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Analyzing Trends and Framework Models for Autonomous Vehicle Transition Strategies

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ABSTRACT The shift from traditional human-driven to autonomous vehicles represents a transformation that is not merely technological, but also social. Currently, the deployment of autonomous vehicles remains largely at level where the human driver continues to be the primary decisionmaker. However, this dynamic is expected to change significantly as higher levels of autonomy are achieved. This study aims to identify the impacts that occur during process transition through emerging trends and theoretical lens of transition studies. The initial stage involved mapping trends in Autonomous Vehicle (AV) research to identify key related topics. This study uses bibliometric analysis of 82 key articles selected through a screening process in a systematic review. VOSviewer and CiteSpace were employed to map the research landscape, identify dominant topics, and trace the evolution of AV studies over time. The analysis highlights both well-established research areas and underexplored gaps. Furthermore, the articles were classified into categories based on transition study dimensions and key actors involedinvolved in facilitating a successful transition. The findings reveal a dominant research focus on users, human factors, and mobility behavior, whereas studies concerning vulnerable road users and the industry transition remain limited. To address this gap, this study investigates the socio-technical factors arising from the identified trends and transition studies while also exploring the roles of key stakeholders. This approach aims to achieve a more balanced perspective. Specifically, the study proposes a novel framework that connects critical actors with core socio-technical dimensions to support a sustainable autonomous vehicle transition. This research thus provides a strategic framework designed to guide and accelerate the shift toward autonomous mobility.

KEYWORDS Autonomous vehicle; Transitions; Bibliometric.

1 INTRODUCTION

Autonomous Vehicles (AVs) are emerging as a groundbreaking technological innovation in the realm of mobility, with the potential to address global concerns such as safety improvement and the escalating demand for mobility (Moradi and Vagnoni, 2018). Human error remains the main cause of accidents, with contributing factors such as drowsiness, fatigue, drunk driving or misjudgments. AVs are designed with proactive safety systems that continuously monitor the vehicle's surroundings and can respond to potential hazards in real-time to reduce human error (Combs et al., 2019).

The transition from conventional vehicles to AVs represents a transformative breakthrough in the field of transportation and also affects how the transportation system operates today. According to the Society of Automotive Engineers (SAE), AVs are classified into six levels, from no automation to full automation. Most new cars on the market today feature only Level 2 automated driving systems, where human drivers are still responsible for controlling the vehicles (World Economic Forum, 2025). The SAE classifies Advanced Driver Assistance Systems (ADAS) features within level 2 vehicle automation. In the Indonesian market, the most advanced vehicles available currently offer ADAS as a driver support system (CNN Indonesia, 2021).

However, control shifts from human to machine as the automation level increases. Progressing toward the widespread adoption of AVs requires detailed preparation. It involves a complex interplay of societal, technological, and governmental factors, where diverse perspectives converge and interact (Jiang et al., 2023). It is imperative to address these gaps to develop a well-informed approach for the seamless integration of AVs into transportation systems, especially in developing countries with their complexity and challenging circumstances. Thus, this study aims to understand the emerging trends related to AV research within the societal implications of technological change in AVs in order to achieve a successful transition.

In transition studies, sustainable transition represents a complex evolutionary reconfiguration process (Marx et al., 2015). This transition is propelled by the convergence of cutting-edge technologies, safety imperatives, environmental considerations, urban planning and infrastructure adjustments, legal and regulatory complexities, and profound economic ramifications (Schrauth et al., 2021; Shetty et al., 2021).

Transition studies are often used to understand the pathways and mechanisms of change within socio-technical systems (Geels, 2005, 2010). However, this concept has weaknesses, since it does not emphasize the role of actors and power dynamics in shaping the transition. This gap reduces the practical impact of transition theories in real-world settings where stakeholders such as policymakers, industry leaders, and researchers participate.

In order to understand the societal impact of AV technology, AVs require further investigation to examine factors of the transportation regime such as human factors and behavior, mobility behaviour, mobility infrastructure, safety, regulations, and industry (Huang, 2023; Nemoto et al., 2023; Hawxwell et al., 2024). Currently, research on AVs that focuses on human and mobility behaviour remains a widely discussed topic. For example, frequently examined topics include user acceptance of AVs (Greifenstein, 2024; Jin et al., 2026) and driver perception (Guan et al., 2024). However, indirect users such as pedestrians and motorcyclists can also influence AV acceptance and this area has not yet been widely explored (Tang et al., 2025). This could become a barrier when AVs operate in mixed traffic environments, where interaction with various road users is inevitable.

From a technical standpoint, cybersecurity issues (Prasetio and Nurliyana, 2023) and supporting infrastructure (Rana and Hossain, 2023) are also critical discussions for ensuring AVs can operate safely and effectively. Another relevant issue is regulation which serves as a legal framework to ensure public safety and accountability (Rowe et al., 2023). Data protection and liability remain hot topics of discussion as well, especially in relation to accidents involving AVs.

Despite identifying key factors impacting the transition to AVs, it is also necessary to develop a broader understanding of the stakeholders involved. Previous studies emphasize the necessity to explore the roles of various stakeholders and collaboration among them in designing effective policies and ensuring the successful transition to AVs (Greifenstein, 2024; Hadid et al., 2025). In practice, AV implementation requires the participation of multi-level actors to define policy priorities and implementation strategies. Central actors such as government or regulators play a crucial role in supporting the AV transition strategy (Schepis et al., 2023). They often act as catalysts for the transition and influence niche actors, including users, researchers, and industry players (Geels, 2012; Emory et al., 2022).

This presents a gap that can be further explored: how factors within the socio-technical system and the roles of stakeholders can contribute to a successful AV transition. At present, research remains limited regarding the role of actors in shaping AV implementation and how their influence affects the transition toward sustainable transportation. Therefore, this study also seeks to develop a framework to address this gap by connecting the role of AV actors with socio-technical factors to support the goals of a sustainable AV transition.

This paper is structured as follows. Section 2 outlines the research methodology. Section 3 presents a summary of the findings from the reviewed literature. The discussion of these findings and the proposed framework are addressed in Section 4. Finally, Section 5 provides the conclusion and suggests directions for future research.

2 METHODS

This study explored publication data sourced from the Scopus database. It used specific keywords and focus areas specified in Table 1 to capture emerging trends in AV research. Bibliometric analysis was performed with VOSviewer and CiteSpace.

The search keywords were developed using a theory-driven approach and refined through multiple iterations. Initially, the first keyword set focused on the core technology, autonomous vehicles. However, an initial evaluation of the search results revealed significant noise that captured technologies outside the study's scope. Consequently, the list of terms was expanded to include relevant synonyms commonly found in the literature, such as self-driving cars and automated vehicles.

Then, a second set of keywords was formulated based on the theoretical framework of transition studies. As the foundational concept, transition is used to analyze how systemic change occurs. Meanwhile, innovation and adoption are explicitly integrated to establish an analytical link between technological development and market adoption. This approach enriches the analysis of socio-technical interdependencies throughout the transition process.

In addition, Figure 1 shows the multi-step methodology, following a systematic and structured approach using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Following article identification, the screening phase applied exclusion criteria to filter out irrelevant papers. This process removed duplicates, irrelevant documents (e.g., book chapters and conference proceedings), and excluded studies misaligned with the research topic and aims, resulting in 82 eligible articles.

Table 1. Keywords and focus areas for emerging trends

Keywords	Articles	Section	Focus
"autonomous vehicle" OR "autonomous car" OR "self-driving vehicle" OR "self-driving car" OR "driverless vehicle" OR "driverless car" OR "automated vehicle" OR "automated car"	65,959	AV documents by year	Trends in AV-related publications
		Key Leading Countries for AV Studies	Countries leading AV research
("autonomous vehicle" OR "autonomous car" OR "self-driving vehicle" OR "self-driving car" OR "driverless vehicle" OR "driverless car" OR "automated vehicle" OR "automated car") AND (transition OR innovation OR adoption)	2,295	Top Journals in AV Transition Studies	Journals focused on AV adoption and transition
		Topic Mapping in AV Transition Studies	Mapping AV adoption and transition topics
		Timeline Evolution	Track how research areas have developed over time
		Transition Studies	Show the most prevalent theories

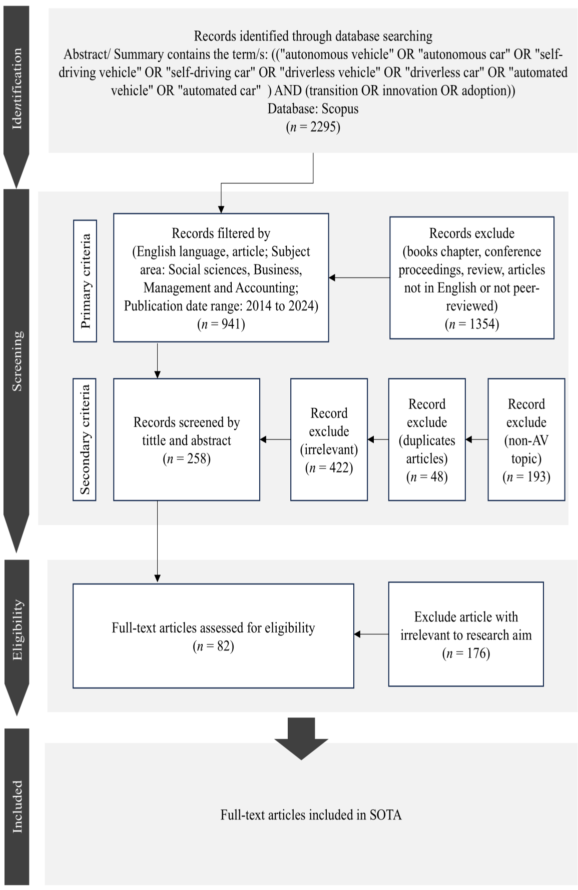

Figure 1. PRISMA steps.

Next, the 82 articles were coded by thoroughly analyzing each article and reviewing its entire content. The study identified and recorded factors influencing the AV transition, the theoretical frameworks applied, and stakeholders relevant to AV transition. After the final coding process, the frequency of each category was aggregated based on the number of articles addressing the related topic. The percentage for each category was obtained by calculating the proportion of papers discussing that category relative to the total number of articles in the research corpus. Appendix 1 presents a summary of the studies relevant to this research.

3 RESULTS

This section presents three key results. The first result highlights emerging trends in AV transition research, including publication patterns, leading contributors, thematic developments in AV topics, and timeline analysis. The second result identifies the stakeholders involved in the transition, while the third result presents critical influencing factors such as human and mobility behavior, infrastructure, safety, policy, and industry during transition.

3.1 Emerging trend for AV transition study

3.1.1 AV Documents by year

Figure 2 illustrates a clear upward trend in publications related to AVs across different subject areas from 2004 to 2024. Over this period, researchers have published 65,959 documents, with minimal activity observed in the early years. The early years (2004-2013) saw relatively few publications. However, from 2014 onward, there is a marked increase in research output. The number of publications began to rise exponentially in 2016. The peak of nearly 10,000 publications between 2022 and 2023 suggests that AV research has reached a critical mass. By 2024, the cumulative number of publications surpassed 60,000. The substantial increase in AV-related publications reflects the expanding interest in this area.

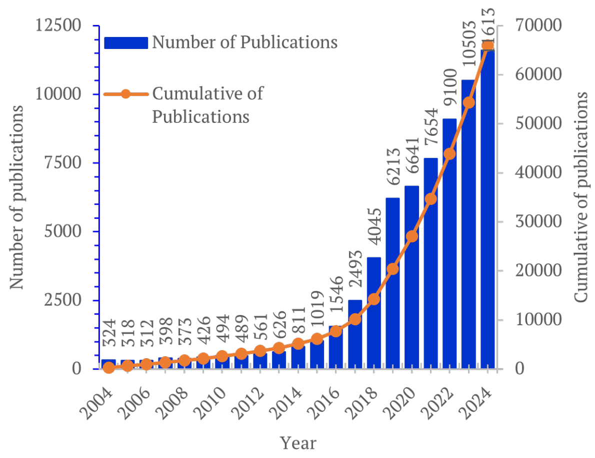

Figure 2. Publication about AV.

3.1.2 Key leading countries in AV studies

Figure 3 illustrates the global distribution of countries with research publications related to AV. The distribution of countries involved in AV studies is dominated by developed countries. As shown in Figure 4, the top ten most productive countries in AV studies are dominated by China and the US, which are the clear leaders, with each country contributing over 12,000 publications.

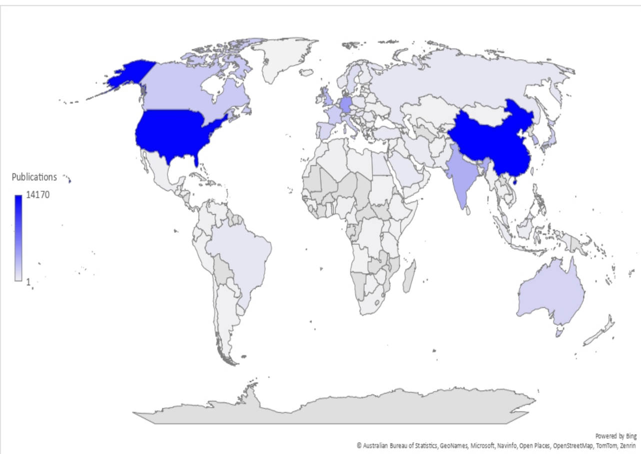

Figure 3. Global distribution of AV publications.

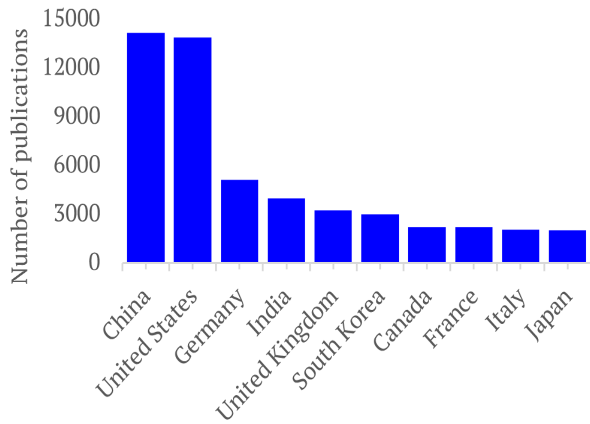

Figure 4. The most productive countries in AV research output.

3.1.3 Top journals in AV transitions studies

Figure 5 highlights the dominance of journals studying AVs in transport research. The result shows the dominant fields (e.g., engineering, social science) within AV studies and identifies the gaps where perspectives are underrepresented. In addition, the interconnectedness of each journal with others also reflects the multidisciplinary nature of AV studies. Figure 6 presents recent research trends that have been actively cited from 2021 to 2024.

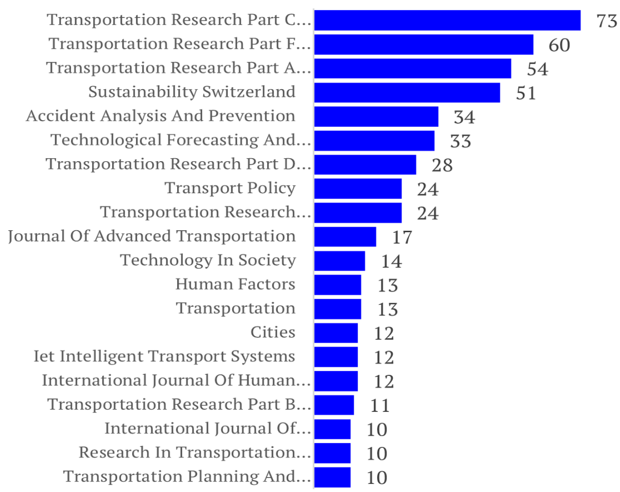

Figure 5. Top 20 Journals on AV Research.

3.1.4 Topic Mapping in AV transition studies

Figure 7 illustrates topic mapping based on text analysis using VOSviewer. VOSviewer analyses the text found in titles, abstracts, keywords, or the content of research documents, rather than relying on keywords specifically designated by the authors. The use of text analysis allows us to identify emerging themes from

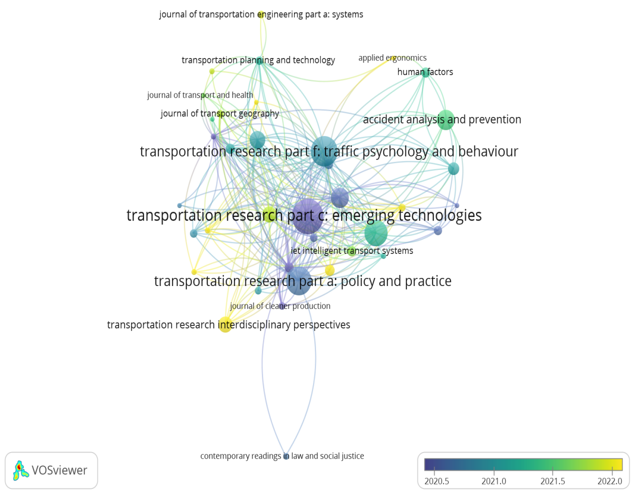

Figure 6. Network of Key Journals in AV.

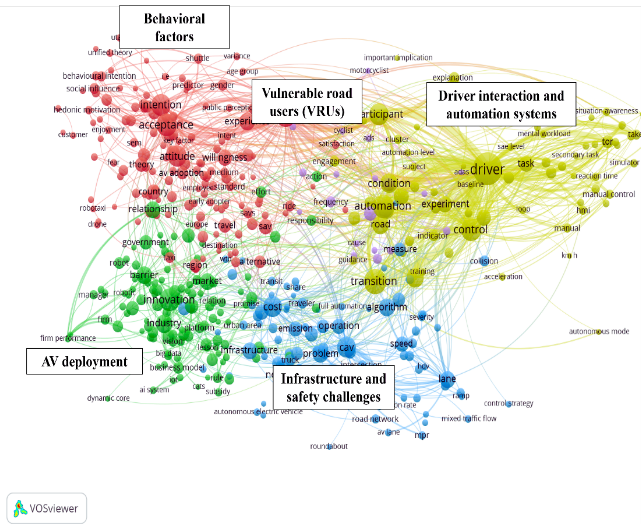

Figure 7. Text analysis for topic mapping in AV transition.

the text without being constrained by predefined keywords. Key parameters for network construction included a minimum term occurrence threshold of 5 and the selection of the 60% most relevant terms based on the software's relevance metric. The network was generated using a full counting method and clustered via modularity-based algorithm. In the resulting maps, node size corresponds to term occurrence weight, and inter-node proximity reflects associative strength.

The topic of user acceptance and behavioral factors is highlighted in the red cluster, with key terms such as trust, acceptance, attitude, intention and willingness. The cluster focuses on the psychological and social dimensions of AV adoption. Thus, this cluster offers insights into how these factors can be managed to increase adoption rates.

The second topic is about AV deployment within the green cluster. Key terms such as innovation, industry, barrier, government and market suggest that researchers are examining the challenges industries face in bringing AV technologies to market and the influence of government policies on AV implementation.

The yellow cluster emphasizes the third topic, with a driver interaction and automation systems theme. Driver, automation, control, simulator and task appear as key terms within this topic. This topic shows the challenges drivers face when transitioning between manual and automated driving by using experimental studies that can mimic real conditions.

Additionally, the blue cluster presents a topic on infrastructure and safety challenges. Key terms such as infrastructure, lane, network and safety reflect the technical challenges when integrating AVs into existing transportation systems. This cluster also explores how AVs interact with road networks, as well as safety considerations.

Last, Vulnerable Road Users (VRUs) form another topic, highlighted in the purple cluster. This cluster is heavily concerned with experimental studies that examine the effects of automation under controlled conditions. Experiment, pedestrians and motorcyclists indicate that research in this area explores how AV systems interact with vulnerable road users. This cluster focuses on user engagement and the effectiveness of different automation levels in maintaining safety and ensuring seamless interactions between AVs and other road users.

Based on topic mapping, AV research is not only about developing the technology itself but also about understanding how it can be integrated into society and existing systems. In addition, the coverage area of research on the topics of AV deployment and VRU is still very limited, so there is still room to explore these topics.

3.1.5 Timeline Analysis

Figure 8 shows the evolution in AV research themes over the past two decades. The timeline visualization captures key topics, their evolution, and interconnections of AV research. Timeline analysis appears to be a visualization using CiteSpace (Chen et al., 2012; Chen, 2017).

The time axis illustrates the chronological development of research. Earlier research topics are positioned on the left and more recent ones on the right. The nodes represent key topics. Larger and darker nodes (such as automation and autonomous vehicles) indicate highly influential or frequently studied topics, while smaller nodes represent emerging or less frequently explored areas. The links between nodes signify relationships, such as co-citation or co-occurrence

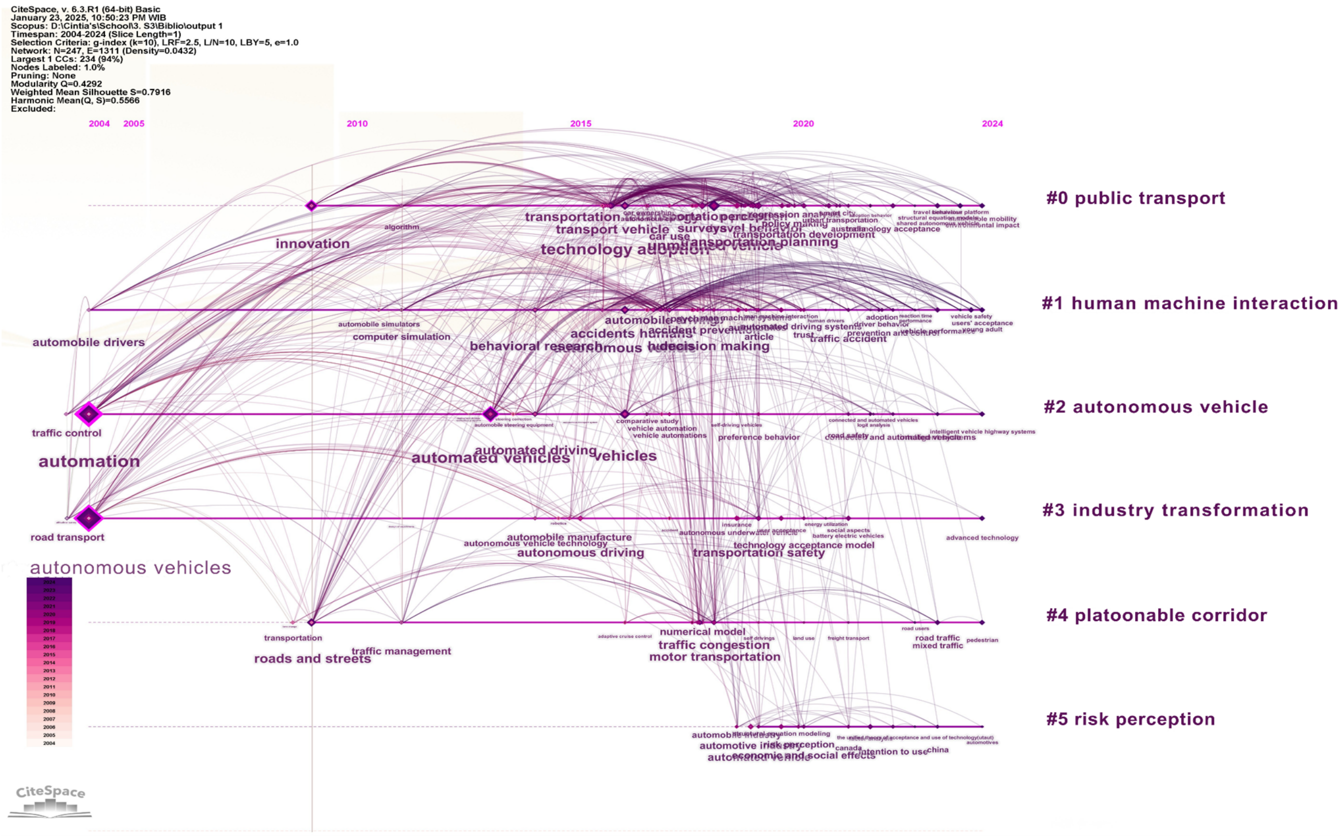

Figure 8. Timeline analysis.

of topics. Thicker links indicate higher relevance between topics and reflect their collaborative impact.

Clusters, identified through modularity, highlight major research focuses, such as public transport, human factors, autonomous vehicles, industry transformation, platoonable corridors, and risk perception. These clusters group related topics to provide insights into thematic areas of study over time. The color gradient of nodes and links visualizes the temporal relevance of topics. Darker colors (purple) indicate earlier years, and lighter colors (pink) represent recent studies. This gradient shows the emergence and evolution of research trends and reveals how certain topics gained or lost prominence over time.

In the early years (2004-2010), research predominantly focused on foundational topics such as automation, road transport, and safety technology. These studies captured the development of core systems and traffic control mechanisms necessary for innovation.

Research themes expanded between 2011 and 2020. Early in this period, studies focused on the initial stages of vehicle automation with the introduction of features like adaptive cruise control. Then, it continuously progressed over time towards self-driving cars and higher levels of autonomy. Mid-period studies highlighted the importance of user interaction, decision-making, and public transportation applications. Topics such as behavioral research, human factors, trust, and safety became key focuses. Additionally, this period also saw mode shifts, such as public autonomous buses and shared autonomous vehicles, reflecting the increasing focus on integrating AV technology into existing transportation frameworks.

In recent years (2021-2024), AV research has shifted toward advanced technological and societal integration. Topics such as machine learning, intelligent systems, and sustainable mobility indicate the field's growing readiness for real-world implementation. Research also increasingly focuses on addressing risk perception, user and pedestrian acceptance, and environmental impact. Moreover, studies on simulation platforms, advanced driving systems, and energy-efficient solutions highlight the importance of scalability, efficiency, and long-term investment in AV systems.

The timeline analysis highlights critical factors to understanding AV transitions, including the role of policy, public trust, infrastructure readiness, and technological maturity. As AV systems move closer to large-scale deployment, these insights can serve as a roadmap for identifying barriers and opportunities in the transition process.

3.1.6 Transition studies

Among the studies (Table 2), the Multi-Level Perspective (MLP) emerged as the dominant framework (27%). This reflects its utility in analyzing socio-technical transitions across niches, regimes, and landscapes. Technology Innovation Systems (TIS) (5%) and governance models (2%) also emerged as complementary frameworks for transition strategies. Meanwhile, integrated frameworks (e.g., MLP + Stakeholder Theory or TAM) appear sporadically (1% each). This reflects a tendency to view AV adoption as a socio-technical transition.

Table 2. Study proportion of theoretical framework

Theoretical Framework	Count	Percentage
Not Defined	38	46%
MLP	22	27%
TIS	4	5%
Governance frameworks	2	2%
SNA	2	2%
Innovation System	1	1%
MLP + Stakeholder Theory	1	1%
MLP and Socio-psychological	1	1%
MLP and TAM	1	1%
MLP Transition pathways	1	1%
Regional Innovation System	1	1%
Safety improvement	1	1%
Social Network Analysis and TIS	1	1%
Social attitudes, technological innovation and urban politics	1	1%
Sustainability transition	1	1%
System theory	1	1%
Technological innovation	1	1%
Transition management	1	1%
UTAUT	1	1%

Furthermore, there is potential for interdisciplinary study since research integrating MLP with other theories remains limited. The results also show that 46% of studies on AV adoption lack a defined theoretical framework.

3.2 Stakeholders involved in AV Transition

This study revealed that the transition to AVs involves a complex ecosystem of stakeholders whose interactions and decisions critically shape transition studies, as shown in Table 3.

Table 3. Study proportion for participatory

Participatory	Count	Percentage
User	61	74%
Vulnerable road user	2	2%
Manufacturing	38	46%
Regulator	49	60%
Other transport provider (e.g. public transit operators, tech companies)	23	28%
Researcher	40	49%

Public users and drivers represent the primary interface with AV technology, and their opinions and experiences provide essential feedback for its development and integration (Axsen and Sovacool, 2019; Curtale et al., 2022). Although findings indicate that existing studies are still heavily focused on the user perspective, the successful transition to an AV ecosystem is not driven by a single entity, but rather by the network and roles of all involved actors.

VRUs are also among the most affected participants in this ecosystem. However, research focusing on their perspective remains limited. This gap is significant, as VRUs provide a critical perspective on safety and social acceptance, as their behaviors and perceptions fundamentally test the real-world integration of autonomous technology (Fitt et al., 2019).

On the supply side, manufacturers and transport/ technology providers act as innovation and integration drivers by developing core technologies and new mobility offerings. They are responsible for developing AVs into safe, reliable, and market-ready products (Lang and Mohnen, 2019; Hess, 2020). Regulators function as guardians of legal frameworks and public safety, serving as a crucial bridge between rapid technological advancement and public welfare, while also acting as policymakers to ensure successful AV adoption (Shammut et al., 2022; Schippl, 2024; Shammut and Imran, 2024). Last, researchers provide the essential scientific foundation and ethical analysis for a responsible and sustainable societal transition (Li et al., 2019).

3.3 Factors influencing transition to AVs

Table 4 reveals a strong focus on the regime level in AV transition studies. Within the regime, human factor behavior (56%) and mobility behavior (52%) dominate research, reflecting the critical role of user adaptation and travel patterns in AV integration. Mobility infrastructure (38%), traffic and safety (28%), and regulation and policy (34%) are moderately studied. Notably, industry (10%) is the least examined.

Table 4. Study proportion for AV transport regime

Regime for transport	Count	Percentage
Human factor behavior	46	56%
Mobility behavior	43	52%
Mobility Infrastructure	31	38%
Traffic and Safety	23	28%
Regulation and Policy	28	34%
Industry	8	10%

3.3.1 Human factor behavior

The successful integration of AVs into transportation systems critically depends on human factor behavior, which encompasses psychological and behavioral responses to AV technology. The findings reveal that the transition to AVs impacts significant human-factor behavior, as summarized in Table 5.

From the user perspective, AV acceptance is often driven by perceived safety benefits, with studies indicating expectations of reduced accidents and improved road safety (Deb et al., 2017). AV acceptance is influenced by perception, attitude and behavioral intention. Trust emerges as the primary barrier, characterized by anxieties over safety, fear of system failures, and serious concerns over data privacy and security. AV adoption requires significant behavioral shifts from the driver's perspective as well, including transitioning from active control to supervisory roles, which can lead to mode-specific trust issues and skill atrophy (Schoettle and Sivak, 2014). The findings also reveal that drivers express strong resistance, largely driven by the fear of job displacement, alongside concerns about the degradation of manual driving skills, challenges in managing technology during human takeover scenarios, and uncertainty regarding legal liability in the event of an accident.

However, AV adoption extends beyond direct users to impact all road users due to shared infrastructure. Broader road user acceptance, including pedestrians, cyclists, motorcyclists and drivers of conventional vehicles, requires addressing behavioral uncertainties in mixed-traffic environments (Pammer et al., 2021; Das et al., 2024). Road users highlight persistent ethical dilemmas in unavoidable crash scenarios and doubt the ability of AVs to interpret unwritten social norms on the road. These concerns are particularly pronounced among pedestrians, cyclists, and motorcyclists, who report heightened unease when sharing road space with AVs. The behavioral triad of AV users, conventional drivers, and VRUs highlights the need for targeted communication protocols (e.g., V2X interfaces for motorcycles) and trust-building measures to ensure safe coexistence.

3.3.2 Mobility behavior

Additionally, AVs are fundamentally reshaping mobility behavior, influencing how individuals and groups select and utilize transportation modes. The findings indicate that the transition to AV could fundamentally reshape the mobility system (Table 6).

First, regarding mode shifting, AVs may provide critical first- and last-mile connections (Axsen and Sovacool, 2019; Lau and Susilawati, 2021). This function could steer users away from private car ownership and toward shared ride-hailing services.

A key transformation is the potential reduction in private vehicle ownership. Shared AV services can replace up to eleven manually driven vehicles per unit, while seamlessly connecting first- and last-mile gaps in public transit systems (Hirschhorn et al., 2019). However, adoption patterns are nuanced. For example, users tend to select among private ownership, shared ownership, or on-demand use based on cost perceptions, preferences, and trip characteristics (Lang and Mohnen, 2019; Liang et al., 2023; Roca-Puigròs et al., 2023).

Second, regarding trip patterns, AVs recast travel time as productive time. This change encourages longer commutes and expands mobility access though early implementation will likely restrict operations to designated areas (Xing et al., 2022). For instance, longer commutes often favor AV adoption due to the benefits of increased travel distance and enhanced comfort (Haboucha et al., 2017).

Third, for ownership models, the prohibitively high cost of AV technology discourages private purchase. The findings suggest promoting the adoption of Mobility-as-a-Service (MaaS) and fostering shared ownership models in dense cities. Despite the advantages of AV, concerns over high purchase and operational costs remain a significant barrier to widespread acceptance (Topolšek et al., 2020). These behavioral shifts underscore the need for integrated policies that

Table 5. Human factor behavior categories affected during transition to AV

Factor	Category	Details	Reference
Human Factor Behavior	User acceptance	• Most of factors used to investigate acceptance are trust, anxiety, perceived safety, willingness to use, behavior intention, perceived control, social influence, previous experience, perceived usefulness, facilitating condition and perceived benefits • Major concerns about data privacy and security • Anxiety for failure or accidents involving AVs	(Epprecht et al., 2014; Noruzoliaee et al., 2018; Sovacool and Axsen, 2018; Axsen and Sovacool, 2019; Fitt et al., 2019; Marletto, 2019; Whittle et al., 2019; Pel et al., 2020; Szabó, 2020; Cugurullo et al., 2021; Milakis and Müller, 2021; Nemoto et al., 2021; Stasinopoulos et al., 2021; Curtale et al., 2022; Schippl et al., 2022; Roca-Puigròs et al., 2023; Schippl, 2024)
	Driver acceptance	• Degradation of manual driving skills due to over-reliance on automation • Anxiety about system reliability in edge cases (bad weather, complex roads) • Confusion over legal liability in the event of a crash • Cybersecurity threats and vehicle hacking • Concern about access to technology and need for specialized training • Fear of job displacement and loss of autonomy (especially for professional drivers)	(Dogan et al., 2017; Eriksson and Stanton, 2017*a*,*b*; Eriksson et al., 2017; Li et al., 2017; Varotto et al., 2018; Vogelpohl et al., 2018; Naujoks et al., 2019; Diederichs et al., 2020; Wang et al., 2020; Zhou et al., 2020; Günthner et al., 2021; Trager et al., 2021; Yu et al., 2021; Ko et al., 2022; Maggi et al., 2022*a*,*c*,*b*; Ansar et al., 2023; Bley et al., 2023; Bonyani et al., 2023; Karakaya and Bengler, 2023; Leitner et al., 2023; Mirnig et al., 2023; Zhang and Ji, 2023; Alms and Wagner, 2024; Neto et al., 2024)
	Road user acceptance	• Specific safety concerns for vulnerable road users (pedestrians, cyclists) • Public anxiety over ethical in unavoidable crash scenarios and ability to understand unwritten social driving norms	(Fitt et al., 2019; Whittle et al., 2019; Pel et al., 2020; Szabó, 2020; Milakis and Müller, 2021; Nemoto et al., 2021; Trager et al., 2021; Sun and Wong, 2023)

address cost barriers, optimize shared mobility networks, and ensure equitable access to AV technologies across diverse user groups.

3.4 Mobility infrastructure

The successful deployment of AVs necessitates comprehensive transformation across three core infrastructure domains, as outlined in Table 7.

Physical infrastructure adaptations, including optimized road markings, standardized traffic signs, and dedicated lanes, are critical for ensuring the safe operation of AVs. These modifications address AVs' reliance on clear visual cues for navigation and decision-making. Concurrently, public opinion suggests cautious implementation, with 64.5% of respondents favoring restricted AV operations on specific roadways (Tengilimoglu et al., 2023) reflecting concerns about mixed-traffic environments. Digital infrastructure forms the backbone of AV functionality, enabling real-time data exchange through advanced connectivity solutions. The deployment of 5G networks emerges as a pivotal enabler that offers ultra-low latency communication essential for vehicle-to-infrastructure (V2I) coordination and hazard notification systems to obscured objects or unexpected traffic conditions (Kuutti et al., 2018; Chen and Huang, 2019).

Energy infrastructure is also the backbone of AV operations, where the selection and placement must be strategically planned. The rapid development of electric vehicles today must be balanced with the readi-

Table 6. Mobility behavior categories affected during transition to AV

Factor	Category	Details	Reference
Mobility Behavior	Mode shift	• Shift from existing modes to AVs • First/last mile solution potential • Reducing private car trips • AV Ride-sharing acceptance for mode shift	(Epprecht et al., 2014; Noruzoliaee et al., 2018; Axsen and Sovacool, 2019; Fitt et al., 2019; Lang and Mohnen, 2019; Marletto, 2019; Whittle et al., 2019; Pel et al., 2020; Szabó, 2020; Canıtez, 2021; Cugurullo et al., 2021; Martin, 2021; Stasinopoulos et al., 2021; Vitale Brovarone et al., 2021; Curtale et al., 2022; Grindsted et al., 2022; Schippl et al., 2022; Sovacool et al., 2022; Nemoto et al., 2023; Roca-Puigròs et al., 2023; Shammut and Imran, 2024)
	Trip patterns	• AVs transform travel time into productive time • Increase travelled distance since longer commutes tend to favor AVs • AV use facilitates more trips due to on-demand availability (for SAVs) • AVs expand mobility access across all societal segments (elderly, disabled, youth) • In the early stages, AVs are most viable for trips within confined areas, such as airports, campuses, and designated zones	(Noruzoliaee et al., 2018; Fitt et al., 2019; Whittle et al., 2019; Cugurullo et al., 2021; Stasinopoulos et al., 2021; Grindsted et al., 2022; Sovacool et al., 2022)
	Ownership model	• Emergence of MaaS over private ownership in dense areas • High upfront cost of AV technology will be a major barrier to private purchase • Potential for fractional ownership or shared ownership co-ops	(Epprecht et al., 2014; Noruzoliaee et al., 2018; Fitt et al., 2019; Kim, 2019; Lang and Mohnen, 2019; Whittle et al., 2019; Szabó, 2020; Acheampong et al., 2021; Canıtez, 2021; Martin, 2021; Grindsted et al., 2022; Schippl et al., 2022; Sovacool et al., 2022; Nemoto et al., 2023)

ness of supporting infrastructure. The trend of new energy-based vehicles, such as those powered by hydrogen, is also beginning to show its potential and open opportunities for energy source diversification for AVs in the future (Asna Ashari et al., 2023). Moreover, these infrastructure elements create an interdependent ecosystem that must be developed cohesively to support AVs' unique operational requirements while addressing public acceptance challenges.

3.4.1 Traffic and safety system

The integration of AV into modern transportation systems represents a significant leap forward in traffic safety and efficiency, as detailed in Table 8. In mixed traffic environments, the unpredictable behavior of human drivers and motorcyclists creates a complex operational landscape for AVs. This can potentially lead to new patterns of congestion and emergent safety risks (Sun et al., 2023).

The findings also highlight that potential cyberattacks targeting AV sensor spoofing or data integrity are discussed (Grimm and Walz, 2024; Shammut and Imran, 2024; Liu, 2020). The high connectivity of AVs makes them prime targets for attacks that could result in mass collisions or data hijacking. These vulnerabilities are compounded by weaknesses in the digital supply chain and the legal complexities of attributing responsibility following an incident.

Moreover, the concept of safety itself has expanded beyond individual AV performance. It now encom-

Table 7. Mobility infrastructures categories affected during transition to AV

Factor	Category	Details	Reference
Mobility Infrastructure	Physical infrastructure	• The need for high-quality, consistent lane markings and signage for machine vision in global standardization • Dedicated AV lanes or zones may be required for early deployment • A potential reduction in parking infrastructure, repurposing land • The impact on street design for safety and pedestrian priority may conflict with AV routing needs	(Epprecht et al., 2014; Marx et al., 2015; Sovacool and Axsen, 2018; Cugurullo, 2020; Szabó, 2020; Martin, 2021; Milakis and Müller, 2021; Vitale Brovarone et al., 2021; Grindsted et al., 2022; Nemoto et al., 2023; Tumminello et al., 2023; Shammut and Imran, 2024)
	Digital infrastructure	• Ultra-reliable, low-latency communication networks (e.g., 5G) are foundational • Real-time data updates • Interoperability and data-sharing platforms between different OEMs and cities	(Milakis and Müller, 2021; Marx et al., 2015; Szabó, 2020; Breitschopf et al., 2023; Nemoto et al., 2023; Grimm and Walz, 2024; Shammut and Imran, 2024)
	Energy source infrastructure	• Smart charging coordination to avoid peak demand spikes from fleets • Wireless/inductive charging roads for continuous operation of shared fleets • Hydrogen infrastructure if fuel cell AVs become prevalent for longer range • Infrastructure for autonomous refueling/recharging without human attendants	(Whittle et al., 2019; Stasinopoulos et al., 2021; Sovacool et al., 2022; Choi et al., 2023; Roca-Puigròs et al., 2023)

passes 'behavioral safety' to prevent hazardous reactions from other road users, ethical protections for pedestrians and cyclists, risks associated with human-machine control transitions, and an urgent need for universal, standardized safety metrics and reporting frameworks.

3.4.2 Policy and regulation

Furthermore, Table 9 summarizes regulatory and policy frameworks addressing critical dimensions such as safety standards, liability structures, and data privacy protections.

Previous studies suggested an urgent need for globally harmonized regulations, structured pilot programs in controlled environments, and specific certification processes that include cybersecurity benchmarks (Hopkins and Schwanen, 2018; Grindsted et al., 2022). Safety and testing regulations established by organizations such as SAE and UNECE vehicle regulation serve as foundational elements, ensuring rigorous validation protocols that build public trust while minimizing accident risks during AV deployment. On the other hand, AVs need clear guidelines for accident responsibility allocation. Current debates focus on whether liability should reside with manufacturers, software developers, or human operators during transitional phases (Nikitas et al., 2019). This legal ambiguity presents significant challenges for insurance models that must adapt to technology where human error becomes less prevalent. In addition, data privacy also emerges as equally critical.

Khan et al. (2023) emphasize the need for proactive legal frameworks to govern the collection, storage, and utilization of the sensitive mobility data generated. Effective policies must balance innovation facilitation with personal privacy protection, particularly regarding location tracking and behavioral pattern analysis. Concurrently, data privacy concerns stem from the pervasive collection of granular movement data without meaningful consent, demanding greater user transparency, control, and robust governance frameworks to prevent misuse (Breitschopf et al., 2023; Shammut and Imran, 2024).

3.4.3 Industry

The findings identify that existing industries will be significantly impacted by AVs, as outlined in Table 10. AVs are fundamentally restructuring the traditional

Table 8. Traffic safety categories affected during transition to AV

Factor	Category	Details	Reference
Traffic and Safety	Mixed traffic	• Challenges between AVs' behavior and human drivers' unpredictable actions • Risk of traffic jams and congestion caused by AVs • Safety risks with other vehicles during the transition • Challenges in interpreting the intentions of other road users without clear signals • Motorcyclists' unpredictable behavior	(Merat et al., 2014; Eriksson and Stanton, 2017*a*; Li et al., 2017; Wang et al., 2020; Trager et al., 2021; Sun et al., 2023)
	Cybersecurity	• Risk of hacking leads to mass collisions or ransom • Challenges in establishing a security certificate for a vehicle's entire digital ecosystem • Insider threats within manufacturing or fleet operations • Difficulty in attributing attacks and applying legal recourse	(Pel et al., 2020; Szabó, 2020; Milakis and Müller, 2021; Nemoto et al., 2023; Grimm and Walz, 2024; Shammut and Imran, 2024)
	Safety	• Behavioral safety, ensuring AV actions do not induce unsafe reactions in others • Interaction with VRUs is a primary technical and ethical challenge • Human-machine handover risks during fallback scenarios • Standardized safety metrics and reporting frameworks	(Zhou et al., 2020; Martin, 2021; Curtale et al., 2022; Karakaya and Bengler, 2023; Mirnig et al., 2023; Tumminello et al., 2023; Alms and Wagner, 2024)

automotive industry's value chain, which now critically depends on cross-sector partnerships with industries like technology and telecommunications (Martin, 2021).

Historically characterized by a pyramid structure with Original Equipment Manufacturers (OEMs) at the apex and tiered suppliers below (Clark and Fujimoto, 1992; Gereffi, 1999), the industry now faces radical decentralization through AV adoption. This technological shift introduces new dominant players, including tech giants, telecommunication firms, and data analytics providers that create a hub-spoke ecosystem that diminishes OEMs' traditional control (Alvarez León and Aoyama, 2022).

Traditional automotive suppliers specializing in mechanical components confront existential threats such as vehicle value shifts toward software and connectivity solutions (Doran et al., 2007; Sturgeon et al., 2008). This transition necessitates unprecedented partnership models, where conventional automakers must collaborate with previously peripheral actors like AI developers and cloud service providers to remain competitive (Kearney, 2020). The emerging ecosystem blends automotive engineering with digital technologies, requiring new competencies in data management, cybersecurity, and MaaS platforms.

On the other hand, the emergence of AVs has created a demand for skilled AV labor (Baumgartinger-Seiringer et al., 2020). The demand for an AV-skilled workforce is driving the creation of new talent in specialized fields such as cybersecurity and AI. This shift enables companies to build more innovative and competitive teams for the future of mobility.

4 DISCUSSION

The results of this study revealed a significant evolution in AV research, reflecting a maturation of both technological capabilities and societal considerations. The research landscape has progressively shifted from purely technological demonstrations toward more holistic integration challenges, with several key trends emerging.

Previous studies identified core transition frameworks such as MLP and TIS (Zolfagharian et al., 2019). These theories serve as the main analytical frameworks for understanding socio-technical transitions; they also

Table 9. Regulation policy categories affected during transition to AV

Factor	Category	Details	Reference
Regulation and Policy	Testing and standardization	• Globally harmonized regulations and performance standards • Testing of pilot programs in controlled environments • Specific certification processes for private AV ownership • Cybersecurity testing and certification standards	(Pel et al., 2020; Szabó, 2020; Canıtez, 2021; Hopkins and Schwanen, 2021; Nemoto et al., 2021; Grindsted et al., 2022; Shammut et al., 2022)
	Liability and Insurance	• Liability shifts from the driver to the product manufacturer or fleet operator • New insurance models are required (shifting liability from user to manufacturer/fleet) • Liability for the ethical decisions programmed into the vehicle	(Pel et al., 2020; Szabó, 2020; Grindsted et al., 2022; Schippl et al., 2022)
	Data privacy concern	• Location and trip data collection creates detailed movement profiles, often without meaningful consent • Consumer transparency and control over what is collected and shared • Elevated risk of data misuse	(Pel et al., 2020; Breitschopf et al., 2023; Nemoto et al., 2023; Grimm and Walz, 2024; Shammut and Imran, 2024)

Table 10. Industry categories affected during transition to AV

Factor	Category	Details	Reference
Industry	Partnership	• Collaboration between tech, auto, telecom, insurance, and infrastructure firms • Public-private partnerships (PPPs) are essential for infrastructure rollout and regulation • Academic and Industry partnerships for foundational research and long-term development • Global Strategic Alliances to distribute massive R&D investments across international markets	(Szabó, 2020; Martin, 2021)
	Supply chain	• Core value moves from hardware/assembly to software, data, and AI • Shift from traditional OEMs to new-tech entrants (AI firms, software giants) as primary actors	(Hess, 2020; Nemoto et al., 2023)
	Data privacy concern	• Massive demand for new roles in AV fields (AI/ML, robotics, sensor, cybersecurity) • Reskilling/upskilling for existing workforce • Knowledge gap among policymakers lacking the technical understanding to govern AVs effectively	(Grimm and Walz, 2024; Shammut and Imran, 2024)

Table 11. Characteristics of government and industry initiatives

Characteristics	Government initiatives	Industry initiatives
Approach	Top-down	Bottom-up
Primary Driver	Policy forces from government	Private sector/market forces
Focus	Public safety improvement	Innovation and technological strong dominance
Deployment	Equitable distribution across regions	Concentrated in specific high-profit areas
Key Collaborators	Government research institutes, universities	Startups, technology companies, industry consortia
Funding sources	Government budgets, research grants	Private investment
Technical	Infrastructure development, system integration, standardization	Product development, user experience, market scalability
Innovation Ecosystem	Public-sector dominated research	Mature startup and private R&D ecosystem
Industrial Base	Weak domestic automotive industry	Strong global OEMs with mature supply chains
Regulation	Proactive; mandatory standards before testing	Reactive; regulations follow technological developments

note the emergence of frameworks from other multidisciplinary studies. A hybrid analytical framework that merges MLP's multi-level structural analysis with stakeholder or technology acceptance could better address critical barriers such as infrastructure gaps, equity concerns, and regulatory challenges. Such an integrated approach would not only reconcile macro-level transition dynamics with micro-level behavioral factors but also facilitate more participatory governance processes and context-sensitive policy interventions. Future research should prioritize developing and testing these hybrid models to generate more effective, locally adapted strategies for AV adoption in diverse socio-technical contexts.

According to Geels, the core of technological transitions resides at the regime. The regime refers to the established socio-technical system governing transportation. Thus, successful AV integration requires coordinated changes across all regime dimensions simultaneously. Figure 9 illustrates a proposed conceptual AV transition based on our findings.

Psychological acceptance and behavioral adaptation emerge as critical determinants of successful AV adoption. Studies consistently demonstrate that public trust remains a significant barrier, with nearly half of potential users expressing reservations about safety and reliability. These concerns are compounded by deeply ingrained mobility behaviors, where personal vehicle ownership and control represent more than just transportation choices but reflect cultural values and personal identities.

Crucially, the acceptance and behavioral adaptation of VRUs can significantly impact the broader adoption of AVs. If these road users feel unsafe, distrustful, or resistant to interacting with AVs, it could hinder large-scale implementation. Although VRU acceptance and behavioral adaptation could significantly impact broader AV adoption, research focusing on this demographic remains limited. The challenge for researchers and policymakers lies in developing strategies that address these human factors through transparent technology demonstrations, comprehensive education campaigns, and gradual exposure programs that allow users to build confidence in AV systems. These suggest that policies and infrastructure planning must address this dynamic VRU acceptance to ensure a smooth and inclusive transition to autonomous mobility.

The infrastructure requirements for AV implementation present both technical and equity challenges. Current transportation networks in most regions were designed for human-operated vehicles, requiring significant upgrades to support autonomous operations. The infrastructure gap is particularly pronounced when comparing urban and rural areas, creating the risk of a new form of mobility inequality. Safety considerations further complicate this picture, as AVs must eventually operate in mixed environments with conventional vehicles and vulnerable road users, requiring new traffic management approaches and liability frameworks that don't yet exist at scale.

The current policy landscape for AVs is characterized by a patchwork of local, national, and regional regulations

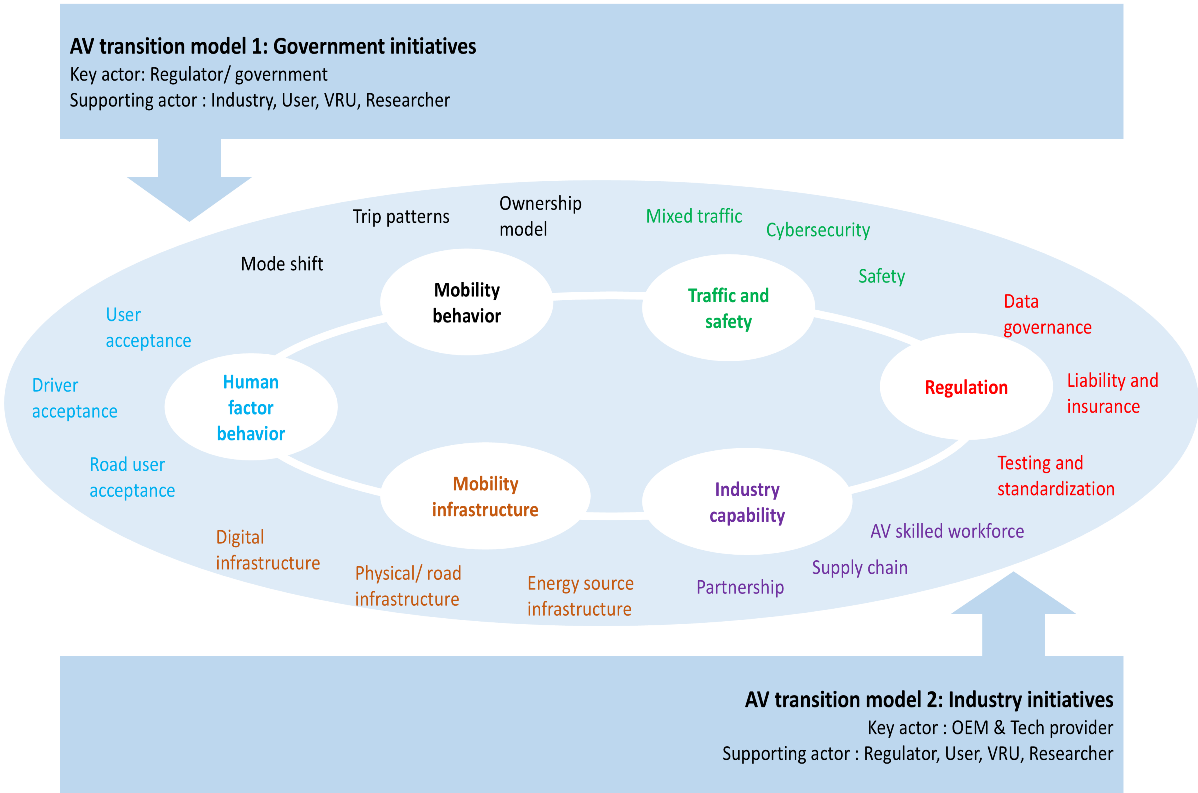

Figure 9. Proposed conceptual AV transition framework.

that often conflict or lack coherence. This regulatory uncertainty discourages investment and slows technological deployment. Meanwhile, established transportation industries and labor groups frequently oppose AV adoption due to legitimate concerns about economic displacement and job losses. These challenges are particularly acute in developing economies, where institutional capacity may be limited and competing transportation priorities are more pressing.

The role of industry and government is crucial in accelerating the adoption of this technology and in becoming a key driving actor during the transition (Canıtez, 2021). Major countries are driving AV adoption with varied strategies. China, Germany, the UK, and the US each have distinct policy approaches and transition scenarios, reflecting varied strategic priorities and socio-technical contexts (World Economic Forum, 2025).

The most widely used transition model to AV is an approach that relies on strong support from government and industry initiatives. Table 11 shows the differences in characteristics between government and industry initiatives.

In the government initiative, the government's role extends beyond setting regulations to include funding projects, directly supporting research and development and AV roadmap implementation. Additionally, the government must create an investment-friendly environment to support high-tech investments and foster investor confidence. Stable policies and a clear regulatory framework facilitate long-term planning, which is crucial for capital-intensive sectors such as autonomous vehicle development. The regulatory certainty helps industry stakeholders allocate resources more efficiently and accelerate the transition from research to commercial implementation. The government can also establish centers or government agencies that are directly capable of coordinating and supporting AV research and development projects. For example, the UK government has run its AV acceleration program. This approach has enabled it to coordinate more than 100 research and development projects with industry, involving more than 200 universities and companies (Centre for Connected and Autonomous Vehicles, 2018).

The second is the industry initiative. Simultaneously, countries with established automotive manufacturing ecosystems benefit significantly from this model. Their strong manufacturing capacity and supply chain networks facilitate the implementation of this technology. This not only accelerates innovation but also strengthens their dominant position, both domestically and globally. However, industry initiatives face significant issues with standardizing rules and standards. For example, when each manufacturer develops its own safety systems and standards, the resulting technologies become incompatible between manufacturers. This condition makes it difficult to create consistent regulations due to differences in systems between manufacturers. Although this model encourages rapid innovation, its long-term success is highly dependent on the government's role in establishing clear rules. Governments must ensure that all AV technologies, regardless of brand, can operate safely and be seamlessly integrated into a transportation system.

Although the approaches of these two transition models differ, synergistic collaboration between governments and industry in the development of AVs also plays an important role in creating an ecosystem that supports sustainable innovation. The industry has the technical capabilities and flexibility to innovate, while the government can create an adaptive regulatory framework and provide supporting infrastructure. Without clear regulatory support and incentives from the government, investment from the private sector may be hampered by legal uncertainty and high risks. Conversely, without active industry involvement, government policies may not align with technological developments and market needs. Therefore, the integration of government support and industry capabilities not only accelerates technological development but also ensures that AV innovation can be implemented effectively, safely, and sustainably in society.

The shift from manual to autonomous vehicle is fundamentally transforming the automotive industry's value chain and partnership ecosystems. This transition is disrupting traditional manufacturing paradigms, as mechanical components are increasingly replaced by sophisticated software systems, sensors, and AI technologies. These changes introduce new challenges in supply chain management, particularly for critical components such as semiconductors, where global shortages have already exposed vulnerabilities in production scalability. The current automotive value chain system, characterized by assembly plants and hierarchical supplier relationships forming a pyramid structure with OEMs at the apex, is transforming into a more collaborative partnership model with the emergence of new technology players. This transformation suggests that future competitive advantages will depend less on manufacturing scale and more on technological capabilities, data assets, and ecosystem positioning. The industry's evolution mirrors patterns seen in other high-tech sectors, suggesting automotive may become more "tech-like" in its business models and value chain structures.

The success of this industrial transformation also will hinge on strategic coordination among manufacturers, technology providers, policymakers, and other key stakeholders to address technical, regulatory, and market adoption barriers while capitalizing on emerging opportunities in the new mobility landscape. This evolution underscores the need for comprehensive strategies that extend beyond technological innovation to include business model adaptation, workforce reskilling, and policy modernization—all essential for enabling a seamless transition into the AV era.

These findings suggest that AV development should not be viewed merely as a technological shift from manual to autonomous systems but must also ensure social equity to facilitate successful implementation. This aligns with the foundational framework by Rip and Kemp (1998) on technological transitions, which emphasizes that technological change inherently carries social implications.

5 CONCLUSION

This study analyzes emerging trends to propose a novel transition model for AV adoption. This model specifically describes the different but complementary paths of government and industry initiatives. The findings also emphasize that successful AV adoption requires moving beyond purely technological considerations to incorporate infrastructure readiness, social equity, and systemic transformation perspectives into both research agendas and practical implementation strategies. The findings also reveal that existing research has predominantly focused on technological adoption drivers while paying insufficient attention to systemic enabling factors, particularly human and mobility behavior. Although understanding user acceptance remains important, the limited emphasis on societal impacts—, such as infrastructure readiness, regulations, and industry readiness—is critical for effective transition planning. Furthermore, these priorities must be supported by deeper industrial insights, as current assumptions about market readiness for this paradigm shift remain underdeveloped.

The study highlights several critical implications for future research priorities in AV transition. First, there needs to be deeper investigation into currently understudied yet crucial adoption areas, particularly infrastructure requirements and VRU-centric AV integration approaches. Secondly, the development of more inclusive participatory frameworks is essential to amplify underrepresented stakeholder voices, especially vulnerable road users such as motorcyclists and pedestrians, since current discussions remain dominated by users. Thirdly, a comprehensive analysis of socio-technical factors and industry- shifting patterns is needed, focusing on how innovative business models and transition strategies can be developed to align with emerging AV trends. Therefore, future research must adopt a more holistic approach that aligns research priorities with the complex, interconnected realities of transportation system transformation.

DISCLAIMER

The authors declare no conflict of interest.

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APPENDIX A

State of the Art (SOTA)

No.	Authors	Country	Underlying Theory	Method		Data Analysis	Participatory Decision Analysis							Regime Transport				
				Qn	Ql		USR	VRU	MFG	REG	OTP	RES	H-BHV	M-BHV	INF	TFS	RGL	IND
1	Grindsted et al. (2022)	Denmark	Socio-technical transitions		✓	Literature review, content analysis				✓		✓		✓	✓		✓	
2	Vitale Brovarone et al. (2021)	Italy	n.d.		✓	Case study			✓	✓	✓	✓		✓	✓	✓	✓	
3	Maggi et al. (2022*a*)	USA	n.d.	✓		Driving simulation, statistical analysis	✓						✓			✓		
4	Wang et al. (2020)	China	Safety improvement	✓		Driving simulation, statistical analysis	✓						✓			✓		
5	Eriksson and Stanton (2017*a*)	UK	n.d.	✓		Driving simulation, statistical analysis	✓						✓			✓		
6	Neto et al. (2024)	Brazil	n.d.		✓	FGD	✓						✓			✓		
7	Yoon et al. (2019)	South Korea	n.d.	✓		Driving simulation, statistical analysis	✓											
8	Milakis and Müller (2021)	Greece	MLP		✓	Literature review, scenario analysis	✓			✓		✓						
9	Naujoks et al. (2019)	Germany	n.d.	✓		Driving simulations, performance metrics	✓						✓			✓		
10	Trippl et al. (2021)	Austria	Regional Innovation System		✓	Interview, secondary data (report and literature)			✓	✓	✓	✓						✓
11	Epprecht et al. (2014)	Switzerland	Socio-technical transitions		✓	Interview, scenario analysis	✓		✓	✓	✓	✓		✓	✓	✓		
12	Schippl et al. (2022)	Germany	Socio-technical transitions		✓	Case study				✓	✓	✓					✓	
13	Eriksson et al. (2017)	Sweden	n.d.	✓		Driving simulations, performance metrics	✓						✓					
14	Lang and Mohnen (2019)	Germany	Socio-technical transition		✓	Interview			✓					✓				✓
15	Breitschopf et al. (2023)	Germany	Socio-technical transition	✓		Energy modeling, consumption analysis			✓	✓		✓		✓	✓			✓
16	Yi et al. (2024)	China	n.d.	✓		Random forest and statistical analysis	✓						✓					
17	Eriksson and Stanton (2017*b*)	Sweden	n.d.	✓		Driving simulations	✓						✓			✓		
18	Maggi et al. (2022*c*)	USA	n.d.	✓		Transition modeling, regulatory analysis			✓	✓		✓	✓					
19	Zhou et al. (2020)	China	n.d.	✓		Experiments, time-motion studies, sentiment analysis	✓						✓					
20	Günthner et al. (2021)	Germany	n.d.		✓	Interviews, user diaries	✓		✓	✓	✓	✓	✓	✓				
21	Diederichs et al. (2020)	UK	n.d.	✓		Usability testing, adaptive interface design	✓		✓			✓	✓					
22	Trager et al. (2021)	USA	n.d.	✓		Simulation studies, user testing	✓		✓				✓			✓		
23	Alochet et al. (2021)	France	MLP		✓	Literature review, case studies	✓		✓	✓			✓			✓		
24	Bonyani et al. (2023)	Canada	SNA	✓		Network analysis, performance metrics	✓					✓	✓					
25	Ko et al. (2022)	South Korea	n.d.		✓	Surveys, statistical analysis	✓			✓	✓			✓	✓			
26	Stasinopoulos et al. (2021)	Greece	n.d.	✓	✓	Modelling, system dynamic			✓	✓		✓		✓	✓	✓		
27	Sovacool et al. (2022)	USA	MLP Transition pathways		✓	Interview, content analysis	✓		✓	✓				✓	✓	✓		
28	Grimm and Walz (2024)	General	Sectoral + TIS	✓	✓	Bibliographic analysis, exploration study			✓		✓				✓	✓	✓	✓
29	Kim et al. (2019)	South Korea	Innovation System		✓	Case studies, interview	✓			✓	✓			✓	✓			✓
30	Mirnig et al. (2023)	Austria	n.d.		✓	Experiments, time-motion studies	✓						✓					
31	Fitt et al. (2019)	New Zealand	n.d.	✓	✓	Interviews and survey	✓	✓		✓		✓	✓	✓				
32	Karakaya and Bengler (2023)	Turkey	n.d.	✓		Experiments, time-motion studies	✓						✓					
33	Sovacool et al. (2020)	USA	Socio-technical transition		✓	Interview, scenario analysis	✓			✓		✓		✓	✓	✓		
34	Bley et al. (2023)	Sweden	n.d.		✓	Driving simulation	✓						✓					
35	Tumminello et al. (2023)	Italy	n.d.	✓		Safety evaluation methods, validation studies	✓		✓	✓				✓	✓	✓		
36	Alms and Wagner (2024)	Germany	n.d.	✓		Surveys, control transition analysis	✓		✓	✓			✓					
37	Köhler et al. (2020)	Netherland	MLP		✓	Scenario analysis, Agent based modelling	✓	✓				✓		✓				
38	Hopkins and Schwanen (2021)	United Kingdom	n.d.		✓	Case studies, energy transition modeling	✓		✓	✓		✓					✓	
39	Rao (2020)	China	MLP	✓		Policy document analysis, regression model	✓		✓	✓				✓	✓	✓	✓	✓
40	Pel et al. (2020)	Netherlands	Governance frameworks		✓	Policy analysis, governance framework assessment			✓	✓	✓	✓					✓	
41	Nemoto et al. (2023)	Japan	MLP	✓	✓	Interview, survey	✓			✓	✓			✓	✓			
42	Marletto (2019)	Italy	n.d.		✓	Interview, stakeholder mapping			✓	✓		✓	✓	✓	✓			
43	Hess (2020)	USA	n.d.		✓	Case studies			✓	✓				✓			✓	

APPENDIX A

No.	Authors	Country	Underlying Theory	Method		Data Analysis	Participatory Decision Analysis						Regime Transport					
				Qn	Ql		USR	VRU	MFG	REG	OTP	RES	H-BHV	M-BHV	INF	TFS	RGL	IND
44	Sun et al. (2023)	Germany	Transition management	✓		Simulation modelling	✓		✓	✓			✓	✓		✓		
45	Sovacool and Axsen (2018)	USA	Sustainability transition		✓	Interview, Content Analysis	✓		✓	✓			✓	✓				
46	Shammut and Imran (2024)	New Zealand	Governance frameworks		✓	Policy analysis, governance framework assessment			✓	✓	✓						✓	
47	Varotto et al. (2018)	Italy	n.d.	✓		Choice modeling, urban planning	✓			✓	✓							
48	Yu et al. (2021)	China	n.d.	✓		Surveys, Driving simulation	✓						✓					
49	Li et al. (2017)	China	n.d.	✓		Traffic flow modeling, driving simulation studies	✓						✓			✓		
50	Čičić and Johansson (2022)	Finland	n.d.		✓	User-centered design, usability testing	✓		✓			✓	✓					
51	Curtale et al. (2022)	Italy	UTAUT	✓		Survey	✓						✓	✓	✓			
52	Noruzoliaee et al. (2018)	Iran	n/d	✓		Simulation modeling, cost-benefit analysis	✓			✓	✓		✓		✓			
53	Dogan et al. (2017)	Turkey	n.d.	✓		Driving simulation	✓						✓		✓			
54	Zhang and Ji (2023)	China	n.d.	✓		Driving simulation, survey	✓	✓					✓	✓				
55	Maggi et al. (2022*b*)	USA	n.d.	✓		Driving simulations, control transfer studies	✓						✓			✓		
56	Whittle et al. (2019)	Australia	MLP and Socio-psychological		✓	Interview	✓		✓	✓		✓	✓	✓				
57	Vogelpohl et al. (2018)	Germany	n.d.		✓	Simulation modeling, urban planning	✓			✓	✓		✓		✓			
58	Ansar et al. (2023)	Canada	n.d.	✓		Mixed logit and mixed latent class	✓						✓					
59	Leitner et al. (2023)	Austria	n.d.	✓		Driving simulations, behavior analysis	✓						✓					
60	Merat et al. (2014)	UK	n.d.	✓		Surveys	✓						✓					
61	Axsen and Sovacool (2019)	Canada	SNA		✓	Interview	✓					✓		✓	✓			
62	Roca-Puigròs et al. (2023)	Spain	System theory	✓		System dynamic modeling, surveys	✓						✓	✓				
63	Cugurullo et al. (2021)	UK	Attitudes, technological innovation and politics		✓	Interview	✓			✓	✓			✓	✓	✓		✓
64	Marx et al. (2015)	Brazil, Germany	MLP		✓	Multiple case studies			✓	✓		✓		✓	✓		✓	
65	Pel et al. (2020)	Netherlands	MLP		✓	Case study of Dutch ITS			✓	✓		✓	✓	✓		✓	✓	
66	Mirzadeh Phirouzabadi et al. (2022)	Global	TIS	✓	✓	Quantitative and qualitative, joint patent analysis	✓		✓	✓		✓			✓		✓	
67	Whittle et al. (2019)	UK	MLP and TAM		✓	Transport expert interviews and literature review	✓		✓	✓		✓	✓	✓	✓		✓	
68	Butt et al. (2024)	Pakistan	TIS		✓	Event-based policy analysis with expert consultation			✓	✓		✓		✓	✓		✓	
69	Sovacool and Axsen (2018)	Global	MLP		✓	Conceptual framework with framing approach				✓	✓	✓	✓	✓			✓	
70	Breitschopf et al. (2023)	Germany	MLP		✓	Framework for inter-system interactions	✓		✓	✓		✓		✓	✓		✓	
71	Canıtez (2021)	UK	MLP		✓	Case studies and model development	✓		✓			✓	✓	✓	✓	✓	✓	
72	Szabó (2020)	Czech Republic	MLP		✓	Delphi method for AV scenarios with expert input	✓		✓	✓	✓	✓		✓			✓	
73	Choi et al. (2023)	Netherlands	MLP		✓	Systematic literature mapping and interviews	✓			✓	✓	✓	✓	✓			✓	
74	Engholm et al. (2021)	Sweden	TIS		✓	Expert interviews and TIS functions analysis	✓		✓	✓		✓		✓	✓		✓	
75	Milakis and Müller (2021)	Germany	MLP		✓	Literature review and research agenda proposal	✓				✓	✓	✓				✓	
76	Martin (2021)	Denmark	MLP		✓	Comparative visual analysis of AV imaginaries	✓		✓		✓	✓	✓	✓			✓	
77	Marletto (2019)	Italy	MLP		✓	Scenario analysis with socio-technical maps			✓	✓	✓	✓		✓			✓	✓
78	Nemoto et al. (2023)	Germany	MLP	✓	✓	Conceptual mapping and interviews with stakeholders	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
79	Figenbaum (2017)	Norway	MLP		✓	Case study on policy and incentives				✓		✓		✓	✓		✓	
80	Li et al. (2019)	China	SNA and TIS	✓	✓	SNA and patent analysis	✓			✓		✓		✓			✓	
81	Mirzadeh Phirouzabadi et al. (2022)	United States	TIS	✓	✓	Lotka-Volterra-based simulation model				✓	✓	✓					✓	
82	Whitmarsh (2012)	United Kingdom	MLP + Stakeholder Theory		✓	Case studies	✓			✓		✓	✓	✓	✓		✓	
		Count		39	50		61	2	38	49	23	40	46	43	31	23	28	8

Note: Qn = Quantitative; Ql = Qualitative; H-BHV = human behaviour; M-BHV = mobility behaviour; USR = user; VRU = vulnerable road user; MFG = manufacturer; REG = regulator; OTP = operator and tech company; RES = researcher; INF = infrastructure; TFS = traffic safety; RGL = regulator; IND = industry.

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