviating concerns about running out of charge. Additionally, digital avatars assist in discovering nearby charging locations, enhancing the convenience of charging electric vehicles (Alvaro-Hermana et al., 2016).

3.7.10. *Electronic toll collection and speed differential warning*

Electronic toll collection in the Metaverse employs automated systems to collect fees with reduced or almost no disruption to traffic flow, thereby improving overall road efficiency (Papadimitratos et al., 2009). Speed differential warning delivers real-time alerts to CAV users about speed differences with surrounding vehicles, enabling informed decision-making for safer driving practices (Ji et al., 2020).

Table 10
Applications of the Metaverse in CAVs.

List of applications	Description			Distinctive strengths
	Latency requirement	Communication type	Message type	
Enhanced situational awareness and immersive navigation	50 ms	Ad hoc, V2V, V2I.	Real-time data sharing.	Satellite navigation, improved safety, and enhanced navigation experience.
Personalized ADAS with XR for dynamic lane change warning	100 ms	Ad hoc, V2V.	Event-triggered, periodic broadcast.	Enhanced driving experience, reliable decision-making.
Real-Time traffic updates and monitoring	200 ms	Infrastructure, V2I, cellular.	Periodic broadcast.	Efficient traffic flow, reduced congestion, active emergency braking with obstacle detection, and emergency vehicle priority.
Advancing CAV testing through Metaverse-enabled virtual test drives	500 ms	V2I, V2V, ad hoc network.	Unicast, broadcast.	Driving efficiency, realistic CAV performance evaluation, time and cost efficiency.
Virtual work zone management in freeways using SLAM	500 ms	Infrastructure, V2I, V2V, ad hoc, cellular.	Unicast, broadcast, event-triggered.	Enhanced safety and mobility, traffic flow optimization.
AI-based urban parking allocation and optimization	200 ms	Infrastructure, V2I, cellular.	Unicast.	Reduced search time, traffic congestion, efficient parking allocation.
Real-time charging solutions for EVs on Highways	500 ms	Infrastructure, V2I, cellular.	Periodic broadcast.	Rapid charging, expansive charging network.
Advanced lane design with inductive power transfer for EVs	100ms	Infrastructure, V2I.	Event-triggered.	Efficient and seamless EV charging, enhanced convenience, uninterrupted vehicle mobility.
Digital avatars for energy trading and charging station locator	100 ms	Adhoc, V2V, V2I.	Event-triggered, periodic permanent broadcast, unicast	Energy management, seamless charging station navigation.
Electronic toll collection and speed differential warning	200 ms	Infrastructure, V2I, ad hoc, cellular.	Unicast, periodic broadcast.	Time-saving, optimized predictive motion, enhanced road safety.
Intelligent virtual in-vehicle design and modeling	200 ms	Ad hoc, V2V, V2I, cellular.	Unicast, broadcast, event-triggered.	Personalized in-vehicle infotainment, cost-effective prototyping and customization, next-level connectivity experience, intelligent drive modes(Gamified driving experience).
Metaverse-enhanced mapping and localization with image-based 3D reconstruction in CAVs	400 ms	V2I, V2V, ad hoc network, cellular, broadcast network.	Periodic broadcast.	Drift-free localization.
Night fog detection using Metaverse technology	100 ms	V2I, V2V.	Event-triggered, time-limited broadcast.	Reducing accidents, enhanced user trust, improved safety in low-visibility.
Controlled junctions and traffic light simulation	100 ms	V2I, infrastructure, ad hoc, cellular.	Event-triggered, time-limited broadcast.	Improved traffic management.
Robust visual mapping and localization for CAVs	200 ms	Ad hoc, V2V, V2I, cellular.	Periodic permanent broadcast, event-triggered.	Improved navigation.
Virtual reality-driven vehicle crashing and safety testing	100 ms	Ad hoc, V2V, V2I.	Unicast.	Enhanced situational assessment, adaptive response to unforeseen situations, identification and mitigation of malicious traffic behavior.

3.7.11. Intelligent virtual in vehicle design and modeling

It enables the construction of virtual vehicles in the twin space to achieve the virtual testing and analysis of various aspects of vehicle design, performance evaluation, monitoring driving states, diagnosing faults, troubleshooting, and providing early warnings (Zhang et al., 2022c). Virtual prototypes can assist in making informed decisions and expedite innovation in the design of vehicles.

3.7.12. Metaverse-enhanced mapping and localization with image-based 3D reconstruction in CAVs

This application enables CAVs to generate realistic 3D maps of the surrounding environment by utilizing a LiDAR-based monocular 3D shaping technique (Bai et al., 2022; Zhou et al., 2022). This technique reconstructs the shape and structure of objects, facilitating precise localization even in GPS-challenged areas.

3.7.13. Night fog detection using Metaverse technology

It aims to leverage advanced systems and deep learning-based techniques, including the transfer learning techniques (Al-Haija et al., 2022) to detect the presence of fog during night-time. These techniques will assist CAVs in navigation through foggy conditions, ultimately enhancing driving safety and overall vehicle performance (Gallen et al., 2011; Zhang et al., 2022b).

3.7.14. Controlled junctions and traffic light simulation

The Metaverse utilizes machine learning techniques such as random forest classification and support vector machines (Saleem et al., 2022) to create virtual representations and simulations of traffic light systems. These simulations are based on real-world traffic patterns and signal timings, aiming to enhance traffic flow, reduce congestion, and minimize fuel consumption and energy usage.

3.7.15. Robust visual mapping and localization in CAVs

Visual mapping and localization leverage visual perception and mapping techniques to generate detailed representations of roads and the surrounding environment. This enables CAVs to achieve precise self-localization on the road, facilitates a comprehensive understanding of their surroundings, and plans maneuvers (Wang et al., 2023b).

3.7.16. Virtual reality-driven vehicle crashing and safety testing

In this application, advanced modeling and simulation tools are used to evaluate the crashworthiness and safety aspects of CAVs, including airbags, seat belts, anti-lock braking systems, and crumple zones. By utilizing these tools, the automotive industry can reduce development time and costs, mitigate real-world crash testing risk, and enhance vehicle safety (Blissing, 2016; Holmqvist, 2016).

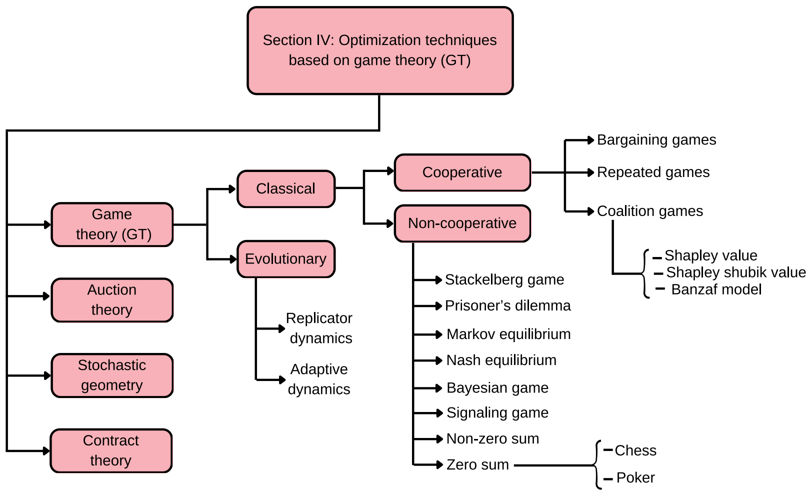

Fig. 9. Taxonomy of optimization techniques in CAVs.

4. Problem statement and optimization techniques based on game theory for CAVs

In Connected and Autonomous Vehicles (CAVs), optimization involves addressing common real-world challenges such as lane-change decision-making, traffic flow optimization, cross-intersection coordination, and resource management. Game theory (GT) offers a structured approach to solving these challenges by modeling interactions between multiple agents, including vehicles, infrastructure, and pedestrians. This section discusses the common real-world CAV challenges and then, as a solution, presents existing game theory-based optimization techniques, including cooperative, non-cooperative, and evolutionary game theory tactics. Further, in Table 11, we have presented the comparative analysis of different game theory optimization techniques and the taxonomy of Section 4 is presented in Fig. 9.

4.1. Cooperative classical game theory

CAVs often face challenges in managing cross-intersections, especially at unsignalized intersections where vehicles from different directions converge without traffic signals. Effective intersection management is essential to prevent collisions, reduce congestion, and optimize travel efficiency. By leveraging cooperative game theory, CAVs can work together to ensure that all vehicles navigate intersections smoothly while optimizing their speed, position, and acceleration.

– Bargaining games

It is a game theory in which two or more players negotiate to determine how to share a jointly produced resource. For CAVs, this shared resource refers to the priority to access intersection. By negotiating a fair distribution of intersection priorities, CAVs can achieve a Nash bargaining solution that maximizes individual payoff while ensuring safe and efficient navigation (Heshami and Kattan, 2021).

A bargaining game is represented as a pair of (F, d), defined as follows:
(a) Set $F \subseteq R^2$ specifies the agreed-upon elements and all feasible collaborative actions, which leads to a feasibility set that includes all conceivable payoffs.
(b) The disagreement point or default point $d = (d_1, d_2)$ represents the relative payoffs for player one and player two if negotiation fails. This point indicates the default equilibrium each player can expect without cooperation (Rios-Torres and Malikopoulos, 2016).

Problem in CAVs: Managing coordinated intersection crossing for CAVs, optimizing the position, acceleration, and velocity to improve traveling efficiency.

Solution: The cross-intersection management problem among CAVs at unsignalized intersections can be effectively addressed through a bargaining approach illustrated in Fig. 10. We consider three vehicles, v_1, v_2, v_3, traveling in one-way streams towards a common intersection. The dot below the vehicle symbolizes its centroid, and the red square represents the intersection zone (default point), where all traffic meets at the common point. As a result, we compute the distance from the vehicle's centroid to the default position to evaluate the likelihood of traffic congestion or collision. The bargaining game theory can be utilized to compute vehicles' ideal position, acceleration, and velocity to address the cross-intersection management problem in CAVs. Instead of employing the traditional first-come, first-served algorithm, a three-layered game-based hierarchical control strategy is used (Mariani et al., 2021; Wang et al., 2021b).

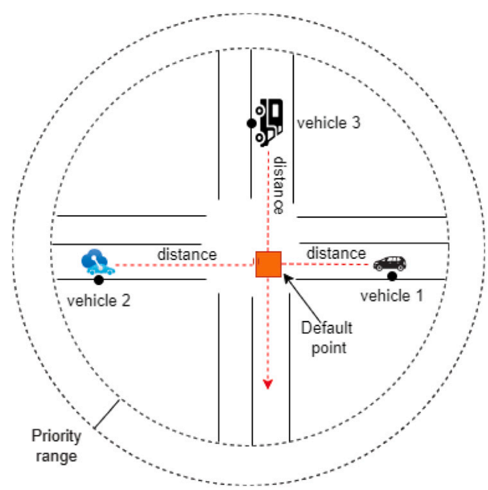

Fig. 10. Crossing intersection problem among CAVs using bargaining game.

- **Priority Negotiation Layer (PNL):** This initial layer is intended to compute the Pareto-optimal solution for crossing order within a given priority zone range. It consists primarily of four phases, i.e. time estimation (individual vehicles negotiate and compute the intersection crossing order), conflict judgment (vehicles analyze the time-to-collision), acceleration planning (vehicles arrange their velocities for higher priority), and priority judgment (the priority is assigned as the vehicle enters the priority zone).
- **Strategy Bargaining Layer (SBL):** This layer facilitates cooperative strategies for acceleration adjustments to reduce trip time.

Table 11
Comparison of different game theory optimization techniques for CAVs.

Author name, Year	Problem formulation	Scheme used	Workflow/Strategy	Parameters Improved	Results/Remarks
Zhang et al. (2017)	Cooperation in heterogeneous network, traffic offloading, mobile crowd-sourcing, spectrum trading.	Contract theory incentive mechanisms.	Cooperation model for offloading data, uploading location, reward design in bi-Lateral or multi-lateral contracting.	Utility of the principal, and cost coefficient.	Analyze of the service provider utility with five reward schemes i.e., 1D reward, fixed salary, multi-dimensional.
Kazmi et al. (2021)	Utilizing resources to encourage privately owned nearby vehicles to partake in resource sharing.	Contract theory-based incentive scheme.	Objective: Maximize CAVs' social welfare makes it possible for the RSUs to offer suitable rewards based on their participation in resource sharing.	Higher resource utilization, lower energy consumption per resource utilization.	29% higher and 17% lower.
Sial et al. (2019)	Interference, spectral efficiency, resource allocation in V2X communication.	Doubly stochastic based cox process mechanisms.	C-V2X mode selection scheme for CAVs is utilized using a bias factor to control interference and traffic congestion.	Vehicle density, transmission power, interference levels, communication range.	Analyze the SINR threshold, vehicle intensity, road intensity, BS intensity on the success probability of the C-V2X.
Iliopoulou et al. (2022a)	Intersection management during traffic congestion, task allocation, autonomous path optimization.	First-price combinatorial auction, second-price the sealed-bid auction, consensus-based auction algorithm.	Winner determination algorithm (WDP) bidding rules can be used to permit the driver to cross the intersection depending on their value of time.	Average bid delay, average weighted waiting time (avgWWT), average travel time.	Market-based auction intersection control policy may be simulated using AORTA and SUMO microscopic simulators for CAVs.
Wang et al. (2021b)	Crossing intersection management.	priority negotiation layer (PNL), strategy bargaining layer (SBL) and strategy optimization layer (SOL).	PNL is designed for Pareto-optimal set, SBL for improving interaction between CAVs, SQL for priority control.	Position, velocity and acceleration of vehicles with respect to time.	Travel time of bargaining zone is minimum compared to negotiated priority and fixed priority.
Lopez et al. (2022)	Lane-changing decision-making scenarios for autonomous vehicles.	Repeated game theory approach.	Nash Equilibrium is used to repeatedly determine the payoffs of the game.	Payoffs matrices.	It provides lane-changing decision-making with a prediction accuracy of 86%, thus reducing the impact of disturbances and crashes caused by inappropriate lane changes.
Wei et al. (2018)	Signal-free intersection management.	Coalition game theory approach, strategic game approach.	Platoon formation game is designed to optimize traffic flow and throughput to avoid road accidents and congestion.	Intersection throughput, reduction in the rate of traffic accidents.	The framework achieves a 99% decrease in road accidents and improves intersection throughput.

- **Strategy Optimization Layer (SOL):** The final layer ensures that priority negotiation is adhered to, further optimizing traffic flow and enhancing intersection efficiency.

– Repeated games

Repeated game theory is a branch of game theory that studies interactions between players that occur over multiple rounds or periods (Mertens, 1990). Unlike one-shot games, where players make decisions without considering the future consequences, repeated games involve a sequence of interactions, allowing players to observe and respond to each other's behavior over time (Kang and Rakha, 2020). In CAVs, repeated game theory enables vehicles to learn and adapt strategies for optimizing merging protocols, lane-changing decisions, minimizing the risk of accidents, and negotiating right-of-way at intersections. Thus, employing repeated game theory in CAVs can bring several technological benefits, such as improving traffic flow, enhancing safety, reducing congestion, and optimizing energy consumption (Ji and Levinson, 2020).

Problem in CAVs: Lane-change decision making

In order to pass slower traffic or get on or off of highway ramps, vehicles frequently switch lanes. In contrast to human drivers, autonomous vehicles must constantly assess their environment and systematically make real-time decisions. Otherwise, it may increase the risk of collision and thus lead to network congestion. Therefore, a lane-changing model that replicates human drivers' decision-making is

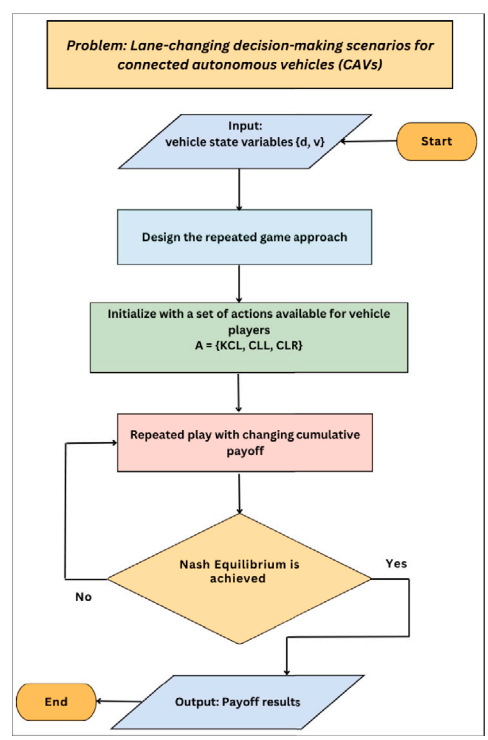

Fig. 11. Flowchart of CAVs lane-changing decision using repeated game theory.

essential for improving the driving performance of CAVs (Dev et al., 2022).

Solution: Formulating a repeated game approach can facilitate lane-change decision-making in CAVs. By frequently making lane-change decisions within the repeated game framework, vehicles can respond adaptively to shifting environmental conditions. This solution enables vehicles to decide when it is safe to change lanes based on the behavior of surrounding vehicles (Kang and Rakha, 2018; Lopez et al., 2022). Fig. 11 illustrates the flowchart for lane-change decision-making using repeated game theory, and the steps for the decision-making process are as follows.

Step 1: Input: Initially, define the lane-changing state variables such as longitudinal distances d and velocities (textitv) with respect to surrounding vehicles.

Step 2: Specify the action structure: Determine the set of possible actions for each vehicle (player). A vehicle player can choose to remain in its current lane (*KCL*), change lanes to the left (*CLL*), or change lanes to the right (*CLR*), with action set $AE = \ KCL, CLL, CLR\$. Each participating vehicle receives a reward based on the actions executed, which helps maintain a safe speed and distance from other vehicles.

Step 3: Iterate and refine with changing payoffs: CAVs update their decision at each epoch by re-entering the game with the newly generated data. Therefore, repeated iterations can be used to optimize the lane-changing decision-making process.

Step 4: Achieving Nash equilibrium for stable state: Finally, Nash equilibrium can be employed to model and analyze repeated games, and it represents a stable state where no player has an incentive to deviate from their chosen strategy unilaterally.

Step 5: Evaluate payoff results: Analyze the set of possible outcomes or payoffs of the repeated games. Interpret the results to evaluate the implications for outcomes, efficiency, or cooperation achieved through lane-changing decisions.

– Coalition games

Coalition games are the main branch of cooperative games that involve the formation of cooperative groups, known as coalitions, which strengthen the players' positions in a game (Saad et al., 2009; Wei et al., 2018). Coalitions serves as the primary decision-making unit that promotes cooperative behavior and enables the design of fair, robust, and efficient cooperation strategies.

Coalition formation plays a crucial role in addressing the key challenges of CAVs. For instance, in multi-lane merging zones (Hang et al., 2021b), coalition games facilitate cooperative decision-making that optimizes merging maneuvers, enhancing driving performance while addressing safety and efficiency. Additionally, coalition games can also be applied to dynamically control traffic lights at intersections, leading to improved traffic flow (Calvo and Mathar, 2018).

Problems in CAVs: Coordination and Traffic Flow Optimization at Intersections **Solution:** The coalition-based game-theoretic framework can help maximize intersection throughput while minimizing accidents and congestion. By forming cooperative groups or "platoons", CAVs work together to streamline traffic flow and enhance safety. Vehicles in these platoons coordinate crossing sequences, manage their speeds, and adapt to each other's actions to achieve efficient and safe movement through intersections (Wei et al., 2018).

This framework also incorporates two-player strategic games to address potential collision risks at intersections. In such scenarios, each CAV acts as an independent decision-maker, observing the trajectories of nearby vehicles' trajectories in real-time. This allows each vehicle to adjust its speed and position to avoid predicted conflicts based on sensory data and predictive algorithms. Several resource allocation measures have been developed in coalition games such as the Shapley value, Shapley-Shubik value, and Banzhaf model that provide diverse strategies for fair and efficient coordination.

Shapley value: The Shapley value offers an efficient solution for reallocating rewards for coalition games, ensuring fairness in the division of the total payoff among the players (Han et al., 2022b). It helps in the tasks of maximizing and distributing additional gain within coalitions in various applications of CAVs such as optimization of EV charging and discharging schedules, decision-making of multi-lane changing, and enhancing the traffic flow (Zima-Bockarjova et al., 2020).

Shapley-Shubik value: The Shapley-Shubik value is a power index used in coalition games to evaluate the relative power of individual players within a coalition. By calculating this value for each player in a coalition game, it is possible to understand the relative importance of each player and make informed decisions regarding resource allocation, cost sharing, or decision-making processes within the coalition (Osicka et al., 2020). For CAVs, the Shapley-Shubik index can be utilized for optimal resource allocation, traffic optimization, and cost-sharing among CAVs.

Banzhaf model: The Banzhaf model is another power index in coalition games to measure the power of individual players within a coalition. It focuses on the pivotal coalitions in which a player's inclusion or exclusion determines the outcome. This model can be applied in CAV for intrusion detection (Anwar et al., 2022).

4.2. Non-cooperative classical game theory

Non-cooperative game theory approaches offer an intriguing decision-making tool for individual vehicles to make autonomous decisions while considering the actions of other agents. This approach enhances vehicle safety, travel efficiency, and security in limited collaboration environments. In the following, we describe the approaches under non-cooperative game theory, which offers a unique framework suited to different aspects of CAV operations.

- **Stackelberg game** – The Stackelberg game follows a strategic approach with two players, i.e., a leader and a follower. The leader initiates a strategy, while the follower moves sequentially that aims to reach a subgame perfect Nash equilibrium (SPNE) (Aujla et al., 2017). This model is well-suited to scenarios in CAVs where a vehicle must lead others in maneuvers such as merging, passing, or exiting at unsignalized intersections. By integrating individual driving behaviors, the Stackelberg game enhances driving comfort, safety, and efficiency in urban settings (Hang et al., 2021a). A Bayesian extension of the Stackelberg game also helps mitigate security threats by optimizing defense strategies in uncertain environments (Halabi et al., 2021).
- **Prisoner's dilemma** – The prisoner's dilemma is a common game theory that is based on the concept of two convicts who tried a crime and were apprehended, but the police did not have enough evidence to prosecute them. As a result, for both prisoners to confess their crimes, the authorities kept them in solitary confinement with no interaction between them. This scenario illustrates that two convicts face incentives to act in their self-interest rather than cooperatively, potentially leading to sub-optimal outcomes for both. In CAVs, this model addresses mobility challenges by computing an intuitive payoff function based on the prisoner's dilemma binary decision algorithm that balances self-interest and improves social impacts such as cooperative lane merging or traffic flow optimization in CAVs (Chremos et al., 2020).
- **Markov equilibrium** – It is a stochastic approach to Markov perfect equilibrium in which individual players must satisfy the Markov property of memorylessness constraints, encode payoff-elevation data, and do not follow negotiation or cooperative policies. In Shou et al. (2022), the authors applied this model in CAVs for dynamic traffic assignment, and the authors designed a

Markov decision game strategy to address the lane change warning problem in Coskun et al. (2019), and the simulation results compute the consistent safe gap in multi-lane traffic scenarios.

- **Nash equilibrium** – It is a game theory approach in which a player adopts strategies where no one has an incentive to deviate unilaterally. This approach can be utilized in the lane change decision-making of CAVs, where each vehicle optimizes its behavior based on the anticipated actions of others. In Zheng et al. (2020), the authors designed a Nash equilibrium game theory approach to compute an optimal decision in the discretionary lane change for V2V communication, and the experimental results reduce total travel delay, improves safety, and stabilize traffic oscillations compared to existing schemes.
- **Bayesian game** - Bayesian game is a strategic decision-making approach that utilizes Bayesian probability to capture uncertainty and model games with incomplete information (He et al., 2010). It is defined by the tuple ($\mathcal{P}$, $\mathcal{A}$, $\mathcal{T}$, $\mathcal{P}_f$, p) where $\mathcal{P}$ represents the set of players in the game, $\mathcal{A}$ is the set of actions or pure strategies available for each player, $\mathcal{T}$ represents the type set of players which captures the private information, $\mathcal{P}_f$ denotes the payoff for each player and p is the probability distribution over all possible types denoted as $p(t) = p(t_1, \ldots, t_n)$ where t_i is the type of player i. The Bayesian game formulation has been applied in Deng et al. (2022) for lane-change decision-making in CAV in dense highway traffic.
- **Signaling game** - The signaling game is a dynamic two-player Bayesian game (Zhang et al., 2018), involving a sender and receiver exchange signals to communicate information (Liang and Xiao, 2012). The signaling approach has been employed in Mabrouk et al. (2019) to design an Intrusion Detection Game (IDG), modeling the interaction between CAVs and an IDS agent to protect against attack from malicious vehicles. The cost of sending a signal is higher for false information, ensuring node truthfulness. False messages are refused by neighbors leading to signal cost loss and expulsion from the network (Do et al., 2017).
- **Non-zero sum** - Non-zero sum game is played where all players are regarded as either a maximizer or a minimizer and there is no constraint on the total utility (Abdalzaher et al., 2016). Thus, everyone involved can win or lose together. This type of game can represent lane-changing decisions in a CAV (Talebpour et al., 2015) where each CAV strives to maximize its own utility, such as reducing travel time, and maximizing fuel efficiency while taking other CAVS' actions into account. Non-zero sum game can also be applied to model attacks on CAV to analyze the system's response and payoffs for the players (Jahan et al., 2020).
- **Zero sum** - A zero-sum game is a type of non-cooperative game played between two players where the total utility or payoff remains constant (Abdalzaher et al., 2016). It describes a relationship where the objective of one player is to maximize the gain, while the objective of the other player is to minimize its losses. This can be expressed as $\sum u_i(s) + \sum u_j(s) = 0$ for all strategy profiles (s), that players can choose from in a game. Games like chess and poker are examples of zero-sum games since the other player's losses offset one player's winning. This model can be utilized in intrusion detection and response, where one vehicle's security gain represents an attacker's loss (Do et al., 2017; Ilavendhan and Saruladha, 2018).

4.3. Evolutionary game theory

Evolutionary game theory is inspired by R. A. Fisher's concept of a genetic algorithm for natural selection. This approach enables systems to reach a stable state like Nash equilibrium, where no player can increase their payoff by unilaterally changing their strategy. Evolutionary game theory can be applied in CAVs, where vehicles must adapt their behaviors dynamically to optimize driving safety, comfort, and travel efficiency. The two widely used evolutionary game theory techniques are listed below.

- **Replicator Dynamics** – The replicator dynamics focuses on the principle of adaptive behavior of organisms and is based on their fitness or success in interactions, which determines their likelihood to replicate certain strategies (Khoobkar et al., 2022). In Qiu et al. (2022), the authors designed a data-sharing approach for CAVs to take data-exchanging decisions to minimize vehicle information leakage while ensuring perception correctness. In addition, the authors created a dynamic orchestration framework to outsource traffic optimization based on the collaboration of route planning and traffic signal timing utilizing replicator dynamics to achieve Nash equilibrium, thus improving overall traffic flow and reducing congestion (Chen et al., 2020).
- **Adaptive Dynamics** – In evolutionary biology, adaptive dynamics is used to examine the evolution of traits in populations. It combines population genetics and ecology concepts to model adaptive behavior in response to environmental changes (McGill and Brown, 2007). Adaptive dynamics GT in CAV systems can help optimize decision-making processes, improve traffic efficiency, improve vehicle safety, reduce traffic flow congestion, and improve overall system performance. This strategy can be utilized in cooperative maneuvers, traffic flow optimization, route planning, and navigation, resource allocation for shared facilities such as charging stations or parking spots, and cybersecurity (Avila and Mullon, 2023).

4.4. Auction game theory

A game-theoretic auction model involves the design and study of auction mechanisms to achieve the desired objectives of efficient resource distribution, revenue maximization, and fairness among participants. The auction-based models can be applied in CAVs to allocate resources such as frequency bands, charging stations, parking spots, intersection control, transportation infrastructure, etc. (Iliopoulou et al., 2022b). Thus, by implementing auction-based game theory, CAV systems can optimize resource distribution, improve overall system performance, and ensure equitable user access.

Recently, intersection control of connected vehicles has become a promising research direction, particularly in high-traffic or unsignalized junctions where real-time traffic data and coordinated decision-making can enhance traffic flow and minimize delays. Auction-based schemes allow vehicles approaching a junction to bid for passage based on priority needs. Various approaches such as first-price, second-price, and sealed-bid auctions have been studied for autonomous vehicle junction control to facilitate fair and timely intersection (Vasirani and Ossowski, 2012). These methods treat intersections as a spatially complex group of scarce resources where access rights are distributed temporally using market-based instruments. The auction-based intersection management strategy is discussed in Takalloo et al. (2021), which optimizes intersection control while enhancing adaptability in dynamically changing traffic conditions, thus providing an effective solution for complex traffic scenarios.

4.5. Stochastic geometry

Stochastic geometry is a branch of probability theory (Hug and Reitzner, 2016) that focuses on the study of random spatial patterns and structures in Euclidean space. This field has emerged as a powerful optimization tool for modeling and analysis of wireless networks (Farooq et al., 2015b,a). The primary aim of the stochastic geometry in network optimization is to anticipate and regulate various performance metrics, including the analysis of mutual interference between transceivers, signal-to-interference-plus-noise ratio (SINR), and outage probability (ElSawy et al., 2016). Stochastic geometry employs point process theory (Hmamouche et al., 2021), an essential component of stochastic modeling to effectively model and analyze optimization

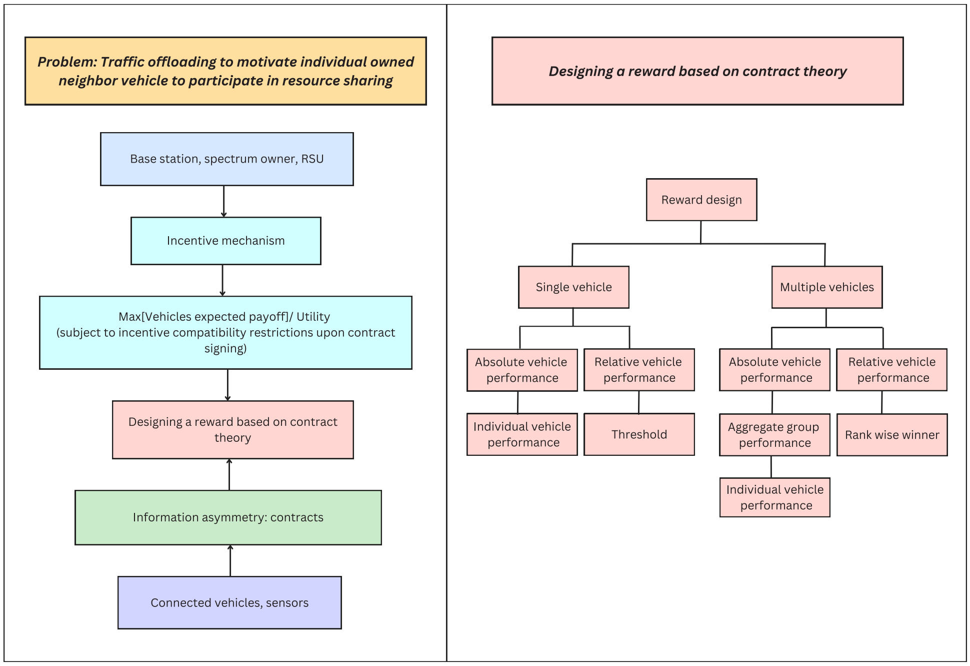

Fig. 12. Flowchart of traffic offloading/maximum resource utilization issue using contract theory.

problems that incorporate uncertainty in wireless networks. By leveraging its capabilities in CAVs, it can address the challenges posed by autonomous vehicles, such as optimizing connectivity, minimizing the interference due to signal collisions, and resource allocation for maximizing channel utilization, ultimately leading to improved network performance (Chetlur Ravi, 2020; Choi and Baccelli, 2022; Chetlur and Dhillon, 2020).

4.6. Contract theory

Contract theory is a game theoretic framework that provides optimal decision-making in scenarios involving negotiation, conflict, and cooperation between individuals or groups of individuals. According to contract theory, legal contracts are made in situations of information asymmetry, which prevents conflicts by ensuring all necessary information is accessible to both parties.

Problem in CAVs: Resource Utilization and Traffic Offloading

With the widespread use of mobile devices and location-based services, CAV networks face challenges such as network congestion, resource-demanding services, traffic offloading, and spectrum trading (Zhang et al., 2017). Despite advanced technologies like V2V communication and cognitive radio, inefficient resource utilization remains a primary concern in wireless networks.

Solution: The contract theory-based incentive mechanisms offer an effective solution for optimal resource utilization to encourage privately owned vehicles to join in resource sharing (Zeng et al., 2022; Kazmi et al., 2021; Liebenwein, 2018). Fig. 12 illustrates the process, which includes the following steps:

Step 1: The first party, acting as "employer", is the authorized spectrum owner, base station, Roadside Units (RSUs), and service provider that initiates the contract to facilitate services to its users.

Step 2–3: In the objective function, the contract theory is used to maximize social welfare or the employer's expected payoff/utility of the connected vehicles subject to incentive compatibility restrictions upon contract signing.

Step 4: Contracts offer rewards or incentives based on each vehicle's contribution. Here, the vehicle's performance is influenced by both absolute and relative performance. These incentives may be structured as efficiency wages and stock options tied to their absolute performance as an employee. The second approach to designing a reward is relative compensation, calculated based on a threshold value or rank that an employee has earned within a group of employees in either an ascending or descending order.

Step 5: Contracts are signed with information asymmetry, where the employer motivates employees by setting expectations and rewards, even if specific employee characteristics are unknown.

Step 6: The second party (e.g., small cells, IoT sensors, and CAVs) acts as employees, providing resources and services per the agreed terms.

Therefore, the contract theory-based approach enables CAVs to improve resource utilization, minimize energy consumption, and enhance task performance, outperforming baseline schemes.

5. Enabling technologies of a Metaverse in CAVs

This section comprises of the integration of the different enabling technologies in CAVs. Fig. 13 presents the taxonomy of Section 3 which is enabling technologies listed as follows: immersive experience technologies, artificial intelligence technologies, computing technologies, Digital Twins in Metaverse, and blockchain in Metaverse.

5.1. Immersive experience technologies within CAVs

Immersive experience technologies play a crucial role in enhancing the overall user experience within connected autonomous vehicles (CAVs). Here are some immersive technologies that can be incorporated into CAVs:

Virtual Reality (VR): VR can create a fully immersive simulated environment within the CAV. Passengers can wear VR headsets to experience virtual worlds, watch movies, play games, or engage in interactive experiences during their journey, transforming the travel time into a more enjoyable and entertaining experience.

Augmented Reality (AR): AR overlays virtual content onto the real-world environment, enhancing the passenger's perception of reality. In CAVs, AR can provide real-time information about points of interest,

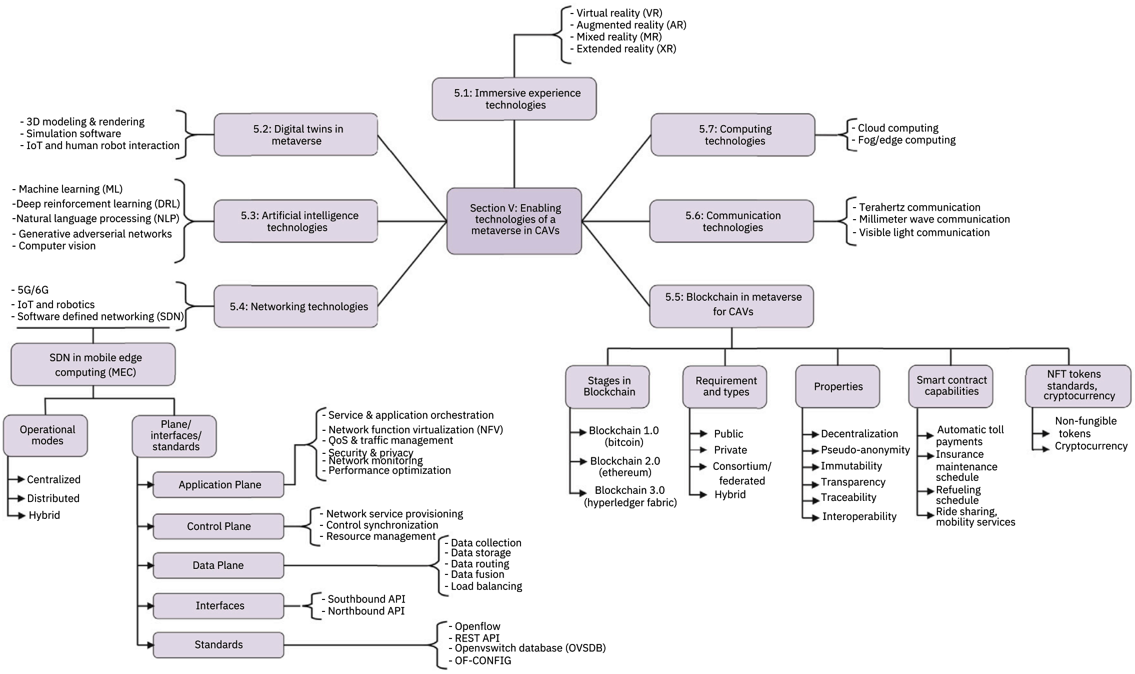

Fig. 13. Taxonomy of enabling technologies of a Metaverse in CAVs.

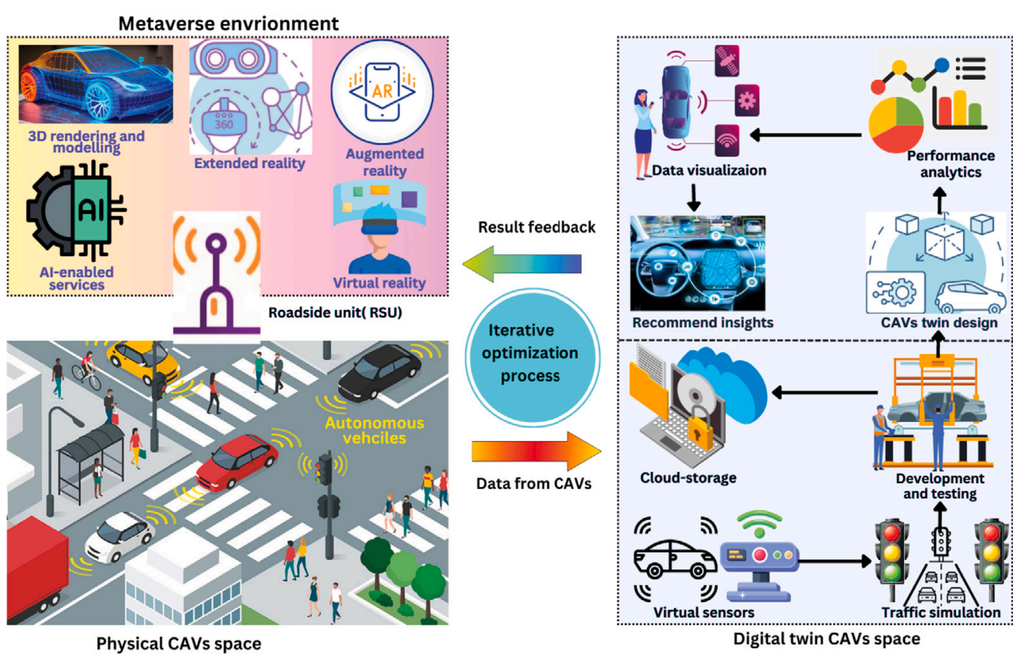

Fig. 14. Digital-twin assisted Metaverse architecture for CAVs.

landmarks, traffic conditions, or safety alerts, displayed directly on the windshield or through head-up displays, enriching the passenger's journey and providing valuable contextual information.

Mixed Reality (MR): MR combines elements of both virtual and augmented reality. It allows virtual objects to interact with the real-world environment, enabling passengers to experience a seamless blend of virtual and physical elements. MR can be used to create interactive and engaging experiences within the CAV, such as virtual companions or interactive storytelling.

5.2. Digital Twins in the Metaverse for CAVs

Digital Twin (DT) has emerged as a digitalization technology that enables virtual representation or a digital replica of a physical object, system, or process. A Digital Twin model is created by collecting real-time data from sensors, devices, and other sources and using it to generate a virtual model that mirrors the physical entity. DT can potentially reshape the future of industries by suggesting potential improvements during the manufacturing process. It enables organizations to monitor, analyze, and optimize the performance of physical systems and suggest possible improvements.

In the context of CAVs, DT can assist in vehicle development, testing, and predictive maintenance. For example, Fig. 14 shows a Metaverse-enabled CAV environment, where first real-time data from the physical CAV space is fed into the Digital Twin. Then, the Digital Twin space virtual model can provide insights, recommendations, visualization, and control actions to assess the performance of the physical components. Thus, DT can revolutionize the development of CAVs by testing and predicting failures before the real production process beings, thereby saving time and cost. Therefore, by integrating the Digital Twin with CAVs, industries can gain valuable insights and make faster decision-making, improving system efficiency and productivity.

5.3. Artificial intelligence technologies in the Metaverse for CAVs

In a Metaverse-enabled environment, autonomous vehicles can continuously exchange data with surrounding infrastructure and vehicles. In CAVs, ML and Deep Learning (DL) techniques, including Federated Learning (FL), Reinforcement Learning (RL), Convolutional Neural Networks (CNNs), and Long short-term memory (LSTM), can be used for crucial tasks such as traffic forecasting, decision making, path planning, navigation control, speed tracking, and pedestrian movement (Chellapandi et al., 2023; Dong et al., 2021). Machine learning models can be trained using vast amounts of virtual data to simulate road scenarios and conditions. These models in CAVs are locally trained on vehicle data, with the trained models sent to a server to create and share a generalized model for perception, prediction, and decision-making (Kiran et al., 2021). In the following, we have presented state-of-the-art, popular ML learning techniques used in CAVs.

Federated learning-based approach for CAVs: With the development of distributed vehicle connectivity, the issue of a centralized framework to collect data from every vehicle is a significant problem. The Federated Learning (FL) model which was coined by Google has been a breakthrough to enable training models on decentralized data sources. With federated learning, the learning process can happen on edge devices, allowing for localized decision-making and improved response time. In CAVs, FL facilitates a collaborative environment where vehicles learn from distributed data, reducing communication overhead, network strain, and improving adaptability to diverse driving scenarios (Zeng et al., 2022; Bachute and Subhedar, 2021).

Reinforcement learning-based approach for CAVs: Reinforcement Learning (RL) has emerged as a promising solution for Metaverse-connected CAVs. It is applied to tasks like motion planning, lane changes, predictive perception, reward learning, and route optimization (Antonio and Maria-Dolores, 2022; Li et al., 2021). During the operation of RL, the agent learns from interactions with the autonomous environment, such as observing the vehicle's state and receiving feedback or rewards based on its actions. The agent gradually learns optimal driving behaviors to maximize rewards and ensure safe and efficient driving. Real-world deployment of reinforcement learning for CAVs necessitates rigorous testing, validation, and compliance with safety regulations to ensure secure and efficient operations (Mathew and Benekohal, 2022).

Computer vision-based approach for CAVs: Computer vision plays a crucial role for CAVs in the Metaverse,enabling environmental perception, informed decision-making, and safe navigation in complex traffic scenarios. In CAVs, computer vision algorithms can be used to perform complex tasks such as road and vehicle detection, pedestrian identification, parking line detection, motion planning, and driver alertness monitoring (Heimberger et al., 2021; Zablocki et al., 2022). Advanced approaches such as Application-specific Integrated Circuit (ASIC), Field Programmable Gate Array (FPGA), deep neural networks, and CNN can be widely used to enhance CAV capabilities (Damaj et al., 2022; Hu et al., 2023). Ongoing research leverages ML and DL models for further advancements. A detailed summary review of these studies is highlighted in Table 12.

5.4. Networking technologies in the Metaverse for CAVs

The 3rd Generation Partnership Project (3GPP) standardization equipped vehicles with communication and sensor capabilities, accelerating V2X communication based on 5G/6G Software Defined Radio Access Networks (SDRANs) (Chaudhary et al., 2017). SDRANs are cutting-edge technology in 5G/6G networks that totally decouples the control plane from the underlying infrastructure/data/user plane. The advantages of the isolation between the two planes, transforming the future Internet in CAVs application with enhanced capabilities such as control flexibility (network programmability), automated configuration, dynamic reconfigurability, maximize network utilization, quick deployment using software upgrades, network slicing and flow isolation, and so on. The possible operational modes of the SDRANs architecture are discussed below.

5.4.1. Operational modes

Fig. 15 depicts the architecture of the centralized vs. distributed and hybrid SDRAN models for CAVs.

- **Centralized approach**: The first method is the centralized model depicted in scenario 1, in which SDN control and network orchestration are centralized for all domains. A master physical network controller is paired with a virtual SDN controller in this paradigm, which is used to set up all domains in the underlying infrastructure (Varma and Kumar, 2023).
- **Distributed approach**: The second approach is the distributed model depicted in scenario 2, in which several virtual SDN controllers are used across all domains and can be managed centrally alongside the master physical network controller (Chaudhary and Kumar, 2019).
- **Hybrid approach**: Finally, the hybrid controller approach combines the centralized control of SDN with the distributed reliability of traditional networks. Hybrid SDN controllers can improve network performance, offering better load balancing, failover, and traffic management.

5.4.2. Data plane

The underlying infrastructure consists of CAVs equipped with sensing and V2V communication capabilities, supported by V2I via 5G/6G networks, Wi-Fi, and roadside units. The 5G SDRAN architecture consists of entities such as the 5G remote radio head unit, distributed unit (DU), central unit (CU), baseband unit, and 5G core network. The baseband unit is split into DU and CU, with network slicing dividing the network into fronthaul, mid-haul, and backhaul domains. Fronthaul refers to the interface between the radio unit and DU, while mid-haul refers to the interface between the DU and CU, and backhaul refers to the next-generation air interface between the central unit and the 5G core mobile network. These domains are located at the base of the macro cellular tower, which act as edge nodes to ensure quality services for CAVs.

5.4.3. Control plane

The virtual SDN controller in the control plane coordinates services across domains via a central physical SDN controller. Network slicing is executed through network virtualization, with a single slice controller interfacing with one or more domain controllers (Garcia et al., 2021). The slice-aware application orchestrator manages slice creation, monitors the network, ensures end-to-end service delivery, interacts with remote applications, and enforces policies during traffic congestion (Chaudhary and Kumar, 2021).

5.4.4. Application plane

The application plane manages the network and is remotely designed by an expert where several network applications such as load balancing, service orchestration, security applications, traffic flow optimization and routing, resource management, and so on are running concurrently.

Table 12
Summary of state-of-the-art ML and DL techniques for CAVs.

Reference	Purpose	Technique used	Simulation environment	Future remarks
Mújica-Vargas et al. (2020)	Motion planning, vehicle control, decision making.	Reinforcement-learning (RL)-based model.	Udacity self-driving car simulator.	Designing good reward functions, incorporating safety in decision-making RL systems for autonomous. agents.
Lee and Ha (2020)	To extract features from sensor image and estimate the steering angle for CAVs.	CNNs and Long Short-Term Memory (LSTM) deep learning methods.	Euro truck simulator.	Exploring multi-agent planning and decision-making systems.
Dong et al. (2021)	Lane changing decision, collision avoidance during CAVs operation.	Deep reinforcement learning.	Microscopic traffic simulation tool SUMO.	Trajectory planning in CAVs.
Antonio and Maria-Dolores (2022)	Autonomous intersection management.	Multi-agent deep reinforcement learning.	Microscopic traffic simulation tool SUMO.	Identify conflicts, the crossing order of vehicles, or the information sharing in V2X communication.
Zeng et al. (2022)	To enable collaborative learning of the autonomous across a group of CAVs.	Federated learning (FL) framework.	Simulation using real traces have been performed using BDD and the DACT data.	Adopting contract theory-incentive mechanism to improve controller design.
Raja et al. (2022)	To collaboratively detect attacks and securely notify the overall CAVs network.	Block-chain integrated multi-agent reinforcement Learning (BlockMARL).	OMNET++ to achieve inter-vehicular communication and SUMO for mobility support.	Developing ML algorithms that would allow CAVs to adapt to the variability of human-driven vehicle behavior.
Rjoub et al. (2022)	To handle rare events, such as traffic accidents sudden lane changes skidding, in order to react proactively and prevent accidents.	Federated learning algorithm.	TensorFlow federated (TFF) platform.	Developing an FL framework that could perform well with the varying data distribution from CAVs.
Gokasar et al. (2023)	CAV-enabled incident detection to predict the future state of the traffic.	Convolution Neural Networks (CNN)-based traffic forecasts.	SUMO traffic simulation software.	Densely distributed larger sensor-based data sources are needed to improve forecast accuracy.
Xia et al. (2023)	Data acquisition and analysis platform for detecting objects in multi-vehicle CAVs environment.	Deep-learning-based object detection algorithm using LiDAR.	UCLA mobility lab.	Designing communication, sensing, and control protocols during multi-modal, multi-vehicle intersection management in CAVs.
Chen et al. (2023)	Speed control approach for CAVs.	Deep reinforcement learning (DRL).	CasADi in MATLAB 2020a simulation.	Using transfer and ensemble learning approaches to boost DRL model training efficiency and reliability.

5.4.5. Interfaces

- **Southbound API (SBI)**: The SBI manages communication between the data plane (user layer) and the control plane using open source protocols such as OpenFlow, REST API, Openvswitch database (OVSDB), OF-CONFIG, and others. In this case, OVSDB aids in the replication and coordination of many virtual SDN switches with the physical switch.
- **Northbound API (NBI)**: Similarly, the NBI manages communication between the application plane (network applications) and the control plane (SDN controller) via the OpenFlow protocol.

The integration of blockchain in the Metaverse for CAVs is explored in detail in the next section.

5.5. Blockchain in the Metaverse for CAVs

Blockchain technology plays a crucial role in the Metaverse by establishing a decentralized, autonomous, and democratic virtual environment (Gadekallu et al., 2022). It enables users, including CAVs, to trade virtual assets, connect with the crypto-economy, and ensures secure, transparent transactions across virtual worlds (Jeon et al., 2022). Additionally, it provides a decentralized open-source environment where users can partake in digital commerce and develop applications. Its tamper-proof nature fosters trust and authenticity, making it ideal for securely sharing data and conducting transactions in the Metaverse, while supporting digital commerce and application development (Aggarwal et al., 2019).

Blockchain-based cryptocurrencies in the Metaverse enable economic transactions and unified digital asset services. The cutting-edge technologies such as Non-Fungible Tokens (NFTs) (Chohan, 2021), Smart contracts (Zhang et al., 2021), Decentralized Finance (DeFi), Decentralized Autonomous Organizations (DAOs), and Decentralized Applications (dApps) can be leveraged to establish robust economic, financial, and governance systems within the Metaverse (Truong et al., 2023). For CAVs, blockchain facilitates secure data sharing, vehicle-to-vehicle payments, navigation assistance, and asset transfers. Its decentralized and transparent nature ensures data integrity and reliable transactions, fostering an efficient CAV environment in the Metaverse (Chaudhary et al., 2019).

In this subsection, we delve into the historical background of blockchain technology and explore the various types of blockchain in the Metaverse. We also discuss important terminologies associated with blockchain and examine how it can be integrated into the Metaverse to benefit connected autonomous vehicles (CAVs).

5.5.1. Stages in Blockchain in Metaverse

The blockchain development within the Metaverse has progressed through three distinct stages, as illustrated in Fig. 16. These stages are discussed below:

- **Blockchain 1.0 (bitcoin)**- Blockchain 1.0 in the Metaverse refers to the initial integration of blockchain technology into virtual reality platforms, which emerged in 2008 with Bitcoin as the first application (Wei, 2022). It enabled virtual platforms to support digital currencies and distributed ledgers, allowing users to store and share digital assets and services within the Metaverse. Blockchain 1.0 provides enhanced network reliability, security,

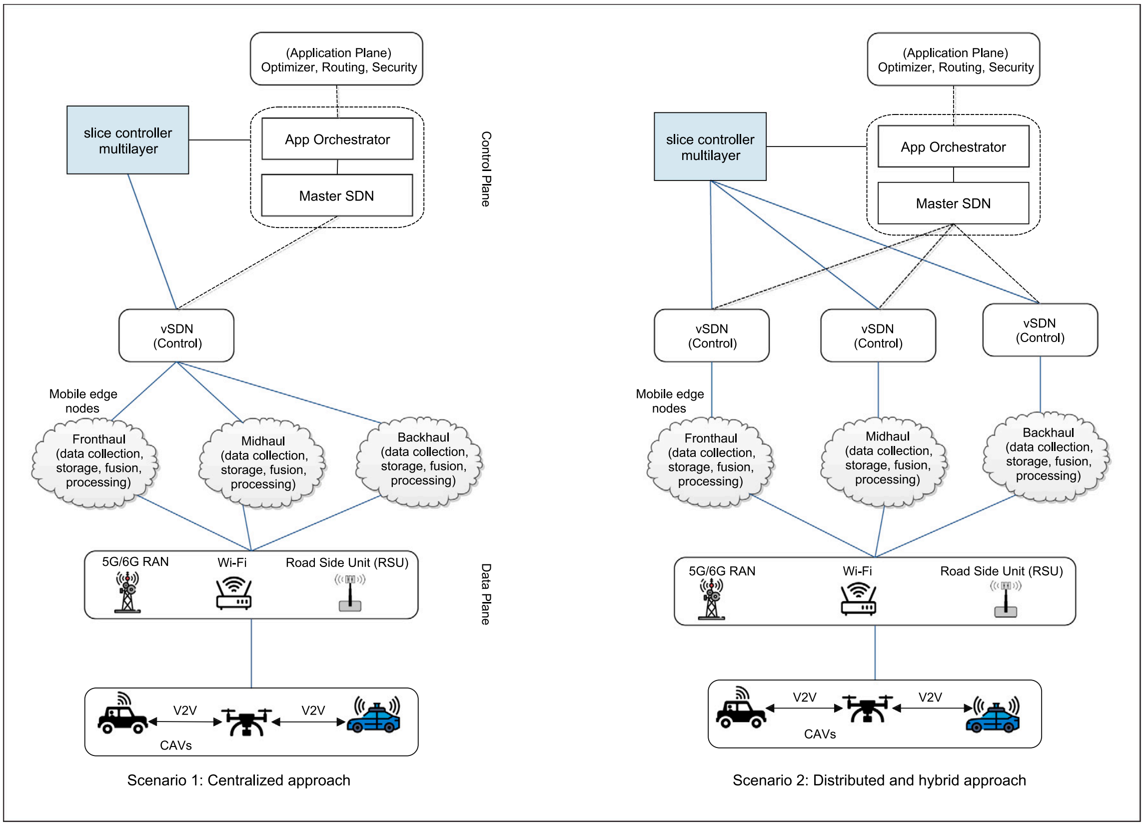

Fig. 15. Centralized vs. distributed, and hybrid SDN controllers in CAVs.

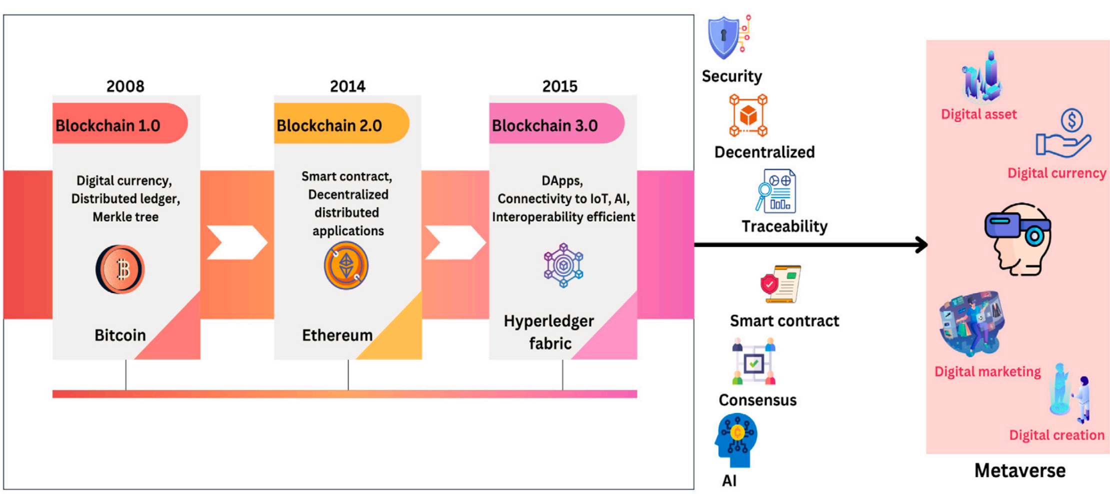

Fig. 16. Blockchain development stages in the Metaverse.

and transparent communication, empowering users with full control over possessions, and cost-effective decentralized solutions.

- **Blockchain 2.0 (Ethereum)**- Blockchain 2.0 is the second generation of the blockchain, which was introduced with the advent of Ethereum (Wei, 2022). It expands beyond digital currencies to incorporate features like smart contracts, and decentralized, distributed applications in the Metaverse (Mourtzis et al., 2023). Blockchain 2.0 enhances interoperability, digital asset ownership, decentralized Metaverse governance, and transparency, fostering trust and creating an immersive virtual environment.
- **Blockchain 3.0 (hyper ledger fabric)**- It emerged in 2015 and represents the next generation of blockchain technology, that addresses the scalability and computational limitations of earlier generations. Hyperledger, an open-source Linux Foundation project, advances cross-industry blockchain adoption (Wei, 2022). It employs techniques such as sharding and decentralized applications (DApps) (Gadekallu et al., 2022) to improve scalability and provide functionalities including supply chain management, peer-to-peer digital asset marketplaces, gaming, and financial services in the Metaverse (Yang et al., 2022).

5.5.2. Requirement of decentralization in the Metaverse and its types

Blockchain is a digital distributed ledger technology that empowers the Metaverse with decentralization and sustainability. It securely

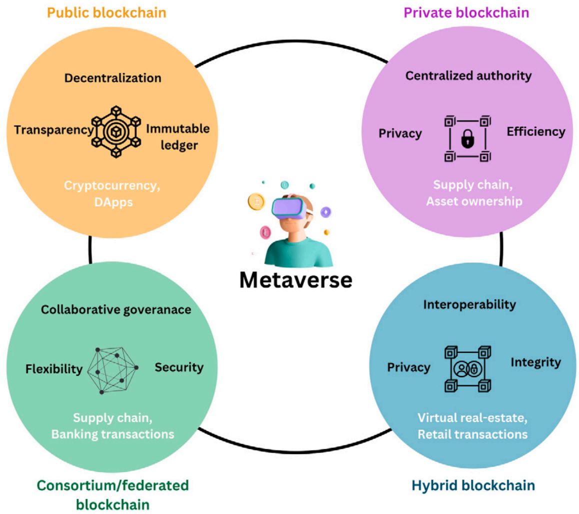

Fig. 17. Types of blockchain in the Metaverse.

stores transactions and data in cryptographically linked blocks replicated across nodes (Cao, 2022). Blockchain technology uses proof-of-work and proof-of-stake mechanisms to establish consensus which ensures data integrity and security. The digital assets transactions, known as cryptocurrencies, are recorded and managed by blockchains, and smart contracts enable automated asset contracting. This consensus-based system provides resilience against tampering and data duplication in the Metaverse (Bhutta et al., 2021).

In the Metaverse, decentralization is an essential requirement that facilitates the establishment of a decentralized infrastructure by distributing data as blocks across the blockchain network. This distribution eliminates single point of failure and ensuring continuous service availability, safety, and trustworthiness of CAVs in the Metaverse (Gadekallu et al., 2022; Chaudhary and Kumar, 2020). As a result, blockchain technology enables peer-to-peer transactions, enhances data integrity, and provides secure digital identities for vehicles, components, and users in the Metaverse. Furthermore, the integration of autonomous technology in the Metaverse improves CAV performance, enhancing customer satisfaction and the overall driving experience.

Blockchain is categorized into different types based on their applications. Fig. 17 illustrates the types of blockchains in the Metaverse in a nutshell.

- **Public**- Public blockchains in the Metaverse are fully distributed, decentralized, and permissionless that is accessible to all stakeholders (Gadekallu et al., 2022; Gupta et al., 2020). Within the Metaverse, any CAV can join the network and access the contents, ensuring transparency, and are secured with proof of work or proof of stake consensus mechanisms. Examples of public blockchains are Bitcoin, and Ethereum, that be used for a cryptocurrency exchange between CAVs and other users.
- **Private**- Private blockchain in the Metaverse is centralized, permissioned, and operates in a closed network with a specific group of participants (Mukherjee and Pradhan, 2021). They provide enhanced security and control over public blockchains and facilitate secure data sharing between CAVs and authorized users in the Metaverse. Hyperledger and Corda are examples of private blockchains.
- **Consortium/Federated**- Consortium blockchains are permissioned blockchains governed by multiple organizations, rather than a single organization as in a private blockchain (Gupta et al., 2021; Fu et al., 2022). They are more secure, efficient, and scalable and can be utilized in CAVs for traffic regulations and toll payments.
- **Hybrid**- Hybrid blockchain is a combination of both public and private blockchain and incorporates the permission-based features and security aspects of private blockchain with the transparency, and flexibility of public blockchain (Jain et al., 2021). It enables confidential data sharing among CAVs while providing robust protection against cyber or GPS-based attacks.

5.5.3. Properties of blockchain in Metaverse

Blockchain enhances the security and privacy of CAVs in the Metaverse through its key properties, including decentralization, pseudo-anonymity, immutability, transparency, traceability, and interoperability as depicted in Fig. 18. These features of blockchain for CAVs in the Metaverse are discussed as follows.

- **Decentralization**- Blockchain-based storage solutions secure the CAVs against malicious activities and protect sensitive information such as user identification, and autonomous vehicle communication, and prevent unauthorized access, tampering, and data loss (Jain et al., 2021; Dargahi et al., 2021).
- **Pseudo-anonymity**- Blockchain in the autonomous network provides pseudonymity, ensuring the vehicle identities to prevent identity-based attacks (Jain et al., 2021). This protects the privacy of CAV owners and users while maintaining transaction authenticity and integrity.
- **Immutability**- Blockchain provides the immutability of vehicle operations within the CAV environment in the Metaverse (Gadekallu et al., 2022). If the intruder attempts to modify the block transaction, then the hash of all subsequent blocks will change and the malicious activity will be easily detected (Gupta et al., 2020). Thus, it contributes to user accountability, transaction integrity, and tamper-proof records for both users and CAVs in the Metaverse.
- **Transparency**- Blockchain provides transparency in the Metaverse where all users in the blockchain ecosystem have access to the immutable ledger of transactions and smart contracts (Gupta et al., 2021). This distinctive property of blockchain mitigates network vulnerabilities and substantially reduces the likelihood of human error or vehicular accidents.
- **Traceability**- Blockchain enables traceability by recording every activity of CAVs in a chain of blocks which will help to track and trace the abnormal activities within the network, including unauthorized or suspicious actions performed by the nodes or any user in the Metaverse (Gupta et al., 2021; Gadekallu et al., 2022).
- **Interoperability**- Blockchain ensures interoperability between virtual worlds in the Metaverse through standardized and open protocols, including cross-chain protocol (Gupta et al., 2020). These protocols enable the exchange of possessions such as avatars, non-fungible tokens (NFTs), and virtual currencies between the virtual worlds, eliminating the need for intermediaries (Ahsani et al., 2023). It allows CAVs to seamlessly interact with other vehicles, network infrastructures, and other stakeholders, facilitating efficient operations in the Metaverse.

5.5.4. Metaverse for smart contract capabilities in blockchain

The Metaverse offers a promising environment for leveraging the capabilities of smart contracts on the blockchain in the domain of connected autonomous vehicles (CAVs) (Jeon et al., 2022). Smart contracts are a self-executing agreement that provides secure and reliable transactions without intermediaries in the Metaverse (Wang et al., 2018). They facilitate value exchange and ensure transparent, immutable rule execution in the Metaverse (Zhang et al., 2021).

Smart contract have transformed the landscape of the automotive sector where CAVs can engage in full-duplex communication to manage

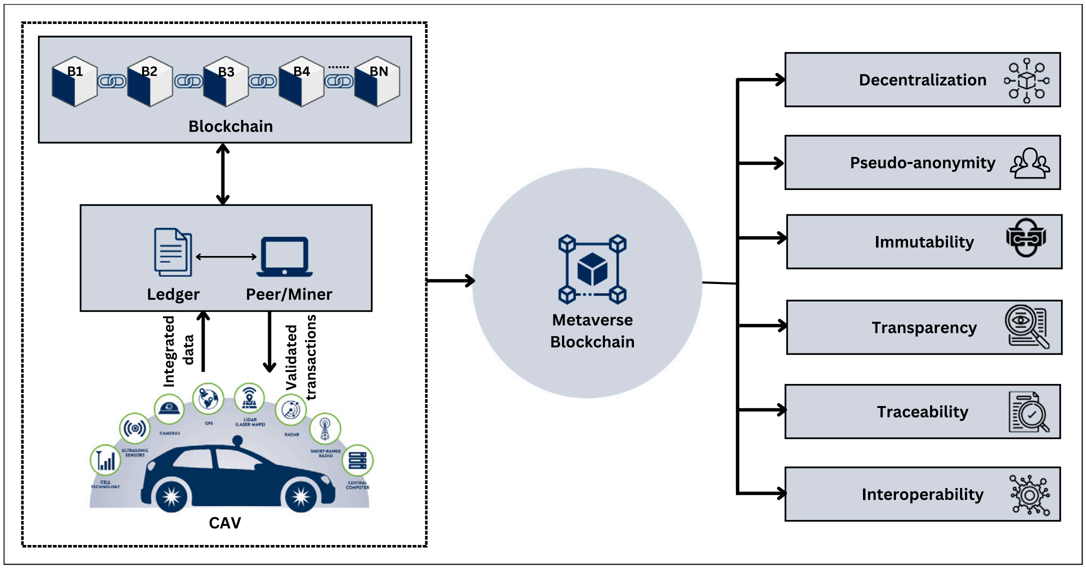

Fig. 18. Blockchain for CAVs in Metaverse.

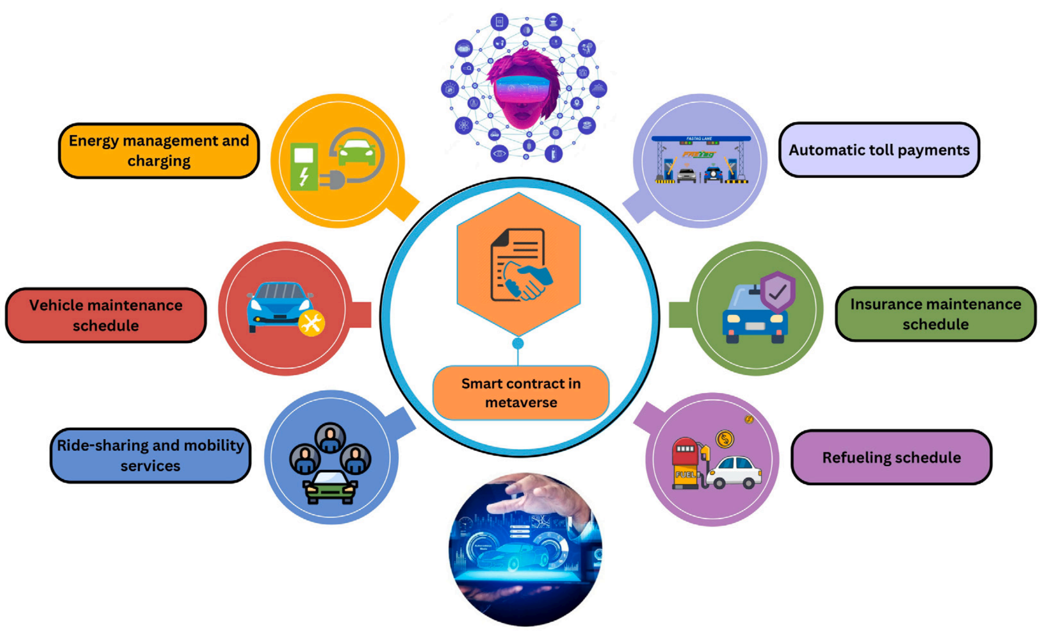

Fig. 19. Smart contract in the Metaverse for CAVs.

transactions autonomously in the Metaverse (Dargahi et al., 2021). Each vehicle or entity is assigned a unique ID for tracking transactions and creating contracts, ensuring transparency and trust among stakeholders (Javaid et al., 2019). Fig. 19 illustrates the smart contract in the Metaverse where CAVs store information related to driver identity, fuel usage, power hub locations, and insurance details on the blockchain. These contracts facilitate ride-sharing, insurance management, energy and charging schedules (Thukral, 2021), toll payments, and vehicle maintenance (Zhao and Wu, 2019). Thus it reduces cost and simplifies contract negotiations while enhancing the capabilities of CAVs in the Metaverse.

5.5.5. Technologies, protocols: Understanding tokens, NFT token standards, cryptocurrency in Metaverse

Blockchain is widely recognized as a fundamental infrastructure of the Metaverse due to its ability to connect isolated sectors and enabling a stable economic system with open, transparent, and reliable rules that govern the interactions and transactions within the Metaverse (Gadekallu et al., 2022). The decentralized virtual economy incorporates digital assets like cryptocurrency, fungible tokens, NFTs, virtual goods, and virtual estate. These assets can be securely traded and exchanged within the Metaverse without intermediaries, fostering transparency and trust without the need for intermediaries (Jindal et al., 2018).

Tokens: Tokens are the digital representation of an asset that proves the ownership of digital assets, virtual currencies, or goods. They are an essential element of blockchain technology, enabling users to create, trade, and earn tokens for economic transactions in the Metaverse. Non-Fungible Tokens (NFTs) (Wang et al., 2021a; Chohan, 2021), derived from Ethereum smart contracts, are unique, non-divisible tokens that ensure the uniqueness of digital assets. NFTs use Ethereum standards like ERC-721 and ERC-1155 for managing unique assets (Ghosh et al.,

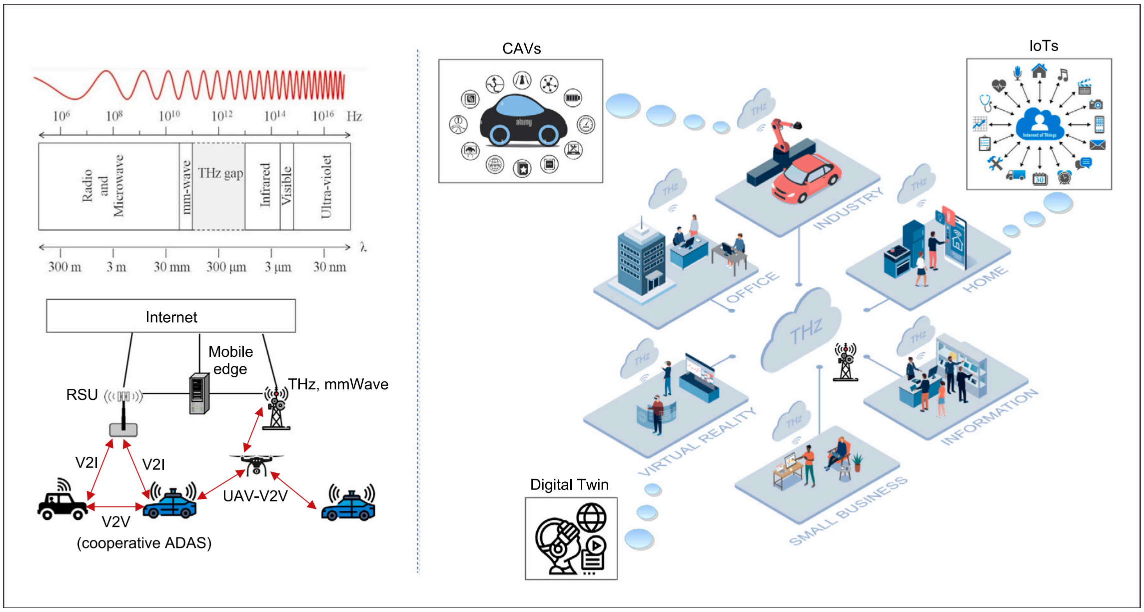

Fig. 20. Communication technologies in CAVs.

2020; Truong et al., 2023). In the Metaverse, blockchain-based NFTs allow avatars to generate and trade content using digital certificates as proof of ownership.

Cryptocurrency in the Metaverse: Cryptocurrencies such as Bitcoin and Ethereum are digital currencies that utilize the decentralized and immutable nature of blockchain technology (Ghosh et al., 2020). As the Metaverse experiences a multitude of transactions, the security and efficiency of these transactions become crucial. Thus, blockchain-based cryptocurrencies offer a promising solution by providing secure, tamper-proof, and transparent exchanges that enable fast, simple, and cost-effective peer-to-peer transactions (Aggarwal et al., 2018).

Since different Metaverses may have their own native cryptocurrencies, the need for cryptocurrency exchanges such as Coinbase and Binance becomes essential. These exchanges facilitate the conversion of various cryptocurrencies, similar to how fiat currencies are exchanged in the physical world. As the Metaverse evolves, multiple cryptocurrencies are expected to coexist, meeting the diverse needs of CAVs and other participants within the virtual realm.

5.6. Communication technologies in the Metaverse for CAVs

IoT and the Metaverse integrate to transform how CAVs communicate, connect, and share information. By constructing digital replicas, IoT enables an immersive experience and use cases in the Metaverse. However, disruptions in communication technologies or insufficient cloud services can hinder data flow, affecting user experiences. Communication technologies such as IoT, cloud services, terahertz communication, millimeter wave communication, and visible light communication enhance interoperability across AR-VR devices and empower the Metaverse. This section discusses the communication technologies used in 6G technology, such as terahertz communication, millimeter wave communication, and visible light communication are presented in Fig. 20, all of which play essential roles.

5.6.1. Terahertz communication

In CAVs, wireless communication occurs for vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) using roadside units (RSUs) or THz communication, vehicle-to-drones (V2UAVs), and vehicle-to-pedestrians (V2P) communication, where terahertz (THz) plays an important role due to the use of high carrier frequency. Sub-terahertz (sub-THz) frequencies range from 90 gigahertz (GHz) to 300 GHz, whereas terahertz (THz) frequencies is an ultra fastest frequency band extending from 300 GHz to 3 THz. The use of THz in 6G wireless networks enables holographic communication to deliver extremely high data rates and extremely low latency in V2X communication (Aslam et al., 2023).

5.6.2. Millimetre wave (mmWave) communication

mmWave is an extremely high-frequency band of the electromagnetic spectrum that ranges between 30 and 300 GHz. mmWave is commonly used for WiFi, point-to-point communications, wireless local area access networks (WLANs), and its application fields include virtual reality, wireless data centers, and connected cars. The authors in Kong et al. (2017) investigated mmWave capability and developed a framework of CAVs multi-gigabit data sharing equipped with mmWave radio. Furthermore, the proposed framework computes the optimal driving strategy in real-time by connecting autonomous vehicles with the Internet of Things and cloud computing.

5.6.3. Visible light communication

Based on the flashing property of Light Emitting Diode (LED), visible light communication and light fidelity (LiFi) are intertwined to provide ultra-high speed, bandwidth efficiency, and secure communication. In Darwish (2016), VLC was used in CAVs for forward collision warnings, enhancing safety by reducing time to collision. Similarly, Soner and Coleri (2021) utilized VLC for vehicle localization, achieving centimeter-level GPS accuracy for collision avoidance and platooning. While traditional methods like LIDAR/RADAR or cameras are costly, Visible Light Positioning (VLP) offers a precise, cost-effective alternative by using VLC signals from LED head/tail lights to estimate nearby vehicle positions.

5.7. Computing technologies

Cloud computing, edge computing, and quantum computing paradigms play a significant role in supporting connected autonomous vehicles (CAVs) by providing computational capabilities and addressing specific challenges (Liu et al., 2019; Aujla et al., 2018). In a nutshell, cloud computing allows organizations and people to access advanced resources and services without extensive infrastructure, utilizing models including Infrastructure as a Service (IaaS), Platform as a Service

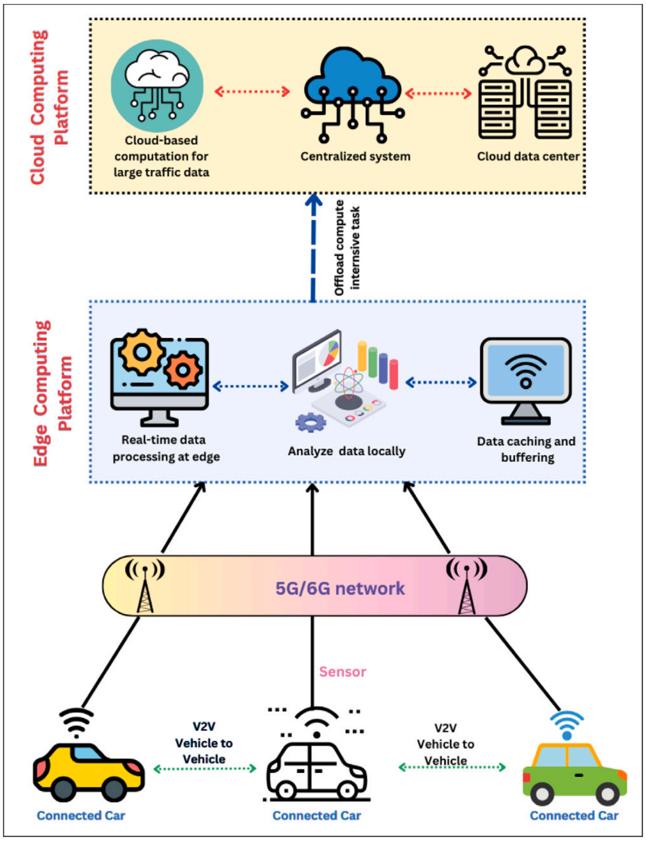

Fig. 21. Cloud/edge computing-based computing architecture for CAVs.

(PaaS), and Software as a Service (SaaS) (Rashid and Chaturvedi, 2019). In CAVs, cloud computing acts as a centralized hub by providing a scalable, high-performance data processing, allowing CAVs to upload, store, and analyze real-time traffic data (Arthurs et al., 2021). This reduces computational and maintenance burdens on vehicles while promoting efficient resource utilization.

To address delays associated with cloud computing and meet the stringent service requirements of IoT and V2X communication, edge computing has emerged as a viable solution. Instead of relying only on cloud infrastructure, edge computing processes data closer to the source at the network edge, and thus reduces latency and enables faster responses for critical CAV operations like collision avoidance, lane detection, localization, and emergency braking. As shown in Fig. 21, a hybrid architecture combining cloud and edge computing allows CAVs to optimize performance (Datta et al., 2017). For example, in CAVs, computation for delay-tolerant tasks such as performing map updates can be processed in the cloud, while delay-sensitive tasks, such as traffic congestion and speed limit management, are handled at the edge (Liu et al., 2023b). Thus, utilizing a cloud computing and edge computing-based architecture can aid in enhancing the QoS of CAVs services by minimizing the latency.

6. Open issues and research directions in Digital Twin for CAVs in the Metaverse

In this section, we discuss various challenges and future research directions related to the integration of Digital Twin (DT) technology and game theoretical models for CAVs in the Metaverse from the following aspects. The taxonomy of Section 6 is depicted in Fig. 22.

6.1. Security and privacy issues in Digital Twin for CAVs in the Metaverse

Digital Twin (DT) integration for CAVs in the Metaverse is expected to enhance transportation efficiency, road safety, and overall mobility while minimizing environmental impact (Sun et al., 2021b; Jiang et al., 2020). However, in recent years, the level of connectivity and automation in the CAVs is escalating the security and privacy risk. The need to store and retrieve vast amounts of data through centralized or third-party servers also introduces risks, including potential unauthorized access, data tampering, and system control by malicious entities (Gupta et al., 2020).

In the Metaverse, privacy concerns are increasing for CAV users, as DT applications rely on wearable technology to capture and store various biometric data, including voice, iris, fingerprints, and other identifiers to create immersive experiences (Ali et al., 2022). However, breaches in Metaverse servers could lead to identity theft, impersonation, false avatar disputes, and compromised user privacy (Chang et al., 2022). Thus, it is crucial to strengthen the security measures for DT-enabled CAVs and the Metaverse infrastructure. This section classifies the potential threats to DT-enabled CAVs in the Metaverse, as shown in Fig. 23. We discuss the critical challenge and outline several possible research directions in the following subsections.

6.1.1. Data-related threats in DT for CAVs in the Metaverse

The data generated and shared by CAVs in the Metaverse can be vulnerable to threats from malicious entities that could gain unauthorized access and extract sensitive information. In the following, we discuss some of the data-related threats in DT for CAVs in the Metaverse.

- *Data Storage and Sharing Risks in DT for CAVs in the Metaverse-* A significant amount of data generated by DT-enabled CAVs must be securely stored and shared in the Metaverse for real-time data analysis and decision-making. The centralized storage systems are vulnerable to breaches, data tampering, and accessibility issues. Blockchain technology can mitigate the risk by enabling decentralized data storage while improving data accessibility and integrity for DT-enabled CAVs in the metaverse (Liu et al., 2020; Yang et al., 2022).
- *Data Interoperability and Privacy Compliance in DT for CAVs in the Metaverse-* The integration of DT for CAVs presents significant challenges in data security, privacy, and regulatory compliance. Stringent adherence to the General Data Protection Regulation (GDPR) or California Consumer Privacy (CCPA) laws is essential for exchanging sensitive data between CAVs, digital infrastructure, and virtual entities. Advanced encryption, strict authentication, and access controls are essential to prevent unauthorized access and breaches. Additionally, collaboration with regulatory bodies ensures a secure, compliant DT framework, fostering trust and supporting reliable DT-enabled CAV deployment in the Metaverse (Belchior et al., 2021).
- *Data Acquisition, Integration, and Authenticity Challenge in DT for CAVs in the Metaverse-* To establish a DT for CAVs in the Metaverse requires real-time collection and processing of data from diverse sources like vehicles, sensors, and roadside units. Heterogeneous data formats and standards pose challenges for data fusion and unification. Furthermore, DT demands high spatiotemporal correlation and real-time processing, requiring advanced data acquisition and integration technologies. Even malicious data modifications can compromise safety, emphasizing the need for robust frameworks. Future research should focus on data fusion techniques, standardization protocols, and blockchain-based validation to ensure data authenticity and an efficient DT experience for CAVs (Deepa et al., 2022).

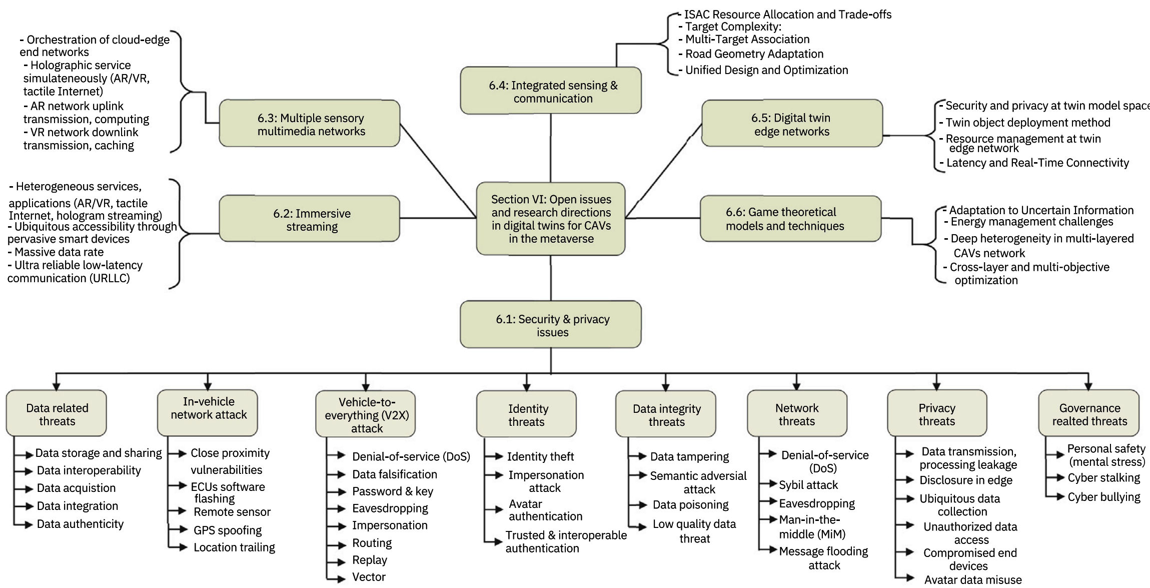

Fig. 22. Taxonomy of Metaverse open issues and research directions in CAVs.

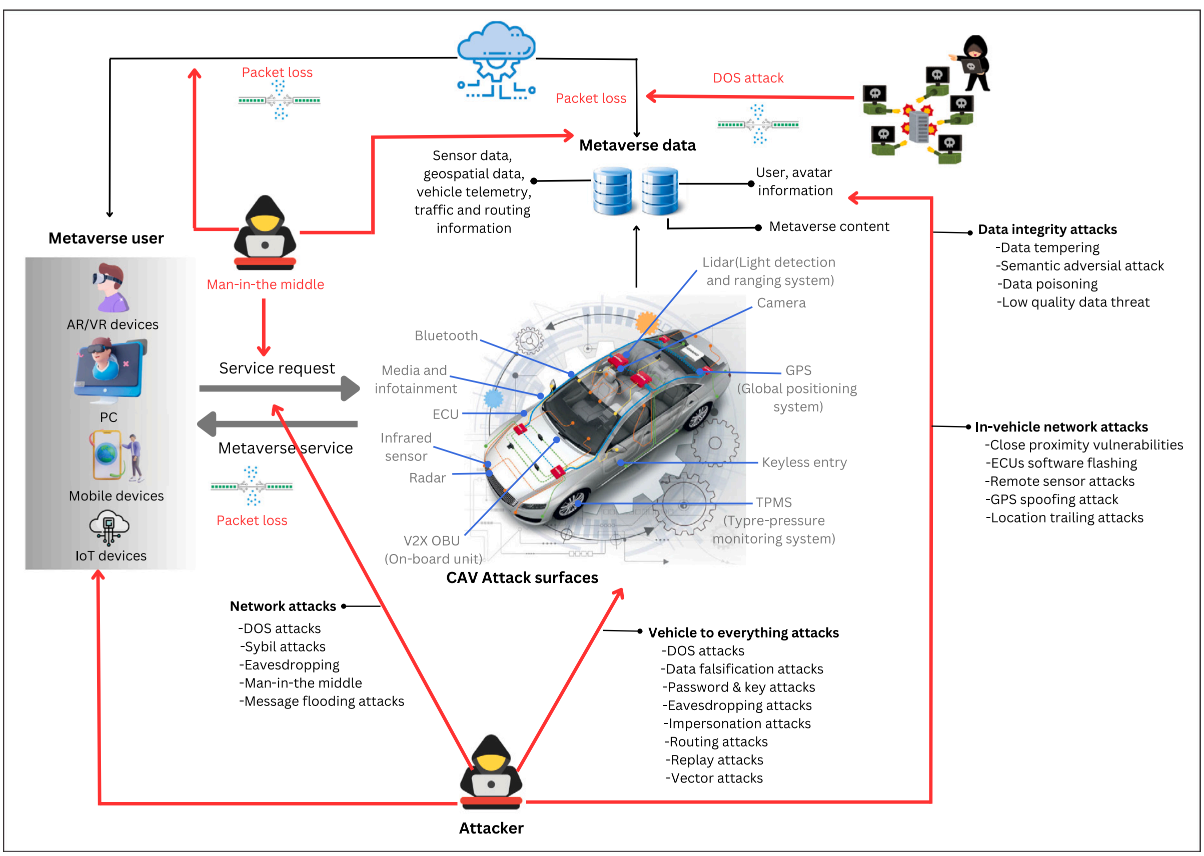

Fig. 23. Security and privacy threats in CAVs in the Metaverse.

6.1.2. In-vehicle network threats in DT for CAVs in the Metaverse

The increasing connectivity in CAVs has raised significant concerns regarding safety and security (Liu et al., 2017). In-vehicle networks rely on protocols such as Controller Area Networks (CAN) and Local Interconnect Networks (LIN) for ECUs communications (Aliwa et al., 2021). These protocols are open to numerous breaches due to a lack of security mechanisms. Various in-vehicle network attacks on DT-enabled CAVs in the Metaverse are classified as follows.

- *Close Proximity Vulnerabilities*- Short-range communication mechanisms such as Bluetooth (Spill and Bittau, 2007), tire pressure monitoring systems (TPMS) (Guette and Bryce, 2008), or keyless entry (Glocker et al., 2017) can expose CAVs to unauthorized access by nearby attackers. Encryption algorithms and cryptographic checksum are reliable techniques to prevent the execution of malicious activities.

- *ECUs Software Flashing Attacks*- Attackers can exploit software vulnerabilities to obtain unauthorized access to ECUs, allowing data corruption and hardware degradation. Countermeasures such as encryption, integrity checks, and authentication mechanisms can be implemented (Alam et al., 2019; Lenard et al., 2020).
- *Remote Sensor Exploits*- In CAVs, various components such as radar, lidar, cameras, and infrared sensors can be vulnerable to remote attacks via wireless networks, potentially compromising DT data accuracy (Petit et al., 2015). To defend against remote sensor attacks, sensor fusion techniques (Lim et al., 2018), spatio-temporal challenge-response (Kapoor et al., 2018), and authentication techniques can be utilized (Matsumura et al., 2018; Cao et al., 2019).
- *GPS spoofing and Location trailing threats*- Unauthorized tracking of CAVs in the Metaverse can compromise user privacy, with implications for DT-driven traffic management. Privacy-preserving solutions, such as k-anonymity techniques (Qiu et al., 2020), and location perturbation (Luo et al., 2019) are the potential mechanisms to improve user location privacy in the immersive space.

6.1.3. Vehicle-to-everything (V2X) threats to DT for CAVs in the Metaverse

The V2X communication in DT-enabled CAVs facilitates real-time data exchange between vehicles and surrounding infrastructure within the metaverse. However, unauthorized access to these communication channels introduces significant vulnerabilities, including Denial-of-service (DoS) attacks, which flood the communication channel with excessive messages in the metaverse as shown in Fig. 23, potentially causing delays, security compromises, and even leading to accidents (Gupta et al., 2020). Countermeasures include sliding mode, adaptive estimation (Biron et al., 2018; Kumar and Mann, 2018; Ohira et al., 2020). In addition, Data falsification attacks can disrupt driving by transmitting false information, leading to traffic congestion and inefficient navigation (Pham and Xiong, 2021). To mitigate this, robust security measures such as forged data filtering, anomaly detection strategy, and cooperative spectrum sensing mechanism can be adopted (Shukla and Sengupta, 2018; Lin et al., 2018).

Other critical threats to DT-enabled CAVs in the Metaverse include Password & key breaches, Eavesdropping, and Impersonation attacks, where adversaries intercept confidential information or create false identities (Parkinson et al., 2017). Mitigation strategies include secure key management, multifactor authentication, anonymization, trust-based recommendation system (Arif et al., 2018; Wu et al., 2018; Liang et al., 2019), and Elliptic curve cryptography-based secure authentication mechanisms (Sutrala et al., 2020). Furthermore, Routing and Replay attacks may alter or repeat messages maliciously, which can be addressed through secure routing protocols and timestamping methods to validate data authenticity (Sánchez et al., 2018; Greene et al., 2020). Finally, the Vector attacks, such as GPS spoofing, eavesdropping, and malicious software injection, emphasize the need for robust cryptographic solutions and multi-sensor validation techniques (Malik and Sun, 2020).

6.1.4. Identity threats to DT for CAVs in the Metaverse

Identity threats pose significant risks in the DT-enabled Metaverse, where the impersonation and exploitation of CAVs and their user/avatar identities can undermine trust and operational security. Identity theft enables adversaries to access personal information, credentials, and digital identities associated with CAVs, user avatars, and digital assets, potentially through phishing attacks, VR/AR hacking, and other malicious activities (Wang et al., 2022). Impersonation attacks further exploit these vulnerabilities by allowing attackers to create false identities that can facilitate fraudulent activities.

To mitigate these risks, avatar authentication is crucial to prevent privacy breaches, as adversaries can develop AI bots or virtual entities in the Metaverse that mimic real avatars and engage in malicious activities. Multi-factor authentication, biometric verification, and digital signature mechanisms are essential to ensure the trust and integrity of user avatars (Falchuk et al., 2018). Moreover, blockchain-based identity management systems further enhance identity verification and cross-platform interoperability (Dionisio et al., 2013; Gadekallu et al., 2022).

6.1.5. Data integrity threats to DT for CAVs in the Metaverse

Data integrity is crucial for maintaining consistent validity and accurate data throughout its lifecycle in DT-enabled CAV applications within the Metaverse. In a data tampering attack, adversaries broadcast false signals which can lead to unsafe driving decisions (Lin et al., 2017). Countermeasures such as blockchain technology, digital signatures, or message authentication are effective for verifying message integrity (Lin et al., 2018, 2017). Semantic adversarial attacks manipulate data semantics to mislead the CAVs, resulting in a collision (Zhu et al., 2021). While a Data poisoning attacks introduce corrupted data, potentially causing traffic disruptions with false congestion information (Zhu et al., 2021).

Furthermore, low-quality data threats emerge when users/avatars or other entities in the Metaverse contribute to inaccurate data to save their resources (Wang et al., 2022), leading to poor decision-making in CAV operations. To address these challenges, robust data quality assessments, including node-centric generation trees and bidirectional buffering mechanisms, can be employed (Ning et al., 2017).

6.1.6. Network threats to DT in Metaverse for CAVs

The reliance of DT-enabled CAVs on wireless communication technologies in the Metaverse makes them vulnerable to various network-related threats such as DoS, Sybil, Eavesdropping, Man-in-the-Middle, and Message flooding attacks. DoS and flooding attacks can flood the centralized server/network infrastructure with massive traffic, leading to service unavailability (Nanda et al., 2019). Further, Sybil attacks involve the transmission of false messages, which can lead to hazardous CAV decisions (Zhang et al., 2014). Countermeasures include trusted certification and resource testing, message validation, and authentication (Baza et al., 2020). Eavesdropping and Man-in-the-Middle (MiM) attacks also intercept or alter communications between CAVs and infrastructure, aiming to capture confidential data or control vehicle operations (Huang et al., 2018; Shen et al., 2020). Countermeasures include encryption, virtual private networks, and time-delay variation methods to secure communication channels in DT-enabled CAV systems within the Metaverse (Al-Kahtani, 2012).

6.1.7. Privacy threats to DT in Metaverse for CAVs

Integrating IoT, wearables, and AR/VR in DT-enabled CAVs within the Metaverse raises significant privacy concerns, as these technologies capture extensive user data, which is vulnerable to privacy threats described below.

- *Data transmission, processing leakage*- It enables adversaries to eavesdrop on CAVs or avatar locations to gain unauthorized access to sensitive information.
- *Disclosure in edge*- It occurs if unauthorized entities gain access to data stored on edge or cloud servers, which can result in privacy leakage in the DT-enabled CAVs in the Metaverse, which may be mitigated through periodic audits and stringent access controls (Bertino and Islam, 2017).
- *Ubiquitous data collection and unauthorized data access*- It poses further challenges as CAVs gather biometric, physical, and behavioral information for immersive experiences in the Metaverse (Falchuk et al., 2018). Attackers can exploit these devices to breach privacy by tampering with data or escalating access rights (Yu et al., 2018; Xu et al., 2022b).

- *Compromised end devices*- The wearable devices and headsets used in the Metaverse can turn out to be an entry point for data breaches and malware that could violate user privacy in DT-enabled CAVs (Shang et al., 2020). MinHash and Bloom filters are some technologies that can be used for privacy protection (Liu et al., 2018).
- *Avatar data misuse*- The attackers extract or manipulate personal information associated with avatars (Falchuk et al., 2018). Multiple Merkle trees and Blockchain technologies for anonymous authentication can be utilized to address these violations (Chen et al., 2021; Peng et al., 2023).

6.1.8. Governance related threats to DT in Metaverse for CAVs

Law enforcement and social standards are essential for establishing a governance system within the DT-enabled Metaverse for CAVs, where interactions between avatars and other entities occur in a virtual space. Without effective governance, the user experience in the DT-enabled Metaverse could be susceptible to threats such as Personal safety risks, Cyberstalking, and Cyberbullying. These can undermine trust, mental well-being, and community integrity in the virtual environment. Therefore, implementing regulatory frameworks and virtual social support systems can help maintain a safe, respectful digital experience for all users.

6.2. Challenges of immersive streaming to DT in Metaverse for CAVs

The integration of DT for CAVs in the Metaverse introduces unique challenges due to the high demands of real-time, multi-modal interaction and seamless integration between virtual and physical environments. DT-enabled CAVs require efficient management of immersive and interactive experiences in the Metaverse. The key challenges in ensuring ubiquitous accessibility, massive data rates, and ultra-reliable and low-latency communications are described below.

- *Heterogeneous Services, Applications (AR/VR, tactile Internet, hologram streaming)*- The delivery of diverse applications, including augmented and virtual reality (AR/VR), tactile Internet, and hologram streaming, require highly reliable and low-latency connections. AR/VR offers immersive visual experiences, while tactile Internet demands rapid haptic feedback with minimal delay. Ensuring robust network infrastructure and low-latency communication is critical for the effective operation of these applications within DT-enabled CAVs (Ning et al., 2023).
- *Ensuring Ubiquitous Accessibility through Pervasive Smart Devices*- DT in the Metaverse provides ubiquitous connectivity, allowing CAVs to access services through various devices, including AR/VR headsets, wearables, and IoT devices. However, ensuring seamless connectivity introduces challenges such as scalability, device compatibility, and privacy, which must be managed to support performance and accessibility (Wang et al., 2022).
- *Massive Data Rate Requirements*- DT-enabled CAVs generate significant data from sensors and devices, requiring high-speed Internet, ample bandwidth, and ultra-low latency to maintain immersive user experiences. Addressing this challenge involves leveraging advanced communication technologies that support data-intensive applications effectively.
- *Ultra-Reliable Low-Latency Communication (URLLC)*- The tactile Internet plays a significant role in the Metaverse by providing users with haptics and kinematics interaction, which is crucial for DT-enabled CAVs. However, these applications are sensitive to network latency and jitter, requiring ultra-reliable, low-latency communications to prevent delays and maintain consistency (Xu et al., 2022a).

6.3. Challenges of multiple sensory multimedia networks to DT in Metaverse for CAVs

Multi-sensory multimedia services within the Metaverse provides an immersive experience for DT-enabled CAVs, necessitating advanced edge-computing and efficient resource allocation mechanisms to ensure seamless communication between CAVs and other entities. The key challenges are described below:

- *Orchestration of Cloud-Edge Networks*: DT-enabled CAVs in the Metaverse require substantial computational resources and consume significant power, leading to increased latency. Efficient orchestration between cloud and edge computing resources is essential for optimized data processing, enabling low-latency communication and real-time cooperation among CAVs, including applications such as cooperative AR vision (Zhou et al., 2022).
- *Simultaneous Holographic Services (AR/VR, Tactile Internet)*: The integration of holographic services in the Metaverse for CAVs poses challenges due to the varied requirements of different applications. While tactile Internet requires ultra-reliable low-latency communications (URLLC), AR/VR applications require enhanced mobile broadband (eMMB) services (Lee et al., 2021). Thus it becomes difficult to design resource allocation schemes for such intricate multi-sensory multimedia services. Future research directions should focus on developing algorithms and technologies for the synchronized delivery of these services in the Metaverse.
- *AR Network Uplink Transmission and Computing*: The application data from AR devices in DT-enabled CAVs is transmitted to the network for processing, requiring robust and low-latency computation for immersive, real-time experiences. Therefore, solutions such as adaptive bitrate streaming, compression techniques, and edge computing can improve the performance of AR network uplink transmissions, enhancing the user experience in the Metaverse (Xu et al., 2022a).
- *VR Network Downlink Transmission and Caching*: The downlink transmission resources and caching capabilities of the network are often utilized by VR services in the Metaverse for the transmission of VR data, such as 3D models, speech and biometric features, HD videos, and interactive elements in the downlink direction. These applications also require low-latency and eMBB (enhanced Mobile Broadband) services which poses a challenge in the Metaverse.Future research should focus on optimizing these protocols to support smooth and reliable VR experiences for DT-enabled CAVs (Wang et al., 2022).

6.4. Challenges of Integrated Sensing and Communication (ISAC) in DT in Metaverse for CAVs

ISAC plays an essential role in DT-enabled CAVs in the Metaverse, which utilizes the shared frequency bands and hardware to create an immersive experience for sensing and communication. This technology combines sensing and communication in wireless networks to improve spectrum efficiency, enabling high data rates and enhanced resolution for real-time obstacle detection and localization. ISAC facilitates immersive and responsive environments, essential for immersive Metaverse applications like V2I communication and lane-change detection systems (Liu et al., 2022; Du et al., 2023). The key features of ISAC are listed below.

- *Sensing-Assisted Communication*- ISAC enhances conventional communication by leveraging real-time localization data facilitate Vehicle-to-Infrastructure (V2I) communication Vehicle -to-Infrastructure (V2I) networks. It can reduce training overhead by improving beam alignment and localization accuracy, essential in high-mobility scenarios (Choi et al., 2016).

- *Communication-Assisted Sensing-* ISAC also enables communication data to support sensing functions. By reusing communication signals for sensing, ISAC reduces the requirement for dedicated sensing resources such as separate radar sensors, minimizing hardware costs and improving energy efficiency.
- *Hardware and Spectrum Efficiency-* With the convergence of sensing and communication technologies onto the same hardware, ISAC minimizes infrastructure duplication, maximizes spectrum usage, and reduces power and equipment requirements. ISAC provides significant benefits for future 6G networks, such as resource sharing and hardware miniaturization, making it highly relevant for DT-enabled CAVs in spectrum-limited Metaverse environments (Wen et al., 2024).

The challenges in implementing ISAC for DT-enabled CAVs in the Metaverse are:

- *ISAC Resource Allocation and Trade-offs:* ISAC systems face the challenge of distributing limited resources such as bandwidth and power between sensing and communication tasks. Ensuring an optimal balance between Quality of Service (QoS) requirements for both sensing and communication, particularly in bandwidth-limited environments, requires sophisticated resource allocation frameworks that prioritize critical metrics like detection probability and achievable sum rate.
- *Target Complexity:* DT-enabled CAVs face difficulties in accurately sensing extended targets with high-resolution mmWave bands. For example, detecting the exact location of a vehicle's communication antenna can be challenging, as mmWave signals may not fully illuminate larger vehicles. Solutions such as dynamic beamwidth adjustments (ISAC-DB) and multi-beamwidth approaches (ISAC-AB) address this issue by ensuring comprehensive target coverage.
- *Multi-Target Association:* In scenarios where multiple vehicles are managed by a single roadside unit (RSU), ISAC faces challenges in correctly associating data streams for multiple CAVs. Techniques such as Joint Probabilistic Data Association (JPDA) and Multiple Hypothesis Tracking (MHT) are crucial to avoiding communication errors and maintaining accurate DT synchronization (Du et al., 2023).
- *Road Geometry Adaptation:* The existing beam tracking methods in ISAC typically assume standard road geometries, limiting their efficacy in complex road scenarios. Advanced tracking models such as Constant Angular Velocity, State-Free, and Curvilinear Coordinate System (CSS) enhance ISAC's effectiveness on irregular roadways by enabling adaptive beam tracking and accurate trajectory prediction (Lim et al., 2019).
- *Unified Design and Optimization:* ISAC requires task-specific models and optimization algorithms to balance sensing accuracy, latency, and energy efficiency, which are challenging to integrate within traditional communication systems (Cui et al., 2023).

6.5. Digital Twin edge network challenges for CAVs in the Metaverse

DTs are bringing remarkable innovations in the autonomous industry by establishing virtual platforms for virtual traffic and driving simulation environments. Integrating Digital Twins with the edge network can mitigate issues such as high transmission latency, and low connection reliability caused by stochastic autonomous vehicle networks (Guo et al., 2022). However, there exist several challenges that must be resolved to witness the large-scale use of DT technology for CAVs in the metaverse.

- *Security and Privacy in Twin Model Spaces:* In DT-based CAV system, communication interfaces like twin-to-device and twin to twin may be susceptible to twin object attacks. If the twin model's security is compromised, attackers could trigger large-scale disruptions in traffic. To mitigate this, blockchain and mobility-aware forensics schemes can be explored to achieve secure communication and privacy protection for CAVs within the twin model space (Zhang et al., 2022b).
- *Digital Twin Object Deployment Accuracy and Adaptability:* In the DT modeling process, creating precise representations of physical entities is vital for accurate modeling, analysis, predictions and simulations. External factors, such as weather and road conditions, can affect vehicles' behavior, making it challenging to develop universally accurate models. Furthermore, the dynamic nature of CAV environments requires regular updates and calibrations of the DT models to maintain relevance. Even the collected data may contain noise or errors that need to be filtered out without losing essential information, presenting a need for robust noise-reduction techniques. To ensure efficient functioning, future research should focus on creating adaptive and self-calibrating DT models that can preserve accuracy under variable real-world conditions and automatically manage noise (Almeaibed et al., 2021).
- *Resource Management in Twin Edge Networks:* The data generated by CAVs places considerable demand on edge network resources. A centralized computing scheme could lead to increased overhead and security risks. Federated learning could be employed within DT edge networks to train resource management models locally, enabling edge devices to optimize strategies without the need to transfer sensitive data to a central server.
- *Latency and Real-Time Connectivity Issues:* Ultra-low latency and high network reliability are crucial for real-time CAV operations, such as collision avoidance and traffic management. However, maintaining stable connectivity in areas with poor coverage (e.g., tunnels, underground parking) can be challenging and disrupt DT operations. Large-scale network connections also increase network pressure, requiring efficient bandwidth management and resilient protocols to ensure continuous data flow. Research into scalable architectures and predictive modeling is necessary to ensure reliable DT-CAV integration within the Metaverse.

6.6. Challenges in game theoretical models and techniques for DT in the Metaverse for CAVs

The application of game-theoretical models to DT-enabled CAVs in the Metaverse presents unique challenges due to the complexity, uncertainty, and resource constraints of this environment (Sun et al., 2021a). The key challenges are described as follows:

- *Adaptation to Uncertain Information in the Metaverse for CAV:* In the Metaverse, CAVs often interact with other vehicles, infrastructure, and virtual entities, usually with incomplete or uncertain information about others' intentions or strategies. Traditional game-theoretical models typically assume complete information or finite strategy spaces, which may not capture the uncertainties present in these dynamic environments. This limitation can lead to suboptimal decisions, affecting traffic flow, resource allocation, and safety. To address this, future research can focus on incorporating AI and machine learning into the game theory to help CAVs adapt in real-time, enhancing resource allocation and safety through hybrid cooperative and competitive strategies.
- *Energy Management Challenges in Green CAV Networks:* Green CAV networks in the Metaverse integrate diverse renewable sources, such as solar and wind-powered RSUs and smart grids. Game theory can offer efficient strategies for resource sharing and allocation. However, the high mobility of vehicles and the fluctuating nature of renewable energy supply create complexities in sustaining consistent power availability. Future research could focus on developing adaptive energy-sharing strategies, including cooperative and auction-based models, that could help alleviate demand

on RSUs and support sustainable energy distribution, enabling green and reliable CAV operations in the Metaverse (Ren et al., 2022).
- *Managing Deep Heterogeneity in Multi-Layered CAV Networks:* Future CAV networks in the Metaverse will consist of diverse systems, such as satellites, UAVs, ground vehicles, and underwater vehicles, interacting across multiple layers (Zhang et al., 2022a). This heterogeneity poses challenges for game-theoretical models, as the vast number of players and strategies complicates decision-making and coordination. The large volumes of data generated by these multi-layered networks further intensify the challenges, requiring efficient processing to avoid high storage costs and latency. Future studies could explore mean-field game theory as a solution, allowing the efficient modeling of interactions among numerous nodes. Integrating mean-field approaches with big data analytics can enable CAVs to balance data processing costs against data utility, optimizing resource allocation and performance in multi-layered metaverse environments (Huang et al., 2010).
- *Cross-layer and Multi-Objective Optimization:* In the Metaverse, CAVs face challenges in optimizing performance across cross-layer interactions and multi-objective trade-offs while balancing diverse objectives like security, quality of experience (QoE), and energy efficiency. Traditional game-theoretical approaches often address single-objective problems, limiting their applicability in this complex and dynamic environment (Sedjelmaci et al., 2021). Future research could explore developing models that dynamically balance multiple objectives using real-time feedback, which could improve CAV performance and the Metaverse experience within complex 6G networks.

7. Conclusion

In this survey, we provided a comprehensive review of CAVs-assisted Digital Twin synchronization in the Metaverse. We begin by introducing the researchers to the background principles of the Metaverse, and then we discuss the architecture of the Metaverse in CAVs. CAVs are a highly adaptable technology that fosters V2X communication innovation by merging contemporary technologies, smart sensors, and complicated algorithms to improve traffic efficiency and road safety. Next, we discuss with the Metaverse features, standards, tools, existing projects, CAVs difficulties with prospective optimization strategies, and cutting-edge enabling technologies for Metaverse CAVs. Furthermore, we explored the robustness of CAV security assaults and presented cutting-edge remedies based on game theory optimization techniques. Finally, we identified unresolved obstacles and offered future research topics for the development of Metaverse systems for CAVs.

CRediT authorship contribution statement

Anjum Mohd Aslam: Writing – review & editing, Writing – original draft, Resources, Formal analysis, Conceptualization. **Rajat Chaudhary:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Aditya Bhardwaj:** Writing – review & editing, Writing – original draft. **Neeraj Kumar:** Writing – review & editing. **Rajkumar Buyya:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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