Autonomous Vehicle Regulation: Why a Fragmented Governance Landscape Is Stalling Self-Driving Cars

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Abstract: The advent of autonomous vehicles (AVs) promises transformative gains in road safety, traffic efficiency, and urban mobility. However, the realization of these benefits is increasingly impeded by a fragmented developmental and regulatory landscape. This study aims to address the regulatory fragmentation problem, examining why such phenomenon constitutes a critical impediment to the responsible deployment of AVs. Drawing on a multi-dimensional analysis across the ethical, legal, societal, and technical facets of governance, this study traces this fragmentation to the persistent dominance of single-paradigm thinking in both policy design and regulatory practice. The central finding is that prevailing governance approaches, whether narrowly focused on innovation, safety, or market dynamics, operate in isolation, creating regulatory inconsistencies that impede technological progress, undermine public trust, and ultimately stall the widespread deployment of AVs. In response, this study proposes a systemic governance framework that synthesizes these fragmented dimensions, including adaptive liability allocation that evolves with technological maturity, multi-layered transparency architectures that enable accountability without stifling innovation, and proactive socio-economic interventions that anticipate labor market transformations. This framework advances a paradigm shift from fragmented, single-paradigm thinking toward integrated, systemic governance. This study contributes to the global conversations on coherent and adaptable regulatory frameworks that reconcile innovation with safety, while ensuring that the deployment of AVs advances social equity in an increasingly interconnected world.

Keywords: autonomous vehicles; self-driving technology; adoption barriers; regulatory fragmentation; ethical-legal dilemmas; public acceptance

Introduction

Autonomous vehicles (AVs), also referred to as self-driving or driverless cars, have emerged as a major innovation poised to revolutionize transportation, holding immense potential to improve urban mobility, traffic efficiency and environmental sustainability (Hossain et al., 2024; Sharma, 2025; Song, 2025). This sophisticated system, powered by advancements in artificial intelligence (AI), sensor technology, and connectivity, promises a future where human error-related accidents are drastically reduced, traffic congestion is alleviated, and new forms of mobility services become commonplace. However, the very complexity and transformative potential of AVs introduce a myriad of challenges that extend far beyond mere technical implementation. These challenges encompass intricate ethical dilemmas, profound legal ambiguities, potential socio-economic disruptions, and significant infrastructural transitions, none of which can be effectively addressed through isolated, single-paradigm approaches (Ahmed & Ahammed, 2024; Bhatia, 2025).

Contemporary global governance frameworks often exhibit a persistent reliance on single-paradigm thinking, which manifests in several ways: a narrow focus on technological solutionism, an overemphasis on market-driven innovation, or a series of fragmented regulatory adjustments that fail to grasp the holistic nature of AV integration (Ghosh et al., 2025; Lozano-Paredes, 2025; Zhu, 2025). Such approaches, while perhaps effective for technological advancements or addressing other specific, isolated issues, prove fundamentally inadequate for the multidimensional and interconnected challenges inherent in widespread AV deployment. For instance, an ethical framework developed in isolation from technical feasibility or legal enforceability risks remaining purely theoretical, while a technical solution designed without considering societal values or legal accountability may face significant public resistance or unforeseen negative consequences (Alasti, 2024; Kulaklıoğlu, 2024). The core bottleneck in existing scholarship and regulatory policy, as this paper identifies, is precisely this persistent fragmentation of ethical, legal, and social dimensions, which not only mirrors but also actively reinforces the limitations of these single-paradigm approaches.

This study thus argues for a fundamental paradigm shift towards systemic governance for AVs, an integrated framework that synthesizes these multidimensional challenges of AV deployment by recognizing their deep interconnections and dynamic interactions. The study begins by mapping the current global state of AV technology and identifying the core challenges shared across jurisdictions. It then undertakes a theoretical deconstruction of these challenges, revealing their embedded ethical underpinnings, legal complexities, and broader social implications. Building on this deconstruction, the study critically examines the persistent fragmentation in existing representative policy designs and regulatory practices, demonstrating the inadequacy of single-paradigm approaches in addressing the complex realities of AV applications. In response, the paper proposes a systemic governance framework, articulating how it operates through interconnected mechanisms to reconcile innovation with safety, accountability, and equity. By underscoring the urgent need for interdisciplinary collaboration and advocating for anticipatory governance that proactively addresses future challenges rather than reactively responding to crises, this proposed paradigm offers a forward-looking roadmap to pave the way for a more responsible, equitable, and sustainable future for AV deployment.

1. The Evolving Landscape of Autonomous Vehicle: Technical Capabilities and Inherent Complexities

Autonomous driving is heralded as a transformative technology with the potential to fundamentally reshape transportation systems and urban environments. The anticipated benefits span multiple dimensions, including a dramatic improvement in road safety, enhanced traffic efficiency, reduced environmental impact, and expanded mobility options for various segments of the population. The technological foundation for AVs, ranging from Level 2 assisted driving to Level 5 fully autonomous driving, relies heavily on sophisticated AI, machine learning, and deep learning algorithms that enable vehicles to perceive their environment, make complex decisions, and execute control commands (Fu, 2025). Perception systems, utilizing a fusion of sensors such as cameras, radar, and LiDAR, are continuously being refined to enhance accuracy and robustness in diverse and often challenging traffic scenarios (Kumar et al., 2025). Decision-making algorithms, often employing reinforcement learning, are designed to navigate complex traffic situations, optimize routes, and respond to unforeseen events (Gao et al., 2024; Li et al., 2026). The control systems, as exemplified by studies like Xu et al. (2025), ensure precise execution of planned trajectories, even under multi-source uncertainty.

The very definition and design of AVs are evolving, introducing more complex challenges. De Vincenzi et al. (2026) introduces AI-defined vehicles (AIDVs) as a new class of robotic systems with autonomous decision-making, proposing a roadmap for integrating AIDVs into realistic transportation systems. This technological evolution, where vehicles are no longer mere machines but adaptive AI systems, fundamentally challenges traditional regulatory paradigms designed for predictable, human-controlled automobiles. Meanwhile, concrete policy developments illustrate the growing gap between technological reality and governance capacity. In December 2025, several Chinese provinces, including Beijing and Chongqing, granted access permits for Level 3 AVs, marking a crucial transition from testing to commercial deployment. Yet this regulatory step forward, while significant, addresses only the technical dimension of certification, leaving unresolved the broader societal implications that accompany real-world AV deployment.

Furthermore, the generation of critical pedestrian scenarios for AV testing, as explored by L. Yang et al. (2025), highlights the inherent safety conflict between AVs and vulnerable road users, a challenge that combines technical perception with ethical considerations of pedestrian safety. More broadly, as AVs become increasingly autonomous and AI-driven, they inevitably encounter ethical dilemmas in collision algorithms, legal ambiguities in accountability frameworks, socio-economic disruptions in labor markets, and infrastructural demands for urban adaptation. These dimensions are not peripheral concerns but core challenges that cannot be resolved through technological innovation alone. In sum, despite impressive technical advancements, the path to widespread AV deployment is inherently fraught with multifaceted challenges that collectively underscore the fundamental limitations of a purely technical, single-paradigm approach.

2. Deconstructing the Dilemmas of Autonomous Vehicle

The integration of AVs into daily life transcends mere technological feasibility, bringing to the forefront a complex web of ethical imperatives, legal certainties, and societal values that profoundly shape, and are simultaneously shaped by, their design, deployment, and public acceptance. This section explores how these dilemmas manifest, interact, and collectively underscore the inherent limitations of fragmented approaches, thereby advocating for their systemic integration into governance frameworks.

2.1 Dilemma in Ethical Considerations

The ethical governance landscape for autonomous driving is largely nascent and fragmented. Although there were several guidelines and regulations related to AVs around the world, the ethical principles guiding autonomous driving behavior have not yet been clearly articulated or even considered in some jurisdictions. The absence of ethical norms further leads to the social dilemma. Firstly, the decision-making processes of AI-driven AVs, particularly in complex and ambiguous scenarios, such as unavoidable accidents, often lack transparency and explainability, making it difficult to understand the rationale behind a particular ethical choice (Ghosh et al., 2025; Verma, 2025). This opacity could erode public trust and hinder acceptance, as human users naturally seek to understand and predict the behavior of autonomous systems, especially when safety is at stake (Kaufman et al., 2025). This suggests that the process of ethical decision-making, not just the technical outcome, is vital for fostering public confidence. Krügel & Uhl (2024) provide empirical support for this claim through a study in Germany, finding that participants were willing to assume risks for the benefit of others, thereby deviating from purely self-preserving collision avoidance. This finding suggests that if ethical programming can reflect such altruistic tendencies, it may help mitigate the social dilemma surrounding AV adoption in Germany by aligning technological behavior with deeply held human values.

Furthermore, ethical considerations extend beyond accident scenarios to encompass data privacy, algorithmic bias, and the potential for misuse of AV technology. AVs are essentially data-gathering machines, collecting vast amounts of personal and environmental data through their myriad sensors. This extensive datafication raises significant ethical concerns about privacy, surveillance, and potential misuse. Perry & Ammari (2026)'s study reveals that the datafied car, as a mobile extension of the "leaky home," continuously transmits behavioral data through connected technologies, thereby rendering private spaces increasingly permeable. The ethical implications of AI bias, transparency, and human dignity risks are also highlighted in the broader context of AI governance (Singh & Gautam, 2025). Without a clear ethical framework, these issues can lead to public distrust, legal ambiguities, and ultimately, hinder the societal benefits that AVs could offer.

2.2 Dilemma in Legal Frameworks

The legal dilemma of the AV adoption involves the adaptation and transformation of existing legal frameworks, as well as the creation of new laws, to govern the development, deployment, and operation of AVs. The fundamental shift in driving decision-making and control from human to AI-driven machine challenges established laws across multiple domains.

Determining liability in AV accidents exposes a fundamental misalignment between traditional legal frameworks and emerging technologies. The 2025 Xiaomi SU7 accident in China illustrates this complexity: while final reports suggest that driver negligence was the main contributing factor, the tragedy was compounded by a critical safety design flaw, the lack of mechanical redundancy in electronic door handles, which fatally hindered post-collision rescue efforts. This interplay between human error and technological failure epitomizes the broader challenge facing AV legal frameworks, where accidents are increasingly multifactorial, involving not only driver behavior but also software glitches, sensor failures, manufacturing defects, or cyberattacks (Ba et al., 2025; Huang, 2024). Traditional tort law, based on assigning fault to a negligent human driver, struggles to apportion liability when the fault is shared between human conduct and systemic design flaws, underscoring the urgent need for institutional innovation in safety standards and legal norms.

Moreover, as automation increases, the “driver” might effectively be the car’s sophisticated AI system or an entire chain of entities including the vehicle owner, the car manufacturer, and the software developer, making it increasingly difficult to directly attribute fault to human drivers. Central to this complexity are the role of manufacturers and the challenges of proving causation with opaque AI models. Due to their multifaceted role as developers, controllers, and beneficiaries, AV manufacturers face complex criminal exposure, which struggle to address such cases through traditional frameworks like liability for producing substandard products or causing major accidents (L. Yang, 2025). Petrauskaitė (2025) further examines these issues in the context of German manufacturer liability for AV accidents, focusing on Volkswagen’s AI-assisted “Travel Assist” feature. Analyzing relevant legal instruments and case law, the study reveals significant gaps in proving causation, exposing the inadequacy of existing evidentiary frameworks. This research reflects the broader tension confronting Germany, and by extension all AV-regulating jurisdictions, namely, how to balance robust accountability mechanisms with the imperative to foster innovation.

Data protection and privacy laws also require significant adaptation. As discussed in the ethical section, AVs generate and collect vast amounts of data, raising fundamental legal questions regarding data ownership, access, usage, and protection. The secure and ethical sharing of AV data across domains adds another layer of complexity. A mixed-methods study reveals fragmentation across national reporting mandates, local technological adoption, and data lifecycle management, underscoring the need for a comprehensive understanding of the socio-technical and legal factors shaping AV data governance (Salas-Niño, 2025). Collectively, these challenges point to the necessity of a multi-faceted approach to data and privacy protection, one that integrates technical security with robust legal frameworks, ethical principles, and societal norms to ensure responsible data handling throughout the AV ecosystem.

2.3 Dilemma in Social Implications

The widespread adoption of AVs, particularly in commercial sectors like trucking and ride-hailing, is expected to have significant economic implications, such as job displacement, which requires workforce retraining and new social safety nets. While AVs could create new high-end employment opportunities in manufacturing, software development, and maintenance, such as algorithm engineers, their widespread adoption is also likely to displace a significant portion of the transportation workforce, redirecting these workers toward low-skilled sectors. Overall, these two trends will lead to labor market polarization and the inequality of social wealth (Autor, 2015). Empirical evidence has supported this assertion. Studies indicate that an increase of one robot per thousand workers correlates with a 0.18-0.34% decline in the employed population ratio and a 0.25-0.5% drop in wages (Acemoglu & Restrepo, 2017). The underlying mechanism is a labor market saturation effect: the displacement of workers into an already crowded low-skilled sector exacerbates competition, thereby driving down overall social employment outcomes and earnings. As Hafiz et al. (2025) acknowledge, employment displacement poses a significant challenge for autonomous public transport. These concerns underscore the urgent need for a systemic approach that integrates social impact assessments and proactive transition policies to ensure equitable access to the benefits of autonomous mobility.

Public acceptance and trust remain critical barriers. A comparative study using the Technology Acceptance Model (TAM) reveals that while China's strong policy support boosts adoption, trust vulnerabilities are significant (Y. Yang et al., 2025). Public sentiment, particularly following AV accidents, tends to be predominantly negative, centring on whether autonomous systems can replace human drivers, whether emergency mechanisms are adequate and mature, and whether firms over-market these technologies, fostering misplaced trust (Y. Yang et al., 2025). As the Xiaomi case illustrates, technological progress is inseparable from social trust and consumer willingness to adopt. If acceptance falters, autonomous driving risks stagnation or backlash, regardless of technical innovation or regulatory improvement (Wang, 2024).

It is worth mentioning that government finance, urban planning and infrastructure construction also have significant impacts on the widespread adoption of AVs. Findings in many jurisdictions have highlighted the dual nature of AVs: while offering significant benefits, their realization is contingent upon comprehensive governmental support and public conditions. For instance, barriers of electric AVs in Italian urban logistics include limited charging infrastructure and range constraints, emphasizing the need for continued investment, policy support, and public-private collaboration (Alsaleh, 2025). Similarly, Sitinjak et al. (2024) highlights AV opportunities for Malaysia, including improved road safety and reduced congestion, but also challenges in regulation, infrastructure, and public acceptance. These studies underscore that the successful integration of AVs into urban environments requires a holistic approach that considers not only traffic flow and efficiency but also environmental sustainability, infrastructure readiness, and the broader socio-economic context.

In sum, this study argues that, beyond the inherent technological limitations, the dilemmas of AV adoption, spanning ethical, legal, and social domains, constitute an interconnected triad. Any governance response that addresses only one dimension while neglecting the others will prove inadequate, not merely because each dimension matters, but because their interactions create dynamics that single-dimensional interventions fail to capture. The path forward thus lies in integrated frameworks that respect these interconnections and harness them for virtuous cycles of governance.

3. The Governance Paradigms of Autonomous Vehicle

The paradigms on governing AVs have evolved from traditional regulatory models to more adaptive and, recently, decentralized approaches. However, a critical examination reveals that even these advanced governance paradigms often fall short of providing a truly systemic solution, frequently remaining fragmented or focusing on specific aspects rather than the holistic integration required for AVs.

3.1 Regulatory Models in Representative Jurisdictions

3.1.1 The United States Model

The United States (U.S.) has adopted a largely decentralized and innovation-driven approach to AV regulation. As highlighted by Lujan Tutusaus et al. (2026), the U.S. model is characterized by state-level regulation complemented by federal guidance, which promotes Level 4 automation. This decentralized structure allows for greater flexibility and experimentation, with individual states often leading the way in developing testing permits and operational rules. For instance, states like California, Nevada, and Texas have been at the forefront of AV testing and deployment (Robles & Mallinson, 2024). The federal government, primarily through the National Highway Traffic Safety Administration (NHTSA), issues voluntary guidelines rather than prescriptive regulations, aiming to foster innovation without stifling technological development. This approach has facilitated rapid deployment and testing by AV companies, allowing for real-world data collection and iterative development. However, the fragmented nature of state-level regulations can create a patchwork of rules, posing challenges for manufacturers seeking to deploy AVs nationwide and potentially leading to inconsistencies in safety standards and liability assignments (Ivanov et al., 2025). While this model encourages rapid innovation, it also places a significant burden on companies to navigate diverse legal requirements and on the public to understand varying rules across jurisdictions.

3.1.2 The European Union Model

In contrast to the U.S., the European Union (EU) has pursued a more unified and safety-focused regulatory framework. Lujan Tutusaus et al. (2026) describe the EU's approach as enforcing a safety-focused framework with structured validation, often seen as more cautious. The EU emphasizes a type-approval system, where vehicles must meet stringent safety and environmental standards before being allowed on public roads. This centralized approach aims to create a single market for AVs across member states, reducing regulatory burdens for manufacturers and ensuring a consistent level of safety for consumers. This cautious stance, while promoting high safety standards and consumer protection, has been perceived by some, including Lujan Tutusaus et al. (2026), as a potential barrier to rapid deployment compared to other jurisdictions. This regulatory caution has coincided with, and arguably contributed to, a notable stagnation in AV technological development and commercial deployment within the EU. Bosch CEO Stefan Hartung (2025) has openly criticized the EU's approach to AV regulation, warning that excessive and ill-calibrated requirements risk delaying Europe's AV future. This stagnation, however, points to a deeper structural tension at the heart of European AV governance: the persistent separation between technological innovation, societal development, and legal certainty. While the EU has prioritized legal predictability and safety assurance, these priorities have not been effectively integrated with the imperatives of fostering innovation or anticipating the broader societal transformations that AV deployment entails.

3.1.3 China's Emerging Model

China's approach to AV regulation is characterized by a centralized hierarchy with national standards and localized pilot programs (Lujan Tutusaus et al., 2026). Ivanov et al. (2025) also identifies China's as a government-oriented strategy. This model aims to balance rapid technological advancement with stringent safety oversight and strategic industrial development. The Chinese government has adopted a top-down strategy, issuing national guidelines and standards while simultaneously promoting controlled testing and deployment in designated zones and smart cities. This centralized coordination allows for rapid policy implementation and large-scale infrastructure development, leveraging the nation's capacity for strategic planning. While China's coordinated approach has led to significant advancements in AV deployment, it also faces challenges related to fragmented governance and ensuring sustained innovation, as noted by Wu et al. (2025). The speed at which AV technology is evolving makes it difficult for central regulatory authorities, let alone multiple local agencies, to keep pace. Regulations risk becoming outdated before they are even fully implemented, leaving ethical guidelines, technical safety standards, and legal regulatory frameworks in China in a nascent and fragmented state, making it difficult to align with other major jurisdictions. Moreover, revenue streams that currently contribute substantially to China's public coffers, including vehicle purchase tax, fuel-related consumption tax, and traffic fines, are likely to decline with the widespread adoption of electric AVs and the corresponding reduction in human-driven infractions. Concurrently, the Chinese government faces mounting pressure to allocate considerable public investment to the development of smart infrastructure, such as vehicle-to-everything (V2X) communication systems and charging facilities for electric AVs (K. Li & D. Li, 2025). China, with a huge population, is facing pressure to adjust its fiscal policy to adapt to the changing balance between its ongoing technological developments and social security systems.

3.1.4 The Singapore Model

Singapore has explored an alternative regulatory pathway through the regulatory sandbox approach, a mechanism that allows companies to test AV technologies in controlled real-world environments under temporary exemptions from certain regulatory requirements. The advantage of this model is its ability to foster innovation by reducing regulatory burdens for early-stage technologies, while still allowing regulators to monitor risks and gather data. It provides a flexible mechanism for learning and adapting regulations as the technology matures. However, the very features that make sandboxes attractive also reveal their inherent limitations. By design, they are temporally bounded and spatially constrained, operating as exceptions to, rather than integrations within, the broader regulatory landscape (Chin et al., 2026). Scaling up successful sandbox initiatives to nationwide deployment still requires a permanent and comprehensive legal framework, yet the transition from experimental exemption to full regulatory compliance remains fraught with challenges. This discontinuity also exemplifies the persistent fragmentation plaguing global AV governance: innovation is encouraged in isolated pockets, but the systemic integration of these learnings into coherent, scalable policy frameworks remains elusive.

3.2 Limitations of Fragmented Governance

The above analyses consistently reveal that current regulatory landscape are often reactive, fragmented, and struggle to keep pace with the rapid technological evolution of AVs, where ethical philosophies, legal frameworks, technological capabilities, and societal needs evolve along parallel but disconnected trajectories. This siloed approach, while seemingly pragmatic for tackling specific issues, ultimately creates significant bottlenecks and systemic vulnerabilities. For instance, ethical frameworks often grapple with the challenge of translating abstract moral principles into concrete algorithmic decisions (Gao et al., 2024; Y. Yang et al., 2025). However, if these ethical considerations are not deeply integrated into the technical design process, they risk remaining theoretical or being retrofitted, leading to suboptimal or even contradictory outcomes. The preference for personal decisions in trolley dilemmas, as identified by Yoo et al. (2025), highlights that public trust is not solely about the "right" ethical outcome but also the transparency and perceived fairness of the decision-making process, which technical solutions alone fail to guarantee.

Similarly, legal and regulatory frameworks, as explored in China, struggle to keep pace with rapid technological evolution. The complexities of liability assignment, data privacy, and cybersecurity demonstrate that existing legal structures are ill-equipped for the novel challenges posed by AI-driven autonomy (Perry & Ammari, 2026). Fragmented national and international regulatory approaches, as noted by Suhariyanto et al. (2024), create an inconsistent and uncertain environment that hinders safe and equitable AV deployment. Meanwhile, as discussed in the EU, a purely legalistic approach, without considering the technical feasibility of compliance or the ethical implications of enforcement, can stifle innovation or lead to unintended consequences. Moreover, the socio-economic and infrastructural impacts of AVs reveal that a narrow focus on technological efficiency or market-driven innovation can exacerbate existing social inequalities or create new ones. Concerns about spatial inequity, perception bias, and the need for inclusive cannot be resolved by technical solutions alone (Hwangbo et al., 2024).

Collectively, these governance limitations underscore a critical insight: prevailing single-paradigm approaches are fundamentally inadequate for addressing the multidimensional reality of AV deployment. When governance is fragmented, these interdependencies are overlooked, leading to suboptimal outcomes in technological development, public acceptance, and overall societal well-being. The persistent fragmentation of ethical, legal, and social dimensions, therefore, not only mirrors but actively reinforces the limitations of single-paradigm thinking, creating a compelling case for a fundamental shift towards systemic governance.

4. Towards Systemic Governance: Integrated Frameworks and Future Directions

Drawing upon the extensive analysis above, the systemic frameworks move beyond addressing individual problems to fostering a holistic and dynamic governance ecosystem.

4.1 Core Principles for Autonomous Vehicle Governance

An effective governance framework for AVs must be built upon a set of foundational principles that guide policy development, regulatory enforcement, and public engagement. These principles are designed to ensure that the integration of AVs is responsible, sustainable, and beneficial for human society.

Firstly, balancing innovation and safety is a fundamental principle of any systemic digital governance framework, which must actively foster technological innovation while maintaining an unwavering commitment to public safety. This principle acknowledges that overly restrictive regulations can stifle progress, yet unchecked innovation can lead to unacceptable risks. Therefore, the framework should encourage research and development, provide clear pathways for testing and deployment, and support the growth of AV industries. Simultaneously, it must establish stringent safety standards, robust testing protocols, and continuous monitoring mechanisms to ensure that AVs operate reliably and safely on public roads. The approach should be dynamic, allowing for adaptive regulation that evolves with technological maturity, as suggested by Shen et al. (2024)'s agile governance concept.

Secondly, ethical principles must be embedded at every stage of AV development and deployment. This requires addressing moral dilemmas, ensuring fairness in algorithmic decision-making, and respecting fundamental human values. Central to this ethical commitment is transparency, particularly regarding how AVs are programmed to handle unavoidable accident scenarios. To move beyond mere rhetoric and genuinely safeguard the public's right to information, a three-tier transparency guarantee system is essential:

(1) Technological Transparency: Mandatory disclosure of AV performance and safety data shall be required to clearly define the functional boundaries and inherent limitations of autonomous driving systems.

(2) Testing Transparency: Testing data should be released regularly, and preliminary investigation reports must be made public promptly following accidents to ensure timely and accurate access to information.

(3) Liability Transparency: AV safety responsibilities, including those related to personal data protection, must be clearly defined and visibly implemented to protect individual rights and strengthen trust in autonomous driving.

Beyond these transparency principles, public trust itself must be actively cultivated as a cornerstone of AV adoption. This involves transparent communication with stakeholders, comprehensive public education campaigns, and meaningful mechanisms for public engagement in policy formulation. Furthermore, the framework should consider the unique socio-cultural values of each jurisdiction, ensuring that ethical guidelines resonate with local societal norms.

Finally, the governance framework must take inclusivity and equity into account to ensure that the benefits of AV technology are broadly distributed across society and that vulnerable populations are not marginalized. The ultimate goal of AV adoption is to advance social equity rather than undermine it, making inclusivity a fundamental requirement from conception to deployment. This includes promoting equitable access to AV services, considering the needs of the elderly and disabled, and mitigating potential negative impacts on employment (Majumdar & Pandey, 2025; Mircea et al., 2025). Meanwhile, policies should address potential spatial inequities in AV deployment, ensuring that all urban and rural areas can benefit. Furthermore, proactive management of fiscal implications, such as revenue losses from fuel taxes, is also essential to sustain public AV services, as highlighted by Cengiz & Saruç (2025). By integrating these considerations, the framework could leverage AVs to create a more accessible, inclusive, and sustainable transportation system for all citizens.

4.2 A Multi-Layered Regulatory Structure for Autonomous Vehicle Governance

To operationalize these core principles, the need to build a multi-layered regulatory structure that integrates legislative, technical, ethical, and data governance components, supported by robust mechanisms for collaboration and adaptation, is paramount.

At the highest level, a comprehensive autonomous driving law or policy is essential. This foundational legislation would establish the overarching legal framework for AVs, defining key terms, setting out general principles for operation, and clarifying fundamental issues of liability and accountability. Central to this framework is a clearly defined liability regime that addresses accidents across different levels of automation, potentially through a tiered approach where human drivers retain responsibility for lower levels (L1-L2) while manufacturers and operators bear increasing responsibility for higher levels (L3-L5). Such a regime should also consider criminal liability in cases of gross negligence and may draw upon established legal doctrines, such as strict liability, product liability, or theories of causation, to address complex scenarios involving multiple actors. Beyond liability, the framework must include dedicated data protection provisions that tackle the unique challenges of vehicular data, including risks of excessive collection, leakage, and unauthorized use, with policymakers able to draw inspiration from frameworks like the EU's General Data Protection Regulation (GDPR) while adapting provisions to their local legal contexts. This includes establishing clear rules for classifying AV data (e.g., personal, operational, environmental), managing its entire lifecycle, from collection to deletion, and putting in place independent auditing and oversight mechanisms to ensure compliance with data governance and cybersecurity regulations, including regular security audits and privacy impact assessments.

Complementing the legislative framework, a robust system of technical standards and certification is essential to ensure the safety and interoperability of AV systems, a layer that would be managed by international standardization bodies in close collaboration with industry and research institutions. Rounding out the regulatory architecture, the framework should also incorporate policies for incentivizing AV adoption and addressing the fiscal implications, as suggested by Cengiz & Saruç (2025). This could include tax breaks for AV purchases, investment in AV infrastructure, and new taxation models to compensate for declining traditional revenue streams.

Furthermore, the integration of ethical principles into law rules is a critical area. The core challenge is to translate abstract ethical principles (e.g., minimizing harm, non-discrimination, human dignity) into concrete, enforceable legal rules that can guide algorithmic design and judicial review. To address this, a multidisciplinary committee should be established, comprising ethicists, technologists, legal experts, social scientists, and public representatives, tasked with developing and continuously updating national or regional ethical guidelines for AVs. This committee could draw upon international frameworks, such as ISO AI standards, while adapting them to local values and regulatory contexts (Sankaran, 2025). Empowering the committee to audit autonomous driving systems against these ethical AI standards would create a robust mechanism for ex ante compliance, while also enabling courts to reference the standards in ex post liability determinations.

4.3 Mechanisms for Interdisciplinary Collaboration and Adaptive Governance

The proposed multi-layered structure requires dynamic mechanisms to ensure its effectiveness and adaptability to evolving challenges. The most fundamental mechanism is the active and continuous integration of insights from diverse disciplines. As evidenced by the fragmentation of ethical, legal, and social considerations in current scholarship, a systemic approach demands that engineers, ethicists, legal scholars, urban planners, social scientists, economists, and policymakers collaborate from the outset of AV development and deployment. This ensures that technical innovations are informed by societal values, legal feasibility, and urban planning considerations, and vice-versa.

Adopting agile governance mechanisms is essential to ensure the framework remains responsive and flexible in the face of rapid technological change. This entails an iterative approach to policy development, allowing for frequent reviews, updates, and adjustments based on new data, technological advancements, and societal feedback. To inform this process, robust systems for continuous monitoring should be established, tracking AV performance, safety incidents, and broader societal impacts, with regular evaluations feeding directly into policy refinements.

Beyond these adaptive mechanisms, systemic governance entails a holistic approach to risk management that considers technical, ethical, legal, social, and environmental risks in an integrated manner. This could require anticipating cascading failures, managing cybersecurity threats (Al-Hawawreh & Hossain, 2024; Ding et al., 2025), and understanding the broader societal impacts of widespread AV adoption. The trajectory planning with dynamic ethical risk adjustment (Liu et al., 2026) and the focus on preventing dilemmas rather than just resolving them are examples of this proactive risk management.

Finally, given the transnational nature of AV technology development and deployment, systemic governance requires greater international collaboration and harmonization of standards and regulations. For instance, participating in international forums and working groups is essential for facilitating knowledge exchange with leading AV jurisdictions, enabling the sharing of best practices, research findings, and lessons learned from real-world deployment. Such engagement can also pave the way for cross-border agreements on AV testing and deployment, promoting international trade and mobility while carefully navigating data sovereignty and legal complexities. The current fragmentation and inconsistency in regulatory approaches across jurisdictions underscore the urgent need for coordinated global efforts to create a more predictable and coherent environment for AVs.

In sum, by integrating these principles and mechanisms into a multi-layered regulatory structure, the future of AV governance can move beyond reactive, fragmented responses to a proactive, integrated, and adaptive system that is capable of managing the inherent complexities of autonomous mobility and ensuring its responsible and equitable integration into society.

5. Conclusion

The journey towards integrating AVs into the fabric of society is undeniably complex, marked by both exhilarating technological promise and daunting governance challenges. This study has revealed a critical insight: prevailing single-paradigm approaches, whether narrowly focused on technological innovation, market dynamics, or fragmented regulatory adjustments, are fundamentally inadequate for addressing the multidimensional reality of AV deployment. What is required, therefore, is a paradigm shift toward systemic governance: an integrated framework that actively manages the deep interconnections among ethical dilemmas, legal ambiguities, socio-economic disruptions, and infrastructural transitions. By synthesizing these multidimensional considerations into a coherent whole, this study has proposed a systemic governance framework capable of reconciling innovation with safety, ensuring social equity, and supporting the responsible and sustainable integration of autonomous mobility into human society. It also argues that the urgent call for interdisciplinary collaboration and anticipatory governance is not merely an academic ideal but a practical imperative for navigating the complex reality of this transformative technology. It should be emphasized that examining emerging developmental issues related to AVs is equally important. Future research can explore a promising direction: exploring the integration of AVs with other evolving technologies to understand how AVs can work in tandem with smart city systems or with public transport to create a holistic mobility ecosystem (de Leo & Miragliotta, 2026).

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