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Quantifying environmental impact reductions through metaverse technologies in transportation: Metrics, Methodologies and Sustainability Outcomes

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Abstract

The metaverse has developed as a transformational digital ecosystem with far-reaching consequences for sustainability, especially in the transportation industry. This research critically examines the environmental effect reductions facilitated by metaverse technologies, focusing on key mechanisms such as virtual simulations, digital twins, remote work solutions, and logistics optimization. The findings demonstrate how these improvements help to reduce carbon emissions, minimize physical travel, and improve transportation efficiency.

The paper examines key metrics and approaches for analysing environmental effect, such as Life Cycle Assessment (LCA), carbon footprint analysis, and digital twin simulations. Despite the metaverse's potential to enhance sustainability, variations in measurement and data availability impede significance quantification. Policy and industrial consequences stress the need for regulatory frameworks that promote green digital infrastructure and responsible metaverse development.

The study also identifies limitations and risks, such as technological barriers, economic feasibility concerns, and resistance to virtual mobility adoption. Without sustainable manufacturing practices and robust e-waste recycling programs, the environmental benefits of the metaverse could be offset by increased digital infrastructure burdens. This paper concludes that while the metaverse presents a viable pathway to decarbonizing transportation, its full potential hinges on sustainable energy integration, global regulatory alignment, and further research into energy-efficient digital architectures.

Keywords: Metaverse; Environmental Sustainability; Transportation Emissions; Digital Twins; Carbon Footprint

1. Introduction

The metaverse, a network of interconnected virtual spaces, is transforming the way people interact by merging digital and physical experiences through immersive technologies such as virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) [1]. While the term was first introduced in Neal Stephenson's 1992 novel *Snow Crash*, it has since evolved beyond fiction into a rapidly expanding digital ecosystem with real-world applications across various industries, including retail, healthcare, education, and transportation [2].

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Different sectors are leveraging metaverse technologies in unique ways. In retail, virtual storefronts and AI-driven avatars enhance customer experiences, while financial institutions use blockchain for decentralized transactions in digital spaces [3]. Healthcare professionals employ virtual platforms for remote consultations and surgical training, improving accessibility and skill development. Similarly, the education sector has embraced metaverse-based learning environments to create realistic simulations that enhance practical learning [4].

The transportation industry is also tapping into the metaverse to enhance efficiency and sustainability. Virtual simulations and digital twins highly detailed virtual models of physical assets enable companies to test and optimize transportation networks without real-world disruptions [5]. Urban planners, for example, use digital twins to design infrastructure and analyse traffic flow, leading to more informed solutions [6]. Logistics firms rely on these virtual environments to simulate supply chain disruptions and refine delivery routes before making adjustments in the physical world [7].

A significant sustainability advantage of the metaverse in transportation is its ability to reduce the need for physical travel. Virtual workspaces, online conferences, and remote collaboration tools limit business-related travel, thereby cutting carbon emissions [8]. The aviation industry is integrating VR-based pilot training, reducing the frequency of fuel-intensive test flights [9]. Similarly, automobile manufacturers use virtual environments to test vehicle aerodynamics and safety features before physical production, minimizing material waste and energy consumption [10].

Despite these benefits, challenges remain. The adoption of metaverse technologies in transportation is hindered by factors including high implementation costs, the need for robust digital infrastructure, and scepticism toward virtual alternatives for traditionally physical experiences [11]. However, as the technology continues to evolve, its role in enhancing transportation efficiency and sustainability is becoming increasingly clear.

This paper critically examines how metaverse technologies contribute to reducing the environmental impact of transportation. It also explores how virtual simulations optimize transportation planning, improve operational efficiency, and support sustainable mobility solutions. In addition, real-world applications in industries such as aviation and logistics are evaluated, where companies integrate metaverse technologies to lower their environmental footprint.

As climate change concerns grow, industries must embrace innovative solutions to meet sustainability goals. The metaverse aligns with these objectives by reducing dependence on fossil-fuel-intensive travel and streamlining supply chains. Furthermore, emerging trends like AI-driven virtual workspaces, blockchain enabled logistics, and autonomous digital simulations position the metaverse as a key enabler of sustainable transportation.

2. The metaverse: an overview

The metaverse is an evolving digital ecosystem that connects physical and virtual realities, allowing users to engage in immersive, three-dimensional environments. At its foundation, the metaverse comprises three key elements: digital identity, immersive environments, and decentralized economies. Digital identity enables users to navigate virtual spaces through customizable avatars. Immersive environments, powered by VR and AR, create lifelike interactions that simulate real-world experiences [1]. Meanwhile, decentralized economies leverage blockchain technology to support digital ownership, secure transactions, and virtual commerce, allowing users to buy, sell, and trade assets within metaverse platforms [12].

The metaverse’s expansion has been shaped by industries such as gaming, social media, and enterprise applications. Early platforms like Second Life and Decentral and paved the way for interactive virtual spaces, while tech leaders like Meta, Microsoft, and NVIDIA continue to invest heavily in metaverse infrastructure [13]. Beyond entertainment, the metaverse is finding applications in diverse sectors. In healthcare, it is being used for medical training and remote consultations. In retail, brands are creating virtual storefronts for digital shopping experiences. The education sector is also embracing metaverse-based learning to enhance remote and interactive training.

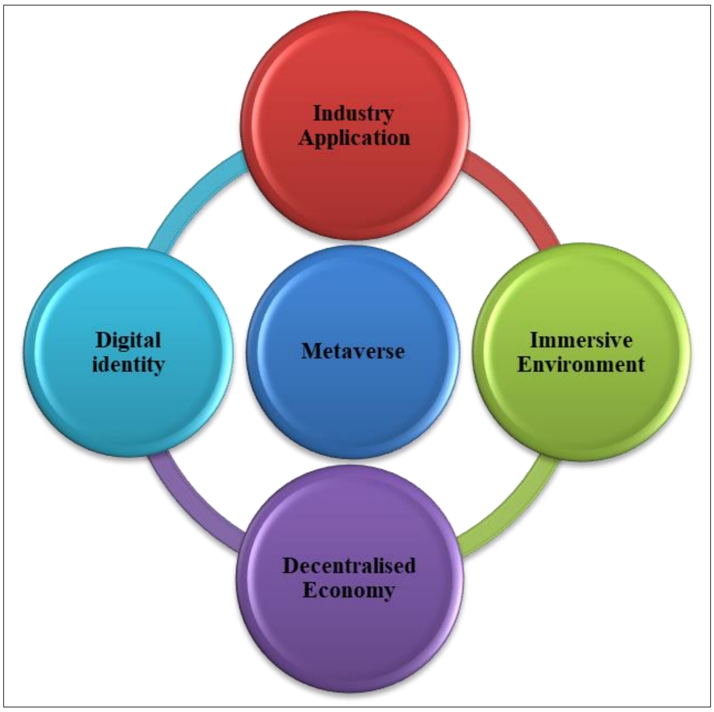

Figure 1 Metaverse Overview (Author)

2.1. Transportation and Its Environmental Impact

The transportation sector is one of the largest contributors to environmental pollution, responsible for a significant share of global carbon emissions [14]. Vehicles powered by fossil fuels release greenhouse gases (GHGs) such as carbon dioxide (CO_2) and nitrogen oxides (NO_x), which accelerate climate change and degrade air quality. Reports estimate that transportation accounts for nearly 25% of global CO_2 emissions, with road transport, aviation, and maritime activities being the primary sources [15].

Beyond its impact on climate, transportation-related pollution poses serious health risks. Poor air quality, especially in urban areas, has been linked to respiratory diseases, cardiovascular issues, and premature deaths [16, 17]. Cities with high vehicle density experience persistent congestion and smog, exacerbated by the widespread use of internal combustion engine (ICE) vehicles [18]. This not only worsens air pollution but also increases fuel consumption and energy demand.

Additionally, the sector's heavy dependence on fossil fuels strains natural resources and raises concerns over energy security, often fueling geopolitical tensions. In response, governments and industries are investing in cleaner transportation alternatives, including electric vehicles (EVs), expanded public transit systems, and smart mobility solutions [19]. However, achieving carbon neutrality in transportation remains a challenge due to infrastructure limitations, economic barriers, and societal resistance to change.

Emerging technologies such as the metaverse offer a novel approach to reducing transportation-related emissions. Through the enablement of virtual collaboration, remote operations, and digital simulations, the metaverse can help minimize the need for physical travel, presenting a new pathway toward sustainability in the transportation sector.

2.2. Metaverse in Transportation

The integration of metaverse technologies into transportation is reshaping how mobility is planned, infrastructure is optimized, and sustainability is achieved. One of the most promising applications is the use of digital twins, the virtual replicas of real-world transportation systems that enable real-time monitoring, predictive modelling, and scenario testing. Cities and transportation agencies utilize digital twins to simulate traffic patterns, optimize urban mobility, and reduce congestion without physically modifying infrastructure [20, 21, 22].

Another key application is virtual simulation for vehicle and traffic management. Transportation stakeholders test new vehicle designs, autonomous driving algorithms, and smart traffic systems within risk-free digital environments before real-world implementation [23]. Automotive manufacturers, use metaverse-driven prototypes to evaluate aerodynamics, fuel efficiency, and safety features before production, helping to minimize material waste and reduce energy consumption [24, 25].

The metaverse is also transforming remote operations and workforce training. Virtual site inspections, logistics planning, and operational training can now be conducted without extensive travel [26]. The aviation and maritime industries, have adopted VR-based simulations for pilot and crew training, significantly reducing emissions from test flights and sea trials [27].

Furthermore, the metaverse supports in the expansion of remote work and virtual conferencing has contributed in the reduction of daily commuting and frequent business travel. As more companies shift toward metaverse-based virtual workspaces, vehicular emissions and urban congestion decrease, contributing to a more sustainable transportation ecosystem.

Nevertheless, successful integration of metaverse technologies into transportation requires robust digital infrastructure, strong data security measures, and well-defined regulatory frameworks to ensure efficiency and accessibility. If these hurdles are addressed, the metaverse has the potential to revolutionize transportation sustainability, optimizing mobility, lowering emissions, and transforming the way people and goods move globally.

Figure 2 Metaverse Integration in Transportation (Author)

2.3. Environmental impact reductions through the metaverse

The metaverse is a powerful tool in reducing environmental impact across various sectors, particularly transportation. Using virtual reality (VR), augmented reality (AR), digital twins, and remote collaboration technologies, has made it possible for metaverse to reshape traditional transportation practices, cutting carbon emissions, and promoting sustainability.

2.3.1. Reduction in Physical Travel

One of the most immediate ways the metaverse mitigates environmental harm is by reducing the need for physical travel, a major contributor to carbon emissions. The transportation sector alone accounts for nearly 25% of global CO_2 emissions, with aviation and road transport being the primary culprits [15]. The metaverse enables virtual meetings, remote collaboration, and digital business environments, drastically reducing business travel and daily commuting.

The growing acceptance of remote work and virtual conferencing is already shifting corporate travel trends. Many multinational companies have reduced their carbon footprint by transitioning to digital collaboration tools, while academic conferences and international summits are increasingly conducted in virtual spaces to minimize environmental impact [28]. The COVID-19 pandemic accelerated this transition, demonstrating that a shift to digital workspaces is both viable and sustainable.

Furthermore, virtual tourism presents an eco-friendly alternative to traditional travel. Platforms offering immersive 3D travel experiences allow users to explore cultural landmarks and historical sites without the need for air travel [29].

2.3.2. Virtual Testing and Digital Twin Technology

Digital twins' virtual replicas of physical transportation systems, vehicles, and infrastructure, enable predictive analysis and optimization without resource-intensive physical testing. In the automotive industry, manufacturers use virtual environments to simulate crash tests, aerodynamics, and fuel efficiency, reducing the waste generated by traditional vehicle testing [30]. This shift significantly cuts material consumption and production-related emissions.

In urban development, digital twins assist city planners in optimizing transportation networks. Through the modelling of real-world traffic flow and testing alternative mobility solutions in a simulated environment, cities can design low-emission transport systems without the risks and costs of large-scale physical modifications [31].

The aviation industry also benefits from metaverse-driven training simulations. Airlines are increasingly using VR-based flight simulators to train pilots without requiring fuel-intensive test flights, thereby reducing emissions and operational costs [9].

2.3.3. Remote Operations and Logistics Optimization

The metaverse facilitates remote operations and logistics management, reducing unnecessary travel and fuel consumption. Supply chain optimization has become more efficient with AI-powered virtual dashboards that enable companies to track fleet movements, optimize delivery routes, and predict disruptions in real-time [7].

Ports and warehouses are also integrating VR and AR technologies to remotely monitor cargo operations, reducing the need for on-site personnel and improving operational efficiency.

2.3.4. Sustainable Urban Development

As cities seek eco-friendly transport solutions, metaverse technologies provide a digital testing ground for policy development. Virtual urban planning tools allow governments to simulate the impact of public transport expansion, congestion pricing, and pedestrianization projects before implementing them in real life [22].

Furthermore, smart city initiatives increasingly rely on the metaverse to design and refine energy-efficient infrastructure through renewable energy integration, sustainable public transit, and optimized road networks in virtual environments [32].

2.3.5. Reducing the Environmental Cost of Manufacturing

The metaverse is reshaping industrial production by digitizing the product design and testing phases, significantly cutting material waste and energy consumption. In automotive, aerospace, and manufacturing sectors, virtual prototyping replaces physical trial-and-error production, reducing raw material usage and industrial waste [24].

3. Case studies

These case studies illustrate how virtual simulations, digital twins, and augmented reality (AR) are transforming industries:

3.1. A. BMW's Virtual Vehicle Testing

BMW has embraced digital twin technology to revolutionize its vehicle production processes by creating comprehensive virtual models of their manufacturing plants and assembly lines, BMW simulate and optimize operations before implementing them physically. This approach has been applied in their Regensburg plant, where "3D human simulation" allows for the virtual planning of assembly processes. Future factory layouts is explored using VR goggles, enabling the company to refine workflows and ergonomics without constructing physical prototypes [33, 34]. This strategy not only reduces material waste but also enhances energy efficiency, contributing to a smaller environmental footprint.

3.2. B. DHL's Augmented Reality in Logistics

DHL has integrated AR into its warehouse operations to boost efficiency and reduce emissions. In a pilot project conducted in the Netherlands, warehouse staff utilized smart glasses equipped with AR software to facilitate the picking process. The glasses displayed digital picking lists and optimal routes, enabling employees to navigate the warehouse more effectively. This “vision picking” system led to a 25% increase in efficiency during the picking process [35]. Through this, DHL has reduced the need for additional labour and resources, subsequently lowering travel-related emissions and fuel consumption associated with logistics.

3.3. C. Airbus's Virtual Pilot Training

Airbus has adopted VR-based flight simulators to enhance pilot training programs. Pilots can undergo comprehensive training in a virtual environment that accurately replicates real-flight scenarios. This method reduces the necessity for traditional in-flight training sessions, thereby decreasing fuel consumption and associated carbon emissions [36]. The virtual training ensures that pilots achieve high safety and performance standards while contributing to the company's sustainability goals.

3.4. D. Singapore's Virtual Urban Planning

Singapore has been a pioneer in employing digital twin technology for urban planning and transportation management. The city-state has developed detailed virtual models that simulate various aspects of urban infrastructure, including traffic flow and public transportation systems. Planners can identify potential congestion points and optimize routes without making physical changes [37]. This allows for the development of efficient, low-emission transport networks, reducing reliance on high-emission infrastructure and contributing to the city's sustainability objectives.

4. Metrics and methodologies for quantifying environmental impact

Table 1 Metrics for Quantifying Environmental Impacts

S/N	Metric	Description	Metric Unit
1	Carbon Emissions Reduction	Measures the reduction in greenhouse gas emissions, specifically CO2, from avoided travel and transportation-related activities.	MTCO2e (metric tons of CO2 equivalent)
2	Energy Consumption and Efficiency	Assesses the total energy usage (in kWh) for metaverse operations, primarily driven by data centres and computational power, and evaluates energy efficiency.	kWh (kilowatt-hours)
3	Virtualization and Material Resource Savings	Quantifies the reduction in material use and waste, such as raw materials, fuel, and the need for physical prototypes in industries like automotive and aerospace.	kg or metric tons (material reduction), tons (waste reduction)
4	Reduction in Commuting and Business Travel	Tracks the reduction in fossil fuel-based transport through metrics like Vehicle Miles Travelled (VMT) reduction, fuel savings, and decreased public transport usage.	VMT (Vehicle Miles Travelled), Liters/Gallons (Fuel Savings), Public Transport Usage (% reduction)
5	Digital Infrastructure Footprint	Assesses the environmental impact of data centers and cloud services supporting the metaverse through metrics like Data Centre Energy Efficiency (PUE), carbon intensity, and server utilization efficiency.	PUE (Power Usage Effectiveness), gCOâ,,/kWh (Carbon Intensity), % (Server Utilization Efficiency)
6	Impact on Air Quality and Urban Congestion	Measures improvements in air quality and reductions in urban congestion due to decreased vehicle emissions and fewer vehicles on the road.	AQI (Air Quality Index), % (Reduction in Congestion)

4.1. Methodologies for Impact Assessment

Assessing the environmental impact of metaverse technologies in transportation requires structured methodologies that can measure sustainability outcomes accurately. Various frameworks provide robust tools for evaluating both the ecological benefits and potential drawbacks of integrating the metaverse into transportation systems. These methodologies not only quantify environmental effects but also help to identify areas for improvement and further innovation.

One of the most comprehensive tools used to evaluate the full environmental impact of any technology is Life Cycle Assessment (LCA). LCA is a framework that assesses the environmental impact of a product, service, or technology across its entire lifecycle, from raw material extraction to end-of-life management [38]. For metaverse technologies, LCA begins with evaluating raw material extraction, which involves considering the resources required for hardware like VR headsets and servers. The production and manufacturing phase focuses on measuring the emissions associated with developing these technologies, including hardware and software. The usage phase compares the energy consumption of metaverse applications against traditional transportation activities, such as business travel or vehicle use. Lastly, end-of-life management assesses the disposal of electronic waste (e-waste) and the potential for recycling metaverse infrastructure.

Another crucial methodology for assessing the environmental impact of metaverse technologies is carbon foot printing [39]. This method quantifies the total greenhouse gas emissions associated with a specific activity, organization, or product. In metaverse applications in transportation, carbon foot printing involves measuring direct emissions, which refers to emissions resulting from energy use in VR infrastructure and cloud computing. Additionally, it includes indirect emissions, which are the emissions avoided by substituting traditional activities like business travel with virtual alternatives. A comparative analysis of traditional transportation emissions versus the emissions reductions enabled by metaverse technologies can provide a clear picture of net environmental benefits over time.

The integration of digital twin technology, a very good methodology for impact assessment, has also become an essential tool in transportation sustainability. Digital twins are virtual models that simulate real-world transportation systems, allowing for real-time monitoring and forecasting. Through the use of real-world data, these simulations help identify optimal sustainability scenarios for instance, determining how much emissions reduction can be achieved through the widespread adoption of remote work. Digital twins also play a key role in optimizing traffic management and public transportation systems, minimizing congestion, and reducing pollution. Moreover, these simulations assess energy efficiency improvements in emerging technologies such as autonomous and electric vehicles driven by AI-based decision-making, further promoting energy-efficient solutions.

Finally, the Environmental Impact Ratio (EIR) is an important means that helps assess the overall sustainability of metaverse infrastructure [40]. The EIR compares the energy consumption of the metaverse against the sustainability benefits it provides. The EIR gives details into the efficiency of these technologies by quantifying whether the reductions in transportation emissions achieved through the metaverse outweigh its digital footprint, and helps identify areas for optimization.

4.2. Challenges in Measuring Impact

Although, the metaverse holds great potential in reducing transportation-related emissions, accurately measuring its environmental impact presents several challenges. These challenges stem from the broad nature of digital technologies and the lack of standardized frameworks for assessment.

One of the primary difficulties in assessing the metaverse's environmental benefits is the lack of standardized measurement frameworks [5]. Unlike traditional industries that rely on well-established sustainability metrics, the metaverse operates within dynamic and decentralized ecosystems. The absence of a universal methodology makes it difficult to apply consistent assessment criteria across various metaverse platforms and applications. Without a clear and unified approach, it becomes challenging to accurately measure and compare the environmental impact of different digital technologies.

Another significant challenge is the high energy demand associated with the infrastructure supporting metaverse technologies [41]. While virtual applications reduce transportation emissions by substituting physical travel with digital alternatives, the underlying infrastructure is energy-intensive. Cloud computing, AI processing, and blockchain transactions, essential components of the metaverse, require substantial computational power. If these systems are powered by fossil-fuel-heavy electricity grids, the sustainability benefits could be partially negated, as the emissions from energy consumption could offset the reductions in travel-related carbon output.

Furthermore, data availability and accuracy pose issues in quantifying the impact of the metaverse on transportation emissions. To measure the reductions in travel-related emissions effectively, reliable tracking systems are necessary [42]. However, many businesses and individuals do not report detailed travel data, which makes it difficult to assess the exact environmental reductions attributable to metaverse adoption. Without accurate and comprehensive data on travel behaviour, it's challenging to determine whether virtual alternatives are truly reducing emissions or if the reduction is negligible.

The implementation of metaverse technologies also faces technological and economic barriers. To adopt these technologies at scale, significant capital investment is required [43]. The high cost of infrastructure and technology development may be a barrier for many companies, particularly small and medium-sized enterprises (SMEs). Additionally, inequalities in internet accessibility and computational power across regions create disparities in who can benefit from the sustainability advantages of the metaverse. Those in areas with limited access to high-speed internet or advanced computing resources may be excluded from the full potential of metaverse technologies, exacerbating existing digital divides.

Finally, e-waste and hardware sustainability concerns present a long-term challenge for the metaverse. As VR headsets, AR devices, and other metaverse-related hardware become more widespread, the environmental impact of their lifecycle must be considered [44]. Without effective e-waste recycling programs, the rapid growth of metaverse infrastructure could lead to an increase in electronic waste. The environmental burden of discarded hardware, if not properly managed, may outweigh the emissions reductions achieved through reduced transportation.

5. Sustainability outcomes and future prospects

The integration of metaverse technologies into transportation presents both short-term and long-term sustainability outcomes. In the short term, virtual meetings, remote workspaces, and digital twin simulations can significantly reduce the carbon footprint associated with business travel and daily commuting. Replacing face-to-face meetings with virtual alternatives, will help reduce the need for frequent air travel and car journeys, leading to substantial cuts in fossil fuel consumption and carbon emissions. Moreover, the ability to host virtual conferences reduces the demand for large-scale, energy-intensive physical events, further contributing to sustainability.

The long-term sustainability outcomes of the metaverse are even more transformative. Virtual infrastructure for transportation planning can lead to optimized traffic management, which not only reduces congestion but also cuts emissions. With the help of digital twins, cities and transportation systems can monitor real-time data and predict urban mobility patterns, making it possible to design greener transportation systems.

Furthermore, the metaverse can play a pivotal role in promoting the adoption of autonomous and electric vehicles through virtual training programs. Companies can train drivers and engineers in handling autonomous systems and maintenance of electric vehicles, by providing platforms for virtual simulations, accelerating the decarbonization efforts in the mobility sector.

5.1. Policy and Industry Implications

Government policies and corporate strategies will play a crucial role in fostering the adoption of metaverse technologies for environmental sustainability. Policymakers can incentivize businesses to adopt virtual alternatives for transportation by offering tax benefits for adopting remote work or by supporting investments in digital infrastructure. Additionally, governments can introduce regulations to ensure that the metaverse's data centres and virtual platforms adhere to strict energy efficiency standards. Policies focused on encouraging green metaverse initiatives could ensure that the technology develops in a way that aligns with global sustainability goals.

For widespread adoption of metaverse-driven sustainability in transportation, however, standardization is necessary. Governments and industry leaders need to work together to establish clear protocols for metaverse-based transportation applications. Ensuring security, accessibility, and interoperability across various platforms will be essential for the success and scalability of the technology.

6. Conclusion

The integration of metaverse technologies into transportation presents transformative opportunities for enhancing environmental sustainability. This study highlights the significant environmental benefits associated with virtual alternatives to traditional modes of transport. The metaverse plays a key role in substantially cutting carbon emissions, especially with the rise of virtual meetings, remote workspaces, and digital simulations that replace fuel-intensive business travel. These virtual alternatives lead to lower fuel consumption and air pollution, offering a cleaner, more efficient way to conduct everyday activities.

The adoption of digital twins has proven to be another pivotal tool, improving logistics efficiency, enhancing urban planning, and helping to reduce traffic congestion. Metaverse makes it possible to optimize transportation systems, further contributing to lower energy consumption and more sustainable mobility solutions. These innovations are in line with global decarbonization goals, reducing reliance on traditional, fossil-fuel-driven transportation systems.

Virtual prototyping, remote pilot training, and AI-powered simulations are transforming these industries by making operations more efficient and environmentally friendly. Through such advancements, the metaverse is helping promote sustainable mobility solutions that align with the broader objective of global decarbonization.

However, there are challenges to overcome. The high energy demands of metaverse infrastructure, particularly from data centres, remain a concern. These data centres, which support virtual environments and blockchain operations, consume large amounts of energy. Regulatory concerns regarding data security and privacy also present obstacles, as does the high cost of VR hardware and limited access to high-speed internet in certain regions. These technological barriers could slow down the widespread adoption of the metaverse, especially in developing nations.

Additionally, there is societal resistance to the digital transformation in transportation, which requires careful and gradual adoption strategies. It will be important to design user engagement initiatives that foster trust and encourage wider acceptance of the metaverse as a sustainable alternative to traditional transportation.

The metaverse holds immense potential in reshaping the transportation landscape by minimizing environmental footprints and promoting efficiency. However, realizing its full potential requires addressing the existing challenges to ensure that its benefits outweigh its drawbacks. Policymakers must enforce clear sustainability standards for the data centres powering the metaverse and encourage the shift to renewable energy sources. Investments in green cloud computing and low-power AI models should also be prioritized to mitigate the carbon footprint of digital infrastructure.

To ensure the successful integration of the metaverse in transportation, businesses must focus on interoperability and standardization. Metaverse applications across transportation networks must seamlessly integrate with existing smart city initiatives. Collaboration between technology providers, regulatory bodies, and transportation stakeholders will be critical to developing a secure, accessible, and energy-efficient metaverse ecosystem. Raising public awareness about the long-term environmental benefits of metaverse adoption can also encourage behavioural shifts and wider acceptance of virtual mobility.

Future research should explore scalable and energy-efficient metaverse architectures, particularly focusing on how AI and blockchain technologies can optimize data usage without excessive energy demands. Additionally, further studies should analyse regional differences in metaverse adoption, identifying strategies to bridge the digital access gaps between developed and developing nations. Also, continued monitoring and adaptation of policies, based on real-time environmental impact assessments, will be essential to ensuring the long-term success of the metaverse in reducing transportation-related emissions. In conclusion, while challenges exist, the metaverse has the potential to revolutionize environmental sustainability in transportation.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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