A Review of Legal Considerations and Liability Allocation in Connected and Automated Vehicles

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Abstract

The introduction of Connected and Automated Vehicles (CAVs) of SAE level 3, 4 and 5 raises high expectations of reduction of traffic congestion, road crashes and vehicle emissions. The automated era might also have potential shortcomings, especially during the transitional phase, where conventional and automated vehicles of different levels of automation will share the road. The interaction of CAVs, conventional vehicles and vulnerable road users (VRUs) will introduce new challenges for road safety. In that context, the objective of this paper is to provide a comprehensive review of current literature in order to identify critical knowledge gaps especially in the development of effective legal frameworks and the implications of liability distribution on CAVs adoption and operation. By addressing these issues, the paper aims to guide interested stakeholders such as, policymakers, researchers and industry leaders in fostering a safer, more efficient, and especially legally sound transition to automation.

Keywords: connected and automated vehicles; liability allocation; legal frameworks

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1. Introduction

Connected and Automated Vehicles (CAVs) are positioned at the forefront of modern transport innovation, presenting promising advances in the sector while addressing long-standing inefficiencies in safety, environmental impact, social equity and urban mobility, that have affected users and policymakers for decades With levels of automation defined by the SAE International framework, CAVs at levels 3 to 5 can assume varying degrees of driving tasks, with level 5 requiring no human intervention or oversight at all under any circumstance.

Studies forecast major reductions in fatalities and injuries tied to the elimination of human error and impaired driving (Fagnant & Kockelman, 2015; AUSTROADS, 2017). Environmentally, CAVs are expected to enhance fuel economy through automation features such as adaptive cruise control, platooning, and smooth acceleration patterns. For example, eco-driving strategies have been shown to reduce fuel consumption by 4%-10% (NRC, 2013a). Hybrid and fully electric AVs also offer further potential in reducing greenhouse gas emissions and dependency on fossil fuels (Folsom, 2012). Projections have indicated that, socially, increased mobility can be expected for elderly users by up to 50% (Meyer & Deix, 2014; Brown et al., 2014), and the impacts of such advancement have already begun to draw attention within transport policy. At the same time, simulations in Zurich reported that shared AVs have the ability to replace up to 14 conventional cars (Boesch et al., 2016).

Yet, this automated future presents significant legal and operational hurdles. During the transitional phase—when conventional vehicles coexist with various levels of automation—the interactions between vehicles and with VRUs become increasingly complex. Human-machine handovers in SAE Levels 3-4 systems may result in crashes if drivers are not prepared to resume control (Martínez-Díaza & Soriguera, 2018; Bellet et al., 2019). More critically in such settings, liability remains ambiguously addressed in the current legal frameworks, and it has posed an ongoing concern among policymakers. To this purpose, a comprehensive review of recent literature has been conducted on the legal frameworks, regulations and liability allocation of CAVs. After a short presentation of the literature review methodology, the review results are presented. This is followed by a discussion section, where the most important research gaps identified in the literature are highlighted. Finally, the conclusion offers suggestions for further research.

2. Literature Review Methodology

The literature review follows the PRISMA methodology to ensure a rigorous and transparent selection process. The sources of information for the current study were ScienceDirect, IEEExplore. IEEE journals, Google Scholar, and TRID. These databases were searched using keyword variation of {("connected and automated vehicles" OR "CAVs" OR "autonomous vehicles") AND ("legal framework" OR liability OR "regulatory issues")}.” Only peer-review academic journal and conference articles were selected in order to maintain control over quality of the inputs.

A total of 608 records were identified from all the database sources using the combined keyword searches. 52 duplicate records were screened out, and the remaining articles (n = 556) were screened based on the titles and abstract, to determine whether each study fulfils the criteria to further be examined for the review. After the exclusion of 482 records that were not in the criteria list, 74 full text articles were assessed for eligibility. A full-text review of each included study was conducted. From all the selected studies identified in the final review (n =39), backward referencing was applied to check for any other available literature that was missed during the initial search, leading to 45 studies in conclusion (Fig.1).

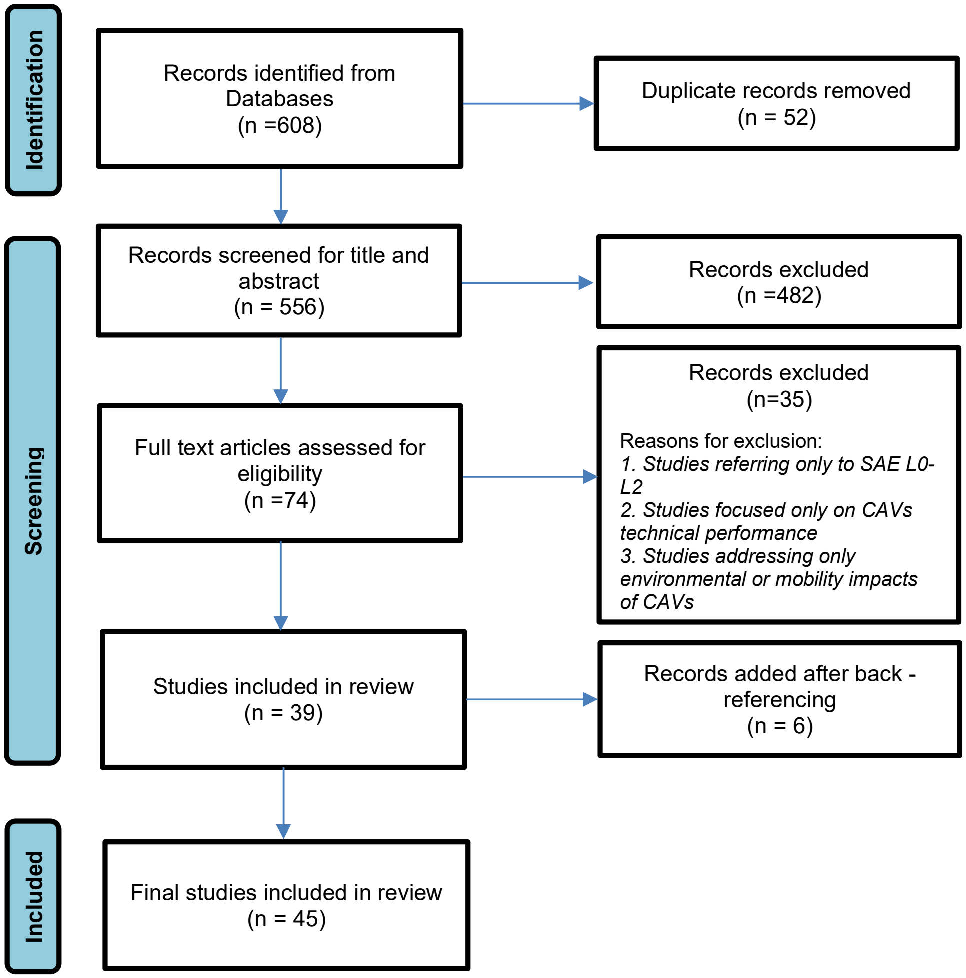

Figure 1. PRISMA flow diagram for articles selection for systematic review

3. *Key Findings*

3.1 Legal Frameworks Across Jurisdictions

The legal frameworks required for CAVs have not been evenly developed between various nations, and significant differences exist in how those regulatory norms are established. Regulatory readiness varies not only in terms of technological adoption but also in the comprehensiveness of liability and operational standards. Eastmant et al. (2023) provide a comparative study across Australia, China, France, Germany, Japan, and the United Kingdom, where the regulatory maturity was found to be broad. Australia developed an end-to-end Automated Vehicle Safety Law (AVSL), focusing on type approval, in-service safety, and liability coverage. Germany and France align in general with the EU regulatory strategy, which emphasizes the need of operational design domains (ODDs) and assigns responsibility to manufacturers, particularly for SAE Level 4 and 5 operations. Additionally, France mandates technical inspections and data recording through event data recorders (EDRs), enhancing legal clarity during post-crash investigations (Milenković et al., 2025). In contrast, China's regulatory landscape is fragmented, with aggressive deployment goals but inconsistent standards across regions such as Shenzhen and Beijing (Eastmant et al., 2023). Even though national strategies support rapid AV development, regional autonomy causes disparities in legal definitions and enforcement mechanisms. On the other hand, the United States provide a unique perspective due to their decentralized legal system. More precisely, Smith (2013) claims that CAVs are "probably legal" under current U.S. laws given the fact that they are not explicitly prohibited. However, current federal safety standards do not clearly address cases where a human driver is missing, and state laws, such as New York's requirement for a hand on the wheel, can be the source of legal ambiguity. Pétervári & Pázmándi (2018) predict that this fragmented system may result in regulatory arbitrage, where developers choose jurisdictions with the least oversight.

The Vienna Convention on Road Traffic, as amended in 2016, permits automated driving systems provided that human intervention is possible. The convention provides an important shift in the legal approach to automation, though this allowance stands limited—because, according to Martinesco et al. (2019), the majority of these systems are operated remotely, resulting in a significant governance gap, especially regarding remote operation with particular concern for liability in cross-border contexts. Based on Almaskati et al. (2023) confirms although automated vehicle regulation is being discussed globally, most nations currently rely on non-binding councils or soft guidelines rather than established laws that have an actual effect. This leaves multinational AV manufacturers facing major risks—specifically when it comes to allocation of liability in cross-border incidents, since harmonized legal standards have not yet been adopted.

To summarize, while countries like Germany, France, and Australia have made substantial progress toward defining CAV liability and operational standards, others—such as the U.S. and China—remain in transitional regulatory stages. Legal fragmentation remains one of the key impediments to global scalability and trust in CAV technology.

3.2 Liability Allocation Models

Liability attribution in CAVs has become one of the most debated topics in safety law as the legal framework has not successfully kept pace with advances in technology or the diversity of operating scenarios that frequently arise (as automation increases in vehicles). Current standard models, which are based on the driver being primarily liable for incidents, reveal significant flaws; these flaws are particularly clear, especially during shared control or full autonomy operations.

Research has grown rapidly to analyze how blame and responsibility get distributed in different scenarios of automation, and Bennett et al. (2020) determined that the level of blame placed on human drivers by human participants can't be defined in a simple pattern or ignore the context. Nevertheless, even in settings where vehicles possess primary control such as in SAE Level 3 and 4, if the human fails to intervene during emergencies, participants continued to assign considerable responsibility to the human occupant. Wotton et al. (2022) gave additional support for such findings: their work demonstrated that variations in the driver behavior (e.g., using a phone, sleeping, or being impaired) had rather little effect on blame assignment. In higher levels of automation, it was common for blame to shift increasingly away from the individual in the vehicle and towards parties who had large influence over system performance, namely vehicle producers, programmers, and even governments. Manufacturers therefore often bear significant public expectation for system safety.

Zhai et al. (2023) have analyzed how blame was attributed in human–machine interaction and found that perceptions of control play a mediating role in blame assignment—individuals tend to assign less responsibility when provided with less control, connecting liability perceptions to perceived intervention instead of actual control mechanisms. From these findings emerges the concept of "moral crumple zones," where individuals are blamed for failures of the CAV system that they did not cause or could prevent. This theory offers an explanation for incidents where blame falls on the human actor rather than on the automated systems or designers, even when those actors had very limited influence, and it has implications for litigation. A defense strategy has been proposed by legal scholars. Chen et al. (2024), building upon the German tort law, assign the manufacturers the initial burden of proof for both product defect and causality, unless they can prove otherwise—which shifts certain litigation risks to manufacturers and encourages stricter safety controls. This model could be especially useful in jurisdictions without consumer protection mandates (e.g. China). Meanwhile, Di et al. (2020) have constructed a hierarchical game-theoritc approach to model liability in automated vehicle environments as a dynamic equilibrium between vehicle users, manufacturers, and regulatory authorities. In their analysis, the application of comparative negligence frameworks, which allocate fault among all relevant actors, creates stronger incentive alignment, minimizes moral hazard, and is expected to improve overall road safety.

Further complicity is added when multi-party liability scenarios are considered, and Alawadhi et al. (2020) describe how responsibility in AV crashes may be distributed among software developers, OEMs, AI system integrators, or even infrastructure managers. A clearer and more consumer-friendly approach is enterprise liability, by which a single entity takes on the complete legal responsibility for any incident that occurs. Single entity liability structures are related with risks of hindering innovation or inflating insurance premiums for AV developers. Dawid et al. (2024) explored the effect of liability assignment on market dynamics. Their research considers how various regimes can shape economic incentives within AV markets; therefore, their model indicates that when more responsibility is given to AV manufacturers, increased investment in safety is expected, also leading to higher vehicle costs thus leading to a possible reduction in adoption rates. Safety technology investment is desirable. It has been proposed that technology deployment, supported by infrastructure investments like Vehicle-to-Infrastructure (V2I) systems, can be deployed to support safer adoption without suppressing innovation. On the basis of their findings, infrastructure support together with a carefully chosen liability distribution may allow safer AV deployment without making business innovation more difficult.

Smith (2013) argues that there should be clarification, rather than simple broadening, of the existing liability doctrines in the United States regarding AVs, because confusion around key legal terms such as “driver” and “control” has resulted in unpredictability for both regulators and technology developers who want to develop autonomous systems, and that the lack of uniformity between state vehicle codes creates obstacles to AV deployment. Uniform definitions of “driver” and “control” are recommended. Kalra et al. (2009) place emphasis on federal pre-emption to standardize how liability is treated across states in the U.S. The regulatory ambiguity is viewed as creating barriers to AV adoption. A shift must occur away from the traditional tort-based frameworks and towards structures that recognize multiple responsible parties, not just drivers. Legislation that is constructed clearly and data-sharing mechanisms will be necessary. International harmonization of regulatory approaches has long been necessary for the control of new technology, but such mechanisms are not always straightforward to implement due to local legal traditions. Risk will need to be redistributed in ways that reflect evolving vehicle operation roles. New legal definitions are required for emerging automated systems and accountability must be promoted by the legal system without hampering innovation.

3.3 Human-Machine Interaction and Legal Ambiguity

The interaction between humans and SAE Level 3 and 4 CAVs creates fresh legal uncertainty, particularly associated with handover scenarios, shared operations, and the requirements from human drivers during critical moments. The inadequacy of existing legal frameworks in addressing the complexity of semi-autonomous control transitions is pointed out by the fact that many countries have not yet implemented them. Recent research (Martínez-Díaz and Soriguerab,2018) identifies that human response, once drivers have been disengaged for some duration as mere observers, tends to be unpredictable. After passive observation periods, re-engagement in the driving task by humans often involves significant delay. This poses safety risks that can even be dangerous and life-threatening. In instances where drivers are suddenly asked to resume control, situational awareness may be lacking or the drivers may not be physically ready. Responsibility during such moments has been made a central topic of legal and technical concerns. Does the driver not react quickly enough, or is it the system that gives the handover without proper safeguards? Legal ambiguity exists here. Indeed, as semi-autonomous systems become more common, handover responsibilities continue to lack clear assignments. This question has yet to be answered, so some intervention in this area in future regulatory reform is necessary.

Bellet et al. (2019) introduced the Human-Machine Transition (HMT) concept, proposing a typology that describes how control changes between people and systems, and they stated that legal organizations often encounter complex scenarios driven by hybrid roles that remain largely undefined in statutory law, especially as people occupying this space may not be fully active or completely passive in the dynamic. Legal systems have yet to define this ambiguous zone. It is argued by Bellet et al. (2019) that legal constructs designed for conventional vehicles struggle when applied to automated technologies, so an urgent need has been supported by their findings for the development of adaptive legal instruments (notably in insurance matters and post-crash protection). This requires crosscutting between various legal structures as current regulations do not address these adequately. Urooj et al. (2018) link the efficacy of handover protocols to interface design, highlighting that many current systems lack adequate alerts or cues to prepare drivers for re-engagement. They also discussed the limited success of handover safety vehicles because of the absence of clear audio or visual alerts and short lead times, which have led to drivers being unprepared for regaining control; a finding important for legal frameworks. When the design of operator interfaces does not satisfy ergonomic standards or match the cognitive requirements of the operator burdens of responsibility may reasonably move from the driver to the manufacturer or software designer.

Martinesco et al. (2019) argue that solutions to difficult liability issues require interdisciplinary approaches where technical, legal, and psychological perspectives are blended to achieve clarity and reliability in responsibility assignment, and such approaches are currently being defined and collaborative models are being adopted. The development of standardized Event Data Recorders (EDRs)—devices used to log interactions between humans and automated systems—is proposed as essential for event reconstruction and the allocation of responsibility, and envisioned as potentially critical for event reconstruction and decision making. However, effective implementation and transparent access to EDR data cannot be accomplished unless legal requirements are established, meaning that even robust implementation remains dependent on legislative support. A distinct solution is suggested by Njoku et al. (2023), who recommend a dual-system approach in which biometric driver identification is used to manage data logging, thereby forming a secure chain of control to resolve the forensic complexity in cases where it can be difficult to know who was controlling the vehicle. A transparent, unchangeable record is critical in these cases. The evidentiary record becomes strong enough for courts to differentiate situations of user negligence from those of technical failure.

Rizaldi and Althoff (2015) recommend that traffic regulations should be transformed to computational logic. Their research has shown such a method allows CAVs to produce demonstrations of legal compliance during their decision-making process, thus offering a new paradigm for liability assessment. This formal logic could also provide a defense mechanism in court, wherein an AV could be exonerated if it can mathematically prove that its behavior adhered to codified traffic norms. There is, however, much ambiguity in existing legal definitions. Most jurisdictions still presume a continuous presence of a legally responsible human driver. Inners and Kun (2017) criticize this presumption as incompatible with SAE Level 3–5 systems, which often require the human to relinquish—and then resume—control unpredictably. They call for legislative updates that redefine what it means to “be in control” and who qualifies as the “operator” in mixed-control situations.

In summary, literature has shown a significant need to reconsider the legal concepts of control, responsibility, and fault as applied to human-machine interaction. Existing tort frameworks are shown as inadequate for handling liability issues because the distinction between user and system is not always clear. This ambiguity is amplified by the rapid pace of technology that is emerging with shifting realities. CAVs have become more autonomous these days while still requiring human fallback. The shifting balance between machine and human input renders current legal assumptions questionable.

3.4 Ethical and Social Considerations

Questions beyond technology and law have emerged with CAVs, and these include major ethical dilemmas as well as challenges related to social equity. As the operation of vehicles transitions from humans to machines, complex moral questions that can influence public acceptance and policy development must be addressed. Machines are now making decisions independently, and this change has introduced new issues that must be considered throughout the design and regulation phases. A frequently discussed ethical concern involves the way CAVs ought to respond in crash scenarios where harm is inevitable, with this issue usually being represented by versions of analytic principles in public debates. This is often illustrated through variations of the classic "trolley problem". It is important to note that consumer perspectives have a direct influence in these debates, and tend to offer a normative framework for action. This impact can't always align with societal goals, so the resulting policies may reflect compromises rather than theoretical ideals. The tension between ex-ante efficiency, which seeks to minimize total harm before an event, and ex-post efficiency is addressed by Feess and Muehlheusser (2024) with the conclusion that individuals tend to prefer CAVs that prioritize passenger safety.

Marra et al. (2022) and Zhan & Wan (2024) have argued that the trolley problem, even though it's often used in philosophical applications, is not applicable in A Vs design since AVs are equipped with predictive planning and dynamic pathing features which alter the set of practical decisions significantly when compared to the simplified assumptions in philosophical analyses, regardless of how simple and explainable the ethical models behind such systems are. However, there remains a requirement for ethical frameworks which are both transparent and manageable by people who are not technical specialists. A configurable ethical decision-making framework, drawing from philosophical systems like deontology and utilitarianism, has been proposed by Millan-Blanquel et al. (2020), and within their model one finds the option for considering legal requirements. This architecture would allow vehicles to reflect societal or individual values but raises many concerns, such as topics of embedded bias; also, issues in ensuring fairness of algorithms, and whether consistent regulatory frameworks would exist. Vehicles could be designed by customers to match their preferences but they would still need to meet legal rules.

Public attitudes towards these kinds of moral dilemmas are in practice inconsistent and present persistent complications for policymakers attempting to guide such legislation. Previously, a more generic problem has been explained in recent research. Bonnefon et al. (2016) demonstrated that individuals generally want AVs to follow utilitarian rules, prioritising the greater good, but they want cars to protect themselves and their passengers instead. The term "social dilemma of AV ethics" is used to refer to this contradiction, and it is repeatedly supported. Yoo et al. (2023) used large-scale surveys and showed that participants often support altruistic AV decisions in theory, but hesitate to purchase such vehicles in practice. Cultural dimensions add further complexity. Ono et al. (2023) compared ethical expectations across Japan, China, and the United States, revealing that people were more willing to support self-sacrificing AV decisions when their choices were made public. This shift—described as a form of "hypocritic" behavior—highlights how perceived social accountability influences ethical preferences. These findings suggest that one-size-fits-all AV ethics policies may not be practical across cultures and jurisdictions.

Martinho et al. (2021) have shown that academic discussion often pays much attention to ethical theory, whereas the manufacturers of autonomous vehicles focus more directly on reducing risks and limiting liabilities, and their review manufacturers' reports from California points out that companies tend to reduce risks and damages as well as to legal defensibility instead of abstract programming based on ethics. Policy alignment will be needed if that disconnect is to be addressed, and the connection between ideals and practice must not be ignored. Ethical questions are crossing the conversation. According to Shavell (2020) owners of AVs ought to carry strict liability for harm caused by their vehicles, while the role of distributing compensation should fall to the state. The compensation process is simplified by this model and accountability is moving toward the public sector. Geistfeld (2017) and Dawid and Muehlheusser (2022) claim that ethical rules and legal structure should be built together, in order to maintain the system's stability and helps prevent gaps for both risk allocation and victim protection.

Social equity topics remain crucial; they are being examined by several researchers in the field, including Milakis et al. (2017) and Meyer & Deix (2014), who point out that AVs can significantly improve accessibility for the elderly, disabled, and low-income groups—provided that access is equitable. However, unless shared or public ownership arrangements such as Mobility-as-a-Service (MaaS) can be broadly utilized, the initial high expense of purchasing AVs might actually worsen existing transport gaps. The topic is not limited to mobility alone, since Cavoli et al. (2017) state that CAVs might discourage people from walking or cycling if not properly addressed by policy intervention. There is a risk that negative trends in physical activity will occur, leading to negative public health impacts by controlling AV entrances and the implementation of active travel options to reduce health problems tied to inactivity. These concerns have been contrasted with the potential changes in land utilization. According to Heinrichs (2016) and also Zhang et al. (2015), planners must consider AVs, as these vehicles may increase suburban sprawl, or infringe on parking guidelines and zoning policies.

In conclusion, legal liability is intricately linked to the ethical and social landscape of CAV adoption, and this relationship forms a core consideration for policy development as risk and legal liability will be strongly connected with the adoption process. Public and private equity are often weighed by policymakers, and a mix of these is often required for legitimate frameworks. Safety, fairness, and accountability are required to be considered during system deployment. The literature suggests that a participatory and transparent approach—engaging ethicists, engineers, citizens, and lawmakers—is essential for creating AV systems that are not only legal and safe, but socially accepted and morally grounded

3.5 Insurance and Economic Impacts

The arrival of CAVs is expected to change long-standing insurance practice. With every new evolution, vehicle control is being switched from human drivers to complex automated systems, meaning that traditional fault-based liability systems do not fit as well. Increasing concerns can be observed among professionals in the insurance industry, actuaries, and lawyers about how liability claims will be shared in a world of automated travel. Profound economic shifts might be brought forth by this integration. One shift is multi-party liability, so a clear assignment of responsibility becomes much harder when compared to systems with only a human driver. Insurers can be found in various industries of the economy: suppliers, original equipment manufacturers (OEMs), software designers, artificial intelligence developers, and vehicle users, as explained by Lin et al. (2025). Traditional car insurance assumes a single, responsible driver. However, in an AV context, especially at SAE Levels 4 and 5, no single party can be clearly designated as liable in all scenarios. Their study shows that technical failures and systemic errors are ranked by industry stakeholders as the most disruptive risks to current underwriting practices.

Kester (2022) conducted interviews with insurers from both the UK and the Netherlands; three main response strategies were identified by insurers. some insurers are participating in pilot projects to understand AV risks first-hand; others are lobbying for clearer liability frameworks; and many are focusing on internal adaptation, re-skilling staff to assess digital vehicle profiles and software reliability. The UK, aided by the Automated and Electric Vehicles Act 2018, is seen as more proactive, whereas Dutch insurers largely remain reactive, expecting legislative guidance before altering business models. Strong and Baker (2015) propose several structural changes to cope with AV-related risks. These include centralized liability pools, product liability insurance that shifts the burden to manufacturers, and real-time data-sharing agreements between OEMs and insurers. These adaptations would allow insurance providers to better evaluate claims and understand contextual driving information. However, these shifts require robust legal support to ensure fair and transparent data exchange, a major sticking point between insurers and vehicle makers.

Yuan et al. (2022), using a a Bayesian random parameter probit model, found that fatality and serious injuries are frequently not tied to which party has been assigned liability by investigators or the legal process, and patterns emerged more strongly when other variables were considered. Factors such as the hour a crash takes place, the driver's age, and traffic signal strength have been found to play a very significant part in shaping crash events; insurance models should therefore be adapted to incorporate these dynamic features into pricing mechanisms. Telematic use and situational data, according to them, can inform future methods of pricing for CAVs insurance, which allows more accurate risk adjustment. Risk distributions between makers of vehicles, infrastructure companies, and older insurance providers were assessed by Vignon and Bahrami (2024); fragmented competition is found by them to often result in lesser investment in safety-focused improvements. A monopolistic or integrated market structure, however, is able to take on the costs of collisions internally and thus produces stronger incentives for higher safety investment. In a game-theoretic model, they show that liability allocation has a direct impact on the incentives to invest in safety technologies, vehicle testing, and infrastructure improvements. A poorly defined liability regime, they contend, may promote cost-cutting and suboptimal AV deployment.

From an economic position, significant reduction in cost linked to accidents, fuel, and travel time may be achieved through widespread CAV deployment, as was suggested by multiple recent studies that focus on cost-saving potentials, but still certain legal and insurance issues are on the horizon. Fagnant and Kockelman (2015) estimate that the total annual savings per AV could range from $2,000 to $4,000, derived from reduced crash rates, optimized route planning, and fewer parking-related costs. Legal frameworks must be created and, at present, the legal frameworks have not caught up to CAVs. Legal ambiguities exist which are slowing down these changes. In the context of long-term economic impact, Ryan (2019) predicts that as automation increases, the insurance market will transition from individual insurance to commercial, system-level, or fleet-based policies. He also notes that software updates, cybersecurity breaches, and firmware versioning may become key liabilities for OEMs and software vendors—requiring entirely new coverage categories. Additionally, vehicle ownership models may change, with consumers opting for shared or subscription-based access rather than owning AVs outright, further reshaping insurance portfolios.

Sheehan (2017) introduces a Bayesian network-based risk model, designed specifically for semi-autonomous vehicles that operate in dual-control modes—vehicles where both human drivers and autonomous systems can control key elements such as sensor performance, how vehicles are driven, and physical properties of the driving environment. His framework incorporates sensor performance, contextual awareness, and driving environment as key variables in real-time risk estimation. This model offers a promising foundation for next-generation insurance algorithms. Finally, Rezaei and Caulfield (2021) capture the skepticism among transportation professionals regarding AV safety claims. Their survey reveals that while many support the theoretical reduction in accident rates, they remain unconvinced about real-world reliability, especially in interpreting unpredictable behavior from other road users. This hesitancy, unless addressed by regulation and empirical validation, could lead to inflated insurance premiums or reluctance among insurers to fully embrace AV risk pools.

In summary, insurance framework and economic models must be entirely reconsidered due to its becoming less straightforward, because a new variable has been introduced in the field. Liability is no longer a binary issue between two drivers; instead, it encompasses a complex ecosystem of digital systems, real-time data, infrastructure interactions, and shared operational control.; such as operational data sharing, digital platforms and the involvement of mixed infrastructures, which all play roles in the dynamic of liability between just two drivers now. Instead, liability encompasses a dynamic and interconnected system involving digital elements, continuous streams and several parties. Adaptable and fair solutions must be co-created by regulators, insurers, and technology developers so that the deployment of CAVs does not become hindered by rigid legal frameworks.

4. Discussion

The migration toward CAVs represents not only a technological leap, but also constitutes a significant transformation in legal, ethical, and societal frameworks. Major progress has been observed as CAV development moves forward. Identified benefits such as improved traffic management and road safety have been consistently reported, and these are widely recognized in multiple studies. Uncertainties regarding liability, regulatory harmonization, or operational accountability have been examined extensively. This section integrates insights from the previous findings to explore overarching challenges and future pathways.

4.1 Legal Fragmentation and Regulatory Incoherence

One of the most consistent themes across the literature is the lack of uniform legal frameworks governing AV operations. Eastmant et al. (2023) and Smith (2013) both highlight how jurisdictional variability hampers the creation of consistent operational design domains (ODDs), safety validation mechanisms, and liability models. Without global coordination, manufacturers and users are left to navigate a patchwork of conflicting standards, especially problematic for cross-border applications and international AV manufacturers. Several researchers advocate for international harmonization of regulatory frameworks. Pétervári and Pázmándi (2018) emphasize the need to distinguish between “robot-objects” and “robot-subjects,” proposing novel legal constructs such as digital personhood for AV systems. However, the political and philosophical implications of such reforms remain contentious and underexplored.

4.2 Persistent Uncertainty in Liability Allocation

Despite technological advancements, legal systems remain deeply reliant on human-centric fault models, making them ill-equipped for scenarios where automation assumes partial or full control. As Bennett et al. (2020) and Zhai et al. (2023) demonstrate, public attribution of blame often lags behind actual system capabilities. Even in SAE Level 5 vehicles, humans are sometimes still perceived as ultimately responsible—a phenomenon known as the “moral crumple zone.” Models like those proposed by Chen et al. (2024), Dawid et al. (2024), and Di et al. (2020) show that hybrid legal models incorporating shared or enterprise liability may be more effective in the AV context. However, implementation remains limited, particularly in jurisdictions where product liability laws are not well developed. A crucial takeaway is that liability must evolve from binary, human-fault frameworks to flexible, evidence-based systems capable of attributing fault in complex cyber-physical environments.

4.3 Data Access, Transparency, and Digital Evidence

Another cross-cutting theme is the critical role of data in assigning liability and evaluating AV behavior. The lack of standardized Event Data Recorders (EDRs), especially those interoperable across manufacturers, is a substantial barrier to fair litigation and insurance adjudication. Njoku et al. (2023) and Rizaldi & Althoff (2015) propose using tamper-proof systems based on blockchain or formal logic as tools to reconstruct incidents and prove compliance with traffic laws. Yet, these tools raise further questions around privacy, data ownership, and third-party access. Kester (2022) reveals tensions between insurers and OEMs regarding access to real-time vehicle data. GDPR constraints in Europe exacerbate this challenge, necessitating policy innovation that balances transparency and accountability with user rights and cybersecurity.

4.4 Ethical and Cultural Differences

The ethical programming of AVs is another unresolved issue, particularly as it intersects with liability frameworks. As illustrated by Feess and Muehlheusser (2024), Yoo et al. (2023), and Ono et al. (2023), ethical preferences vary significantly between individuals, contexts, and cultures. This raises the dilemma of whether AVs should be governed by universal ethics or locally configurable moral settings—and who should make these decisions. More broadly, the literature suggests that ethical behavior in AVs cannot be fully codified through logic alone. Public trust depends not only on the ethical design of AVs, but also on the visibility, transparency, and perceived fairness of those systems. This reinforces the argument that AV ethics and liability must be co-developed through participatory processes involving ethicists, regulators, and diverse public stakeholders.

4.5 Impact on Insurance

The insurance industry is nowadays moving through a period of uncertainty, facing new risks which will be driven by CAVs, and as actuaries consider risks in this new landscape, it becomes evident that traditional actuarial models lack the ability to reflect these uncertainties because these models were designed around human-driven vehicles with individual liability structures that are disrupted by CAV technology. In addition, CAV technology is driving risks beyond our control. Risk pricing and claim adjustment become more complicated with the rise of multi-party liability, mentioned by Lin et al. (2025) and Vignon and Bahrami (2024) the responsibility of stakeholders in the value chain, since the boundaries between driver, manufacturer, and software provider liability are blurred in autonomous settings; as a result, standardised protocols for assigning responsibility may often be lacking, leading to a landscape where insurers face operational difficulties in developing products and resolving claims. These new variables impact industry practices. Proposed solutions include remote technology updates, cooperation with OEMs, and underwriting models that use real-time telematics data, which offer possibilities for risk allocation clarity. Rezaei and Caulfield (2021) stress that unless insurers are confident in AV safety and forensic capabilities, premiums may rise, deterring adoption and contradicting broader policy goals of safer roads.

4.6 Gaps in Public Understanding and Trust

Studies by Zhang et al. (2024) and Pöllänen et al. (2020) have observed repeatedly that public views regarding the competence and reliability of autonomous vehicles (AVs) are often misaligned with reality. This misalignment is significant and sometimes gets shaped by public sentiment or misconceptions, which do not always reflect the current technical status of AVs. This can affect future policy if not directed carefully. Educational initiatives, along with demonstrations which involve the public directly, are necessary responses; in engaging stakeholders these programs serve to reduce this gap in perception. An informed public is needed for the development of policies, so deployment can proceed in safe conditions. It was found in the research that delaying engagement efforts increases the chance of misunderstanding and that further misunderstanding might result. Stakeholders contributed to ongoing discussions, so active measures are needed.

5. Conclusion

This literature review reveals that while CAVs offer transformative potential for mobility, safety, and environmental performance, the absence of well-defined legal frameworks, particularly concerning liability, remains a major barrier to widespread adoption. A diverse body of research has explored various models for liability attribution, ethical challenges in AV behavior, and emerging insurance strategies, yet critical gaps remain.

One major gap in the literature concerns the link between liability allocation and actual traffic or safety outcomes. Although models such as enterprise liability or comparative negligence are well-theorized, little empirical research has been conducted to evaluate how these legal frameworks influence road user behavior, AV manufacturer investment in safety features, or crash frequency in real-world deployments. Similarly, how differing liability regimes affect user trust, uptake rates, and compliance behavior in mixed traffic remains underexplored.

Another underdeveloped area is the examination of how legal uncertainty itself may influence system design or traffic efficiency. For example, manufacturers might choose overly cautious or aggressive algorithms depending on jurisdictional risk exposure, which could lead to unintended safety outcomes in complex traffic scenarios.

To address these gaps, future research should:

- Investigate how different liability models (e.g., strict liability, no-fault, shared liability) influence the behavior of manufacturers, developers, insurers, and users.
- Conduct simulation and field studies to examine the real-world safety impact of liability frameworks in transitional traffic environments.
- Explore the behavioral economics of liability from both user and insurer perspectives, including risk aversion, moral hazard, and blame avoidance in CAV design.
- Evaluate the systemic implications of liability design on road safety, congestion, and infrastructure planning.

In conclusion, while the legal debate on CAV liability has advanced significantly, the dynamic relationship between liability allocation and traffic remains insufficiently addressed. Closing this gap is critical not only for legal clarity and public trust, but for realizing the full safety and efficiency benefits promised by automated mobility.

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