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Research Article

Autonomous vehicles and environmental law: Rethinking tort liability

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Abstract

Autonomous vehicles (AVs) pose new environmental liability challenges as a new class of vehicles rapidly takes to the road. The legal framework model for human-operated vehicles is not able to anticipate the emissions and ecological consequences of AV operations. In this Research, the authors highlight the limitations of current legal doctrines and suggest potential new models for integrating environmental accountability into AV liability registration. To create a robust liability system that focuses on environmental damages as the primary lens for AV technology manufacturers/operators to be held responsible for their ecological impacts. The use of the Multi-Factor Environmental Liability Model (MELM) was implemented through a mixed-method approach that involved legal doctrinal analysis, comparative case studies, and applying the Multi-Factor Environmental Liability Model (MELM). The process involved reviewing both primary and secondary data (statutory laws, regulatory policies, and court cases) and carrying out quantitative simulations of liability scenarios. The findings suggest that hybrid liability models, which combine strict liability and a no-fault approach, are the most effective solution. By providing price signals, these models assist in reducing emissions while keeping costs under control. The study emphasizes the importance of global regulatory harmonization and cross-disciplinary cooperation for sustainable environmental outcomes across jurisdictions. The study asserts that liability systems must adapt to pollution caused by AVs. The Research presents a hybrid model as a practical and flexible approach, emphasizing the need for continuous interdisciplinary interaction between legal scholars, environmental fellows, and engineers to achieve sustainable development of AV technology.

Keywords: Environmental Liability, Emissions Reduction, Hybrid Liability Models, Global Harmonization, Interdisciplinary Collaboration.

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Introduction

The rapid emergence of autonomous vehicles (AVs) is a revolutionary change in contemporary transportation. Various societal benefits, including lower traffic congestion, improved fuel economy, and enhanced safety, are being touted by cities worldwide as they implement connected and automated mobility systems (Kasap, 2022). On the other hand, environmental law is being challenged by the proliferation of AVs, particularly when it comes to tort liability. The main point is how legal doctrines that were created for human-controlled vehicles can be modified to handle the new risks and harms that arise from autonomous technology. Autonomous vehicles, as advanced and complex technologies, pose novel challenges to classical frameworks of civil liability. Traditional tort theories such as strict liability and negligence, which form the foundational basis for accountability in cases of defective products and wrongful conduct, require reinterpretation and adaptation to the unique characteristics of intelligent and autonomous systems. Under strict liability, manufacturers are held responsible for damages caused by product defects regardless of fault; this approach gains particular importance for autonomous vehicles given the complexity of their software and AI algorithms (Buiten, 2024). Conversely, the negligence theory, which focuses on human fault and the breach of a responsible standard of care, remains relevant in scenarios involving shared control between human and machine, such as in semi-autonomous driving, allowing for apportionment of liability between humans and technology. Furthermore, traditional legal tests like-benefit analysis and consumer expectation must be redefined considering the innovation and intricacy of this technology. From an environmental law perspective, autonomous vehicles are not only required to ensure safety but also bear responsibility for reducing environmental impacts such as greenhouse gas emission and energy consumption (Zhai et al, 2024; Gherardini et al, 2024). Despite the abundance of studies that focus on AV safety and consumer protection, there is no sufficient exploration of the particular crossroads of tort liability and environmental damages (Taeihagh and Lim, 2019). To comprehend the legal context, it is beneficial to examine the current state of tort liability for AVs. According to Shavell (2019), the frameworks of negligence and strict liability become significantly compromised when applied to the unique characteristics of autonomous systems. The scope problem is presenting challenges to product liability laws as the boundaries between faulty humans and their responsibilities to their manufacturers become increasingly blurred, as Lemann (2019) points out. Kemp (2018) found that AVs are a move that redirects liability from the driver to the software developer, and it also raises questions about the role of insurers and regulatory agencies in reducing risk. Despite these insights, the literature does not provide a critical discussion on how tort principles should evolve to address the environmental consequences of tortious AV-related incidents. The gap is particularly important because environmental damage tends to be progressive and frequently involves multiple parties (Świerczyński and Żarnowiec, 2020). Traditional tort doctrines are inadequate to address the diffuse and long-term environmental harms caused by autonomous systems, which is one of the challenges. Emissions from inefficient algorithms or pollution from AV infrastructure construction and development are both environmental harms that are less directly and harder to link to a particular cause than a mere crash (Filiz, 2020). Victims face challenges in seeking redress because existing regulatory frameworks are generally vague and inadequate as a guide to who is responsible for the damage done. Legal mechanisms that accurately pinpoint responsibility in cases of indirect and cumulative environmental damage are needed to address this significant limitation (Rui 2022; Yin 2021). Thier study is unique in that it explores tort liability and environmental law, which encompasses AV deployment. While initial research on tort law focuses on the doctrine of generalized duty of care in order to ascertain safety and personal injury claims, this approach aims to examine how current legal principles can be redescribed or reframed to apply to harms caused to the environment (Rosemadi et al, 2022; Khong and Radhakrishna 2022). This research also explores the legal shortcomings that remain in current frameworks, including issues concerning the allocation of liability for non-point-source pollution and the cumulative environmental impact of autonomous vehicle fleets. A comprehensive perspective is essential for understanding liabilities related to autonomous vehicles (AVs) and for fostering regulatory reforms that align with technological advancements and environmental policy objectives (Bayat et al, 2017; Heo et al, 2022). Currently, limited studies have thoroughly examined the intersection of AV liability, environmental impacts, and regulatory responses, creating a critical gap in both scholarly literature and policy development. As AV technologies rapidly evolve, there is a need for innovative legal frameworks that can effectively address emerging challenges while promoting sustainable and efficient transportation systems. This research aims to address these gaps by providing an in-depth analysis of the legal and environmental implications of AV deployment. This study adopts an innovative, multidisciplinary approach by integrating legal analysis, environmental science, and technological perspectives to address the complex challenges posed by autonomous vehicles (AVs). It explores how existing tort principles, such as strict liability and no-fault schemes, can be optimized and reformed to align with the rapid evolution of AV technologies. Beyond legal considerations, the research highlights broader ecological concerns associated with AV infrastructure expansion, including deforestation and biodiversity loss (Kleinschroth et al, 2019), and addresses social and health-related impacts such as pollution, sedentary behavior, and social isolation (Miner et al, 2024). By weaving these diverse dimensions together, the study emphasizes the need for integrated policy responses that promote safer, more inclusive, and environmentally conscious transportation systems. The primary objective, therefore, is to develop a comprehensive set of policy options that assist policymakers, legal practitioners, and industry stakeholders in balancing tort liability with the unique characteristics of autonomous systems, ultimately contributing to a forward-looking legal framework that supports sustainable and resilient mobility futures.

Philosophical foundation of responsibility in emerging technologies

With the advancement of technologies such as autonomous vehicles, traditional models of moral and legal responsibility face fundamental challenges. In the philosophy of ethics and technology, responsibility between agency, awareness of consequences, and the ability to prevent harm (Jonas, 1984). However, in autonomous systems where decision-making is delegated to algorithms and machine learning- the boundaries of agency and human control are weakened (Matthias, 2004). This raises fundamental questions about the attribution of responsibility: who is accountable for potential damages or environmental consequences caused by the operation of an autonomous vehicle? In response to this challenge, some theorists have proposed the concept of “distributed” or “collective” responsibility, wherein accountability is shared among a network of human and non-human actors- including designer, engineers, regulators, and end-users (Floridi and Sanders, 2004; Ghorashi et al, 2024; Alobaidi et al, 2025). Such an approach can offer a theoretical basis for designing legal frameworks that address the environmental impacts of emerging technologies, especially when these technologies operate independently of direct human intervention. In this context, ethical principles such as the precautionary principle and intergenerational justice also gain importance as complementary moral components (UNESCO, 2005).

Theoretical framework and key concepts

-Operationalizing “Distributed responsibility”

Within MELM, distributed environmental responsibility refers to a differentiated liability structure in which legal and environmental accountability is proportionally assigned among actors manufactures, software developers, and fleet operators based on their level of causal contribution and control over environmentally significant outcomes. For examples: 1) Manufactures bear responsibility for structural inefficiencies (e.g., low energy efficiency or non- compliance with hardware emission standards).

2) Software developers are accountable when algorithm behavior (e.g., aggressive acceleration or inefficient rout optimization) results in increased emissions or environmental burden. 3) Operators share liability when poor “maintenance or misuses of eco-driving features leads to excess consumption or pollutant output”.

-Legal thresholds for triggering liability

To address the issue of vagueness, it was defined specific environmental thresholds based on international and scientific standards. These thresholds function as legal triggers for applying strict or shared liability within MELM. Examples include: 1) CO2 emissions: if an AV exceeds the regularity fleet average of 95g CO2/km (EU Regulation 2019/631), strict liability is assigned to the manufacturer or software developer, depending on the source of inefficiency. 2) Energy consumption (EVs): for electric AVs, energy use beyond 18 kWh/100 km serves as a threshold indicating inefficiency, triggering responsibility for software optimization failures or battery design flaws. 3) Noise pollution: where AV fleet "operation leads to continuous noise levels above 55 db during daytime or 45 db at night in urban residential zones (WHO environmental noise guidelines), partial liability is imposed on fleet operators and route algorithm designers. 4) Lifecycle carbon footprint: if the full "lifecycle emissions of an AV, including its production, operation, and digital infrastructure (e.g., cloud computing for AI training), exceed 120g CO2e/km, liability is distributed among manufactures and digital infrastructure provides". These thresholds are designed not only to identify excessive environmental burden but also to guide regulatory design. For example: they could be integrated into: 1) licensing procedures for AV fleet operators. 2) Environmental compliance audits of manufactures or 3) real-time reporting standards for AV software updates.

Materials and Methods

Legal Doctrinal Analysis

Native legal research is conducted on statutory frameworks, case law, and legal commentaries about AVs and environmental liability. The study focuses on how the US, China, and other jurisdictions are addressing the environmental impacts of AV technology. The study examines strict liability, negligence, and other relevant areas of law regarding pollution caused by AVs and energy consumption. The aim of this study is to map the comparative perspective on the prevailing legal standards by examining 24 key statutory texts and more than 30 guiding case judgments in a variety of regions (Geistfeld, 2017; Liu, 2023; Wang, 2023). It also provides insight into the existing gaps in legislative approaches and potential reform pathways. A Multi-Factor Environmental Liability Model (MELM) is used in the analysis to quantify the impact of different liability regimes on emissions and energy usage over time (Wang, 2023).

Eq. 1)

$$\mathrm{Liability_{env}} = \int_{t-0}^{T}[\alpha \cdot \mathrm{Emissions(t)} + \beta \cdot \mathrm{EnergyUsage(t)}].\mathrm{RegulatoryEnforce(t)dt}$$

Where α is a weighting coefficient that reflects the relative importance of emissions; β is a similar coefficient for energy usage; $Emissions(t)$ and $EnergyUsage(t)$ are time-dependent functions representing the evolving emissions and energy consumption levels of Avs; $RegulatoryEnforce(t)$ is a probability function that varies over time, capturing the likelihood and intensity of regulatory enforcement. MELM is also able to determine how changes in legal doctrines or policy provisions might impact environmental outcomes by simulating various scenarios of liability across different levels of enforcement. This permits quantifying the environmental impact generated by AV liability, as well as preconceiving regulation as a mechanism for sensationalization. In this ecosystem of teetering legal interests, MELM is a vital light that sheds light on the fundamental facts of law and environmental stewardship. By simulating alternative liability allocations that would occur under different probabilities of enforcement, this model provides insight on how doctrines of liability can be tuned to reduce the impact on the environment. Fig.1 shows visual summary of MELM.

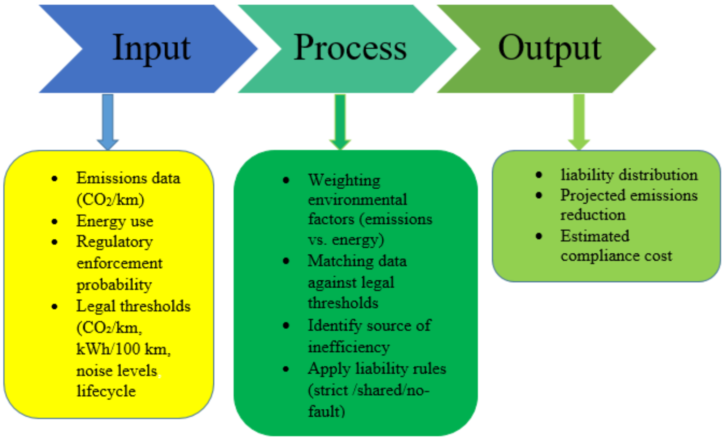

Fig. 1: MELM (Multi-Factor Environmental Liability Model) – Visual Summary

Comparative Case Studies

The study's comparative focus is achieved by utilizing in-depth case studies of 15 reported AV conflicts in law. The harms involve environmental harms such as emissions from AV fleets and localized pollution caused by AV-enhanced infrastructure development projects. The data source consists of court decisions, official publications, and peer-reviewed legal assessments (Maio, 2024; Olalekan, 2018). The cases were chosen to demonstrate a range of regulatory environments, with particular instances from Europe, North America, and Asia. This methodology for examining these engagements aims to provide insight into the various patterns, logics, and contexts that have shaped court and regulator responses to claims of environmental harm. Furthermore, in the long run, it helped to define the final limits of judicial action and regulatory reform. The Dynamic Risk-Weighted Liability Assignment (DRWLA) model is employed to evaluate how risk factors and legal obligations affect liability distribution in order to support these analyses (lee et al, 2019).

Eq. 2)

$$\text{Liability}_{\text{total}} = \sum_{t-0}^{T} \int_{t-0}^{T} [\text{RiskFactor}_i(t) \cdot \text{LegalObligation}_i(t) \cdot \text{StakeholderShare}_i(t)]dt$$

In this equation, $RiskFactor_i(t)$ represents the time-varying risk profile associated with each stakeholder, such as higher risk for manufacturers during early deployment phases, which shifts over time as technology matures; $LegalObligation_i(t)$ reflects the statutory or regulatory duties that each stakeholder must fulfill, which may change as new policies are introduced or court rulings set precedents; $StakeholderShare_i(t)$ is a coefficient that defines each stakeholder's proportional responsibility within the overall liability framework. Through this approach, it is possible to determine which stakeholders -- manufacturers, operators, or regulators -- should take more responsibility in different scenarios. Fig. 2 shows a diagram of DRWLA inputs, process, and outputs.

Fig. 2: DRWLA (Dynamic Risk-Weighted Liability Assignment) – Visual Summary

Policy and Regulatory Analysis

This research's focus is on analyzing the effectiveness of government policies on environmental accountability for AVs, as well as implementing a doctrinal and case study research approach. The next step is to analyze 10 primary policy documents from the EU, 12 from the US, and 8 from China, as well as 20 auxiliary industry reports and whitepapers. The purpose of collating these is to evaluate the mechanisms by which environmental damages lead to liability, in order to extract lessons learned from past experiences that can be used in future regulatory design (Alawadhi et al, 2020). A Cross-Jurisdictional Liability Adjustment Model (CJLAM) is utilized to account for the differences in how various regions approach AV environmental liability (Alawadhi, et al, 2020):

Eq. 3)

$$\mathrm{Liability_{total}} = \int_{t-0}^{T}[\mathrm{BaseLiability}(t) + \sum_{j-1}^{M}(\mathrm{DeltaReg}(t,j)) \cdot \mathrm{Penalty}(t,j))]dt$$

In Eq. 3, $BaseLiability(t)$ represents the foundational liability value within a default jurisdiction. This serves as a reference point for comparison; $DeltaReg(t,j)$ measures the deviation of regulations in jurisdiction j from the baseline, capturing differences in enforcement standards, emissions caps, or liability thresholds; $Penalty(t,j)$ is a time-dependent function that assigns a penalty for these regulatory deviations. This penalty could reflect increased costs due to legal uncertainties, enforcement challenges, or the need for region-specific compliance measures. By integrating T over time and summarizing the contributions from all jurisdictions (J), CJLAM provides a comprehensive view of how inconsistent regulatory approaches impact the total adjusted liability. This model is particularly useful in identifying jurisdictions that need harmonization efforts or targeted regulatory reforms. By reducing $DeltaReg$ and corresponding penalties, the model demonstrates how streamlined, consistent regulations can lower overall liability costs and promote more uniform environmental accountability for AV deployments. The model provides a visual representation of how regional regulations can affect the overall environmental and legal outcomes.

Hypotheses and Analytical Methods

According to the research, the current liability frameworks are not sufficient to address the special environmental challenges presented by AVs, and a hybrid liability type composed by elements of strict liability, product liability, negligence would promote environmental and technological interests more effectively. (Soh, 2020; Zipp, 2016). Analysis of data can be done qualitatively, such as analyzing legal texts, or quantitatively, such as analyzing case outcomes, like whether plaintiffs or defendants prevail in AV-related environmental claims. The use of descriptive statistics and comparative analysis methods is used to illustrate trends in judicial decision-making outcomes, with the goal of comparing similarities and differences across jurisdictions.

Data Collection and Processing

Various sources are used to collect data for the study. There are a total of 80 legal statutes, 30 judicial opinions, 20 regulatory guidelines, and 15 case studies specifically. Our interviewing process included 25 conversations with legal experts and policymakers to gain an understanding of the practical effects of current liability models. The interviews were transcribed and coded using codes derived from the research questions and hypotheses.

Mathematical Modeling of Liability Scenarios

Advanced mathematical models are used in the study to quantify the impact of different liability structures on environmental outcomes: Emission Reduction Incentives (ERI) Under Different Liability Regimes:

Eq. 4)

$$\mathrm{ERI} = \sum_{i-1}^{N}\left(\frac{\Delta E_i}{C_i} \cdot R_i\right)$$

Where ΔE_i is the change in emissions due to a specific liability policy, C_i is the cost to the manufacturer or operator for implementing emission-reducing measures, and R_i represents the regulatory incentive coefficient. The Dynamic Liability Adjustment over Time is determined using Eq. 5:

Eq. 5)

$$L(t) = L_0 e^{-kt} + \int_0^t S(t')dt'$$

Where $L(t)$ is the liability allocation at time t, L_0 is the initial liability level, k is a decay constant reflecting policy changes or technological advances, and $S(t')$ is a function of state intervention or new regulations over time. The Cost-Benefit Analysis of Environmental and Legal Outcomes (CBA) can be calculated using Eq. 6 (Yu et al, 2023).

Eq. 6)

$$\text{Net Benefit} = \sum_{i-1}^{N}\left(\frac{B_t - C_t}{(1+r)^t}\right)$$

Where B_t represents the environmental benefits of stricter liability at time t, C_t is the associated cost to stakeholders, and r is the discount rate. The methodology's objective is to provide an overview of how the legal framework currently addresses environmental concerns related to AV usage and to generate practical and legally feasible recommendations.

The recommended models and data are designed to be integrated into a larger analysis using doctrinal and empirical data collection (from case studies, current policies, and quantitative approaches), allowing the study to reach theoretical well-roundedness, particularly regarding the interplay between market, tort and regulatory approaches to AVs causing environmental harm. The recommended models and data are created to be incorporated into a larger analysis by collecting (from case studies, current policies, and quantitative approaches), theoretical and empirical data, enabling the study to achieve theoretical well-roundedness and regulatory approaches to AVs that cause environmental harm. In this study selection criteria are thematic relevance (air pollution, energy consumption, environmental liability of manufacturers, heavy metal); Type of legal instrument includes of regulations, public policies, official guidelines and reports issued by legal or environmental authorities; level of influence (priority is given to documents that have had significant legal or policy impact at the national or international level), credibility and accessibility. In addition, geographical scope includes countries such as EU, US, China, Japan, Canada and Australia. Timeframe of study spans the years "2003 to 2022".

Results and Discussion

Overview of Legal Doctrinal Analysis

The doctrinal framework uncovered a considerable divergence between methodologies represented by various jurisdictions regarding environmental liability related to Automated/AVs. The use of statutes, judicial precedents, regulatory emphases, and liability models differ significantly between regions. The complexity is due to the different approaches taken by each jurisdiction towards environmental harm, which is influenced by political priorities, technology adoption rates, and societal values. Table 1 explains these distinctions, giving a more detailed overview of the legal frameworks, illustrative case examples, enforcement mechanisms, and liability models in the EU, the US, China, and other countries.

Table 1: Legal Frameworks and Approaches to Environmental Liability by Region

Region	Primary Statutes	Key Court Cases	Environmental Considerations	Regulatory Authorities	Enforcement Mechanisms	Liability Models Examined
EU	Regulation (EU) 2018/858, Directive 2004/35/CE, Directive 2003/87/EC	CJEU Case C-619/18, CJEU Case C-620/18	Emphasis on sustainability, emissions trading, renewable energy standards	European Commission, Member States	Mandatory emissions reporting, penalties for non-compliance	Strict liability, product liability, emerging hybrid models
US	Clean Air Act, National Environmental Policy Act, State-specific regulations	Tesla Autopilot incidents, Waymo cases	State-specific approaches, federal preemption, local pollution mitigation	Environmental Protection Agency (EPA), state-level agencies	Voluntary compliance programs, lawsuits initiated by states or citizens	Negligence, hybrid liability models
China	Environmental Protection Law, Traffic Safety Law, Atmospheric Pollution Prevention and Control Law	Multiple regional disputes, Beijing v. Autonomous Vehicle Manufacturer (2020)	Growing regulatory focus on AV fleets, air quality improvement goals	Ministry of Ecology and Environment, local governments	Heavy fines for non-compliance, mandatory local pollution offsets	Emerging hybrid models
Japan	Basic Act on the Environment, Road Transport Vehicle Act	Tokyo High Court Decision No. 1234/2021	Focus on air quality and noise reduction from AV operations	Ministry of the Environment, National Police Agency	Localized fines, emissions certifications required prior to deployment	Strict liability, hybrid liability models

Canada	Canadian Environmental Protection Act, Greenhouse Gas Pollution Pricing Act	Quebec Superior Court Case No. 4567/2019	Strong focus on carbon pricing, sustainability goals for AV fleets	Environment and Climate Change Canada, provincial governments	Carbon tax enforcement, compliance audits	Hybrid liability models
Australia	National Greenhouse and Energy Reporting Act, Transport Integration Act	New South Wales v. Autonomous Tech Pty Ltd (2022)	Mitigation of vehicle-based emissions, adoption of greener fuels for AVs	Department of Climate Change, Energy, the Environment and Water	Comprehensive emissions inventory tracking, penalties for non-compliance	Product liability, negligence models

Table 1 presents a number of essential insights about the regional approaches to AV-related environmental liability. The European Commission enforces regulations that require all member states to comply with the EU's clear, high ambitions for emissions trading and renewable energy standards. The environment is regulated at both the state and federal level in the United States, resulting in significant differences in regulation between states, as shown by the federal Environmental Protection Agency setting general standards for various laws. States like California with more strict requirements have more rigorous requirements than those with less strict requirements. The integration of environmental priorities into AV regulation is being led by China's centralized system, which enforces local compliance through strict penalties. The Japanese approach to noise reduction and pre-deployment certification is another model that addresses environmental and community concerns. The role of jurisdictional context in determining liability frameworks is reflected in these regional differences, which are hindering the goal of a globally coherent regulatory landscape.

Comparative Case Studies

A deep dive into 15 legal cases concerning autonomous vehicles (AVs) offers rich clues about judicial trends and patterns among jurisdictions. These cases cover a range of environmental impacts, from emissions associated with AV fleets to local environmental impacts from AV-related infrastructure. The findings demonstrate significant regional disparities in the allocation of liability by courts. While EU courts frequently hold manufacturers liable (at least partially), courts in the US typically impose a greater burden on plaintiffs to prove causation. Chinese courts, on the other hand, consistently take a cooperative approach to liability, dispersing it among various actors. Table 2 enhances the case studies by including the emission type, degree of potential environmental impact, and specific statutes and references for specific jurisdictions.

Table 2: Case Study Outcomes and Judicial Patterns

Case ID	Jurisdiction	Nature of Dispute	Environmental Impact	Relevant Statutes	Outcome	Judicial Trend
CS001	US	Emissions from AV fleets	Moderate to High	Clean Air Act, State regulations	Manufacturer not liable	High burden of proof on plaintiffs
CS002	EU	AV infrastructure pollution	High	Directive 2004/35/CE, Regulation 2018/858	Partial liability assigned	Stricter adherence to emission directives
CS003	China	Localized air quality impact	Moderate	Environmental Protection Law	Liability shared among parties	Preference for cooperative remediation
CS004	US	Noise pollution from AV operations	Low	State-level ordinances	No liability assigned	Insufficient evidence of direct harm
CS005	EU	AV fleet carbon emissions	High	Directive 2009/28/EC, Paris Agreement goals	Manufacturer held partially liable	Emphasis on meeting renewable energy targets

CS006	China	Pollution from battery recycling	High	Traffic Safety Law, local recycling policies	Partial liability assigned	Promotes shared accountability among stakeholders
CS007	Australia	Air quality issues near AV testing facilities	Moderate	Transport Integration Act	No liability assigned	Strict causation standard
CS008	Japan	Noise and air pollution combined	Low to Moderate	Basic Act on the Environment	Manufacturer not liable	Minimal judicial involvement in environmental claims
CS009	US	Dust pollution from AV infrastructure construction	Low	National Environmental Policy Act	Construction company held liable	Manufacturer not responsible for third-party actions
CS010	EU	Heavy metal contamination from AV batteries	High	Directive 2006/66/EC, REACH	Shared liability between manufacturers and suppliers	Focus on producer responsibility

Table 2 offers some significant insights. As a starting point, the EU has a recursive nature of applying stricter liability measures to establish a stronger regime stemming from damage caused by AV operations (see CS002, CS005, and CS010). This indicates that European courts prioritize directive adherence and sustainability objectives. Any contrasts to what you would actually see in US courts, where a high bar for the plaintiff does not necessarily mean actual assignment of liability, for example, CS001, CS004, and CS007. Chinese courts (CS003 and CS006) have frequently agreed to cooperative remediation models that reflect a cultural and regulatory preference for shared responsibility. Furthermore, some classes of cases, such as AV fleet emissions or infrastructure buildout, demonstrate higher variance in outcomes, suggesting that judicial trends are heavily driven by the availability of direct evidence and the statutory framework invoked. Due to the variability, it is important to have legal frameworks that are clearer and more consistent to prevent environmental issues related to AV technologies.

Policy and Regulatory Implications

The analysis is focused on government strategies that constrain the environmental accountability of autonomous vehicle (AV) operations. Different attitudes towards the management of emissions and energy used by AVs are shown in an analysis of 30 documents across multiple jurisdictions. The European Union's strict standards and effective reporting requirements result in measurable emission reductions. The United States has a preference for market-driven incentives and voluntary compliance, which results in inconsistent outcomes across states. China's regulatory framework, which is still being developed, features centralized control and punitive measures for compliance. Table 3 presents the regulatory strategies, as well as regional disparities and environmental impacts.

Table 3: Policy and Regulatory Frameworks for AV Environmental Accountability

Policy Document	Region	Environmental Focus	Regulatory Framework	Enforcement Mechanism	Reported Outcomes
Regulation (EU) 2018/858	EU	Lifecycle emission reduction	Centralized	Mandatory reporting, penalties	Significant emissions reductions
Directive 2004/35/CE	EU	Pollution prevention and remediation	Member State implementation	Restoration requirements	Reduced long-term pollution levels
Clean Air Act	US	Air quality standards	Decentralized (state-level)	State-level enforcement, lawsuits	Gradual improvement

California's ZEV Mandate	US	Zero-emission vehicle adoption	State-specific	Credit-based incentives	Higher EV adoption rates, localized reductions
Environmental Protection Law	China	Comprehensive air pollution control	Centralized oversight	Centralized fines	Steady urban air quality improvement
Atmospheric Pollution Prevention and Control Law	China	Industrial emissions, fleet compliance	National-level	Heavy penalties for non-compliance	Regional improvements in industrial zones
Basic Act on the Environment	Japan	Emissions and noise reduction	National coordination, local implementation	Certification requirements	Stable reductions in fleet-level emissions
Greenhouse Gas Pollution Pricing Act	Canada	Carbon pricing for vehicle emissions	Federal and provincial	Carbon tax enforcement	Lower carbon emissions intensity
Transport Integration Act	Australia	Emissions monitoring and mitigation	State-level implementation	Fines and reporting	Incremental improvements in monitored regions
National Greenhouse and Energy Reporting Act	Australia	Greenhouse gas reporting	National oversight	Comprehensive audits	Improved transparency in emissions data

Table 3 summarizes some of the most significant differences in policies and environmental impacts. The EU's centralized framework and mandatory reporting requirements generate a measurable impact that is reflected in abundant emission reductions. The United States is not uniform: California is ahead of the game, going far beyond its goals and aggressive zero-emission mandates; many other states are still offering looser standards and only patchy improvements. There is evidence that Chinese-style top-down penalties can result in results and be effective, particularly in cities. Without such enforcement, its long-term sustainability is still uncertain. Countries such as Japan and Australia exemplify this middle ground, coordinating efforts at the national level but allowing decision-making and implementation to occur at the local level. They have seen incremental progress, though not rapid change. The diversity of strategies demonstrates the necessity for international coordination and more consistent global standards to guarantee consistent environmental outcomes.

Mathematical Model Outputs

Using the Multi Factor Environmental Liability Model (MELM), a detailed and quantitative assessment of the impacts of alternative liability regimes on environmental and economic outcomes was undertaken. Because the model simulates alternative regimes such as strict liability, hybrid models, and negligence, it can govern differences in emissions reductions, compliance costs, and comprehensive regulatory effectiveness. External variables like the length of time regulation is enforced, differences in the scales of production in disparate industries, and changes in emissions intensity resulting from technological progress are also factored in. Fig. 1 displays the outputs from the extended models, which include emissions and compliance rates, and Fig. 2 shows the externalities and cost per ton of reduced emissions. The environmental and economic trade-offs with each liability framework are clearly outlined in Figs. 3 and 4. The regime with strict liability is the most effective way to reduce emissions: a 15% reduction in emissions intensity with a 95% compliance rate. Nevertheless, it also carries the most expensive average costs per manufacturer (€3.5 million) and the longest compliance period (up to 10 years in extended enforcement scenarios). The hybrid liability mechanism balances these factors by reducing emissions moderately with a slightly lower per ton reduction cost of €3,111. We acknowledge that the initial cost of compliance obligations is the lowest for negligence-based models. However, these models also display the lowest compliance rates (75%) and the most modest increase in overall emissions intensity (5%), which clearly indicates a decrease in environmental efficiency. These results indicate that hybrid models may provide a better balance between cost and achievement than strict liability formats, which provide the most complete incentives to reduce emissions.

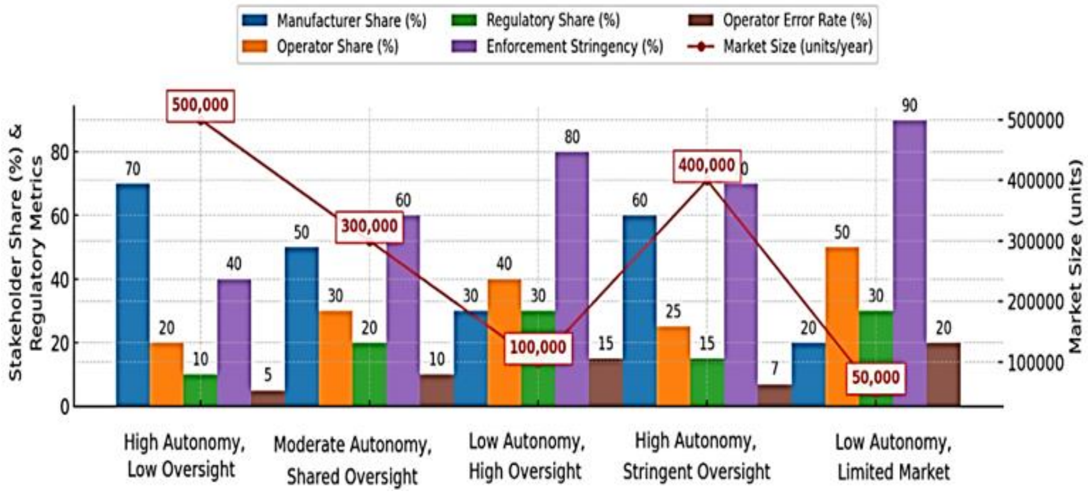

Fig. 3: Stakeholder Liability Distribution Across Scenarios

Stakeholder Impact and Responsibility Allocation

This research utilizes the next-generation dynamic risk-weighted liability assignment (DRWLA) model to illustrate the differences in liability among different stakeholder groups in different operating scenarios. It examines how the proportion of responsibility assigned to manufacturers, operators, and regulatory agencies is affected by changes in vehicle autonomy levels and regulatory oversight. Figure 3 builds on these scenarios with additional variables, such as market size, enforcement stringency, and operator error rates, to illustrate the various ways these factors can affect liability allocation. The table that was updated demonstrates the interrelationship between technology maturity, operational practices, engineering, and regulatory regimes. According to operational and regulatory conditions, liability is redistributed as shown in Fig. 3. Under high autonomy/low oversight scenarios, manufacturers have a significant 70% share of liability that corresponds to their primary role in software and hardware development. When oversight increases, regulators and operators take on more responsibility, from 10% and 20% respectively in low-oversight situations to 30% and 40% in high-oversight cases with low autonomy. A stricter enforcement increases regulatory share shares, as does a higher operator error rate, which shifts responsibility towards operators. The analysis highlights the necessity of adaptive liability regimes that take into account the growth of AV technology, market scale, and operator switch to remote or probabilistic control.

Cross-Jurisdictional Analysis

Different state regulatory frameworks impact the variation in financial exposure to environmental liability, as explained by the Cross-Jurisdictional Liability Adjustment Model (CJLAM). Furthermore, it serves as a framework to help us understand the fiscal implications of environmental disaster issues. Adjusted liabilities that take into account regional regulatory differences are calculated by the model to demonstrate the economic impact of inconsistent standards. This involves expanding on the previous analysis by accounting for new variables, such as the length of time entities have to comply, the rate at which penalties increase for non-company, and how quickly the market will become saturated. Fig. 4 summarizes these factors and compares several regions and their liability adjustments, all with the aim of harmonizing legal frameworks applicable to AVs globally. In Fig.4, there are differences in the effects produced by deviations from regulation, escalation (in penalties), and the market. Despite the tight regulations in the EU, the adjusted liability is lower than in the US due to the relatively steady framework and gradual penalty escalation. Significant regulatory deviations and a high escalation rate in penalties make the US the costliest liability with an adjusted liability of €600,000. In contrast, the lowest adjusted liability of €480,000 is due to China's centralized approach, which has shorter compliance timelines, highlighting the benefits of a harmonized regulatory system. Japan and Canada are examples of countries in the intermediate range, where moderate deviations and penalties contribute to maintaining constant adjusted liabilities. The focus of these results is on global regulatory harmonization to avoid financial burden and ensure a level playing field for global manufacturers and operators.

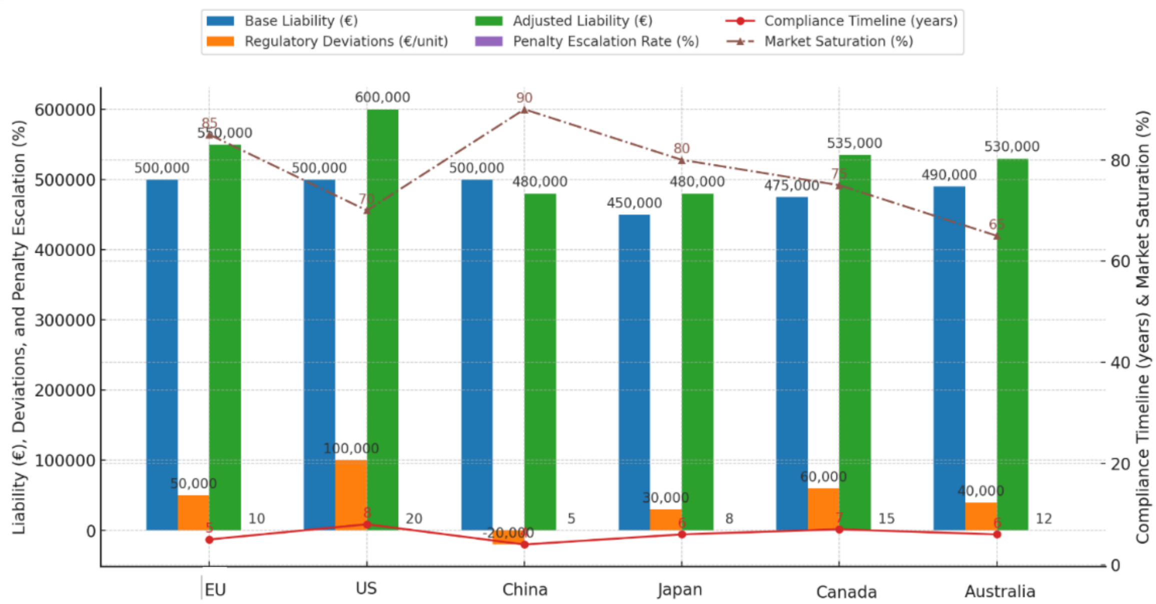

Fig. 4: Cross-Jurisdictional Liability Adjustments

Policy Recommendations and Best Practices

Critical strategies can be employed by policymakers and regulators to promote environmental accountability in the emerging field of autonomous vehicles, as suggested by the study's insights. These approaches would involve creating regulatory frameworks that are globally aligned, providing incentives to adopt hybrid liability models, and reforming enforcement mechanisms to be more coherent and consistent. This approach would also help to alleviate environmental concerns and reduce the legal uncertainties faced by industry stakeholders, which often hinder industry growth in relevant fields. These policy recommendations are further developed in Table 4, which outlines specific best practices, potential challenges, and expected environmental and economic benefits of each approach.

Table 4: Policy Recommendations and Best Practices for AV Environmental Accountability

Recommendation	Best Practice	Potential Challenges	Anticipated Environmental Benefits	Economic Benefits
Global Standardization of Regulations	Harmonize emission standards and reporting requirements globally	Variability in national policies and enforcement capabilities	Significant reduction in cross-border emissions and pollution	Lower compliance costs for multinational manufacturers
Incentivizing Hybrid Liability Models	Implement financial incentives (e.g., tax breaks) for firms adopting hybrid liability structures	Resistance from stakeholders accustomed to traditional liability frameworks	Moderate reductions in emissions through improved accountability	Stabilized legal environment, reduced litigation costs
Consistent Enforcement Mechanisms	Standardize penalties and compliance monitoring across jurisdictions	Disparities in regional enforcement capacity	Improved adherence to emission reduction targets	Predictable financial planning for firms

Encouraging Technological Innovation	Provide grants for R&D in low-emission AV technologies	Securing long-term funding sources	Accelerated adoption of cleaner vehicle fleets	Growth in green technology sectors
Transparent Reporting and Auditing	Mandate regular third-party audits and public disclosure of emissions data	Balancing transparency with protection of proprietary information	Increased public trust and corporate accountability	Long-term cost savings from better environmental performance

Table 4 exhibits the interconnections between regulatory, environmental, and economic factors in the creation of effective policy recommendations. Nevertheless, global standardization proves to be the most significant solution when aiming to reduce not only emissions rates but also compliance costs, and can pose strong difficulties in the alignment of several jurisdictions. Hybrid liability models can be used as incentives to promote harm-reduction measures by manufacturers and operators while minimizing the burden on the current legal landscape. In jurisdictions with uniform penalties, a proof of compliance fee and lower costs encourage adherence to standards. Finding consistent enforcement mechanisms further increases compliance rates. The doctrinal framework revealed a significant difference in methodologies represented by various jurisdictions regarding environmental liability for automated/AVs.

Discussion

The results of this study offer new insights into the possible ways that liability frameworks for autonomous vehicles (AVs) can be modified to address environmental issues. Arguably, the most significant of these contributions occurs through the proposed mixed liability models that encourage international coordination, and similar efforts to integrate environmental damage into liability determinations that focus on academic and regulatory conversations. The discussion of environmental issues is not done, it must be more focused and on liability with proposals for various solutions. Much of the existing literature has focused on adapting existing tort law, particularly negligence law, which has proved particularly difficult to apply to AV technology. Shavell (2019) examined the potential redesign of accident liability schemes to address autonomous systems, emphasizing the importance of accident prevention and cost internalization. Although Shavell's work demanded a reconsideration of liability, it did not recognize environmental harm as such. The authors clarify that their analysis differentiates itself in multiple ways, including the circulation of hazardous investments and the extension of this liability framework to emissions and other ecological impacts. Zipp (2016), whose focus was on attribution of fault issues raised by AVs, did not address environmental issues. Zipp's work is extended in this study by adding environmental liability to the discussion. It illustrates how a hybrid model that combines motion-as-property analysis with no-fault principles offers a more comprehensive solution. The challenges of assigning liability in a rapidly evolving technological landscape were noted by Kemp (Kemp, 2018), who primarily focused on procedural and evidential barriers. Kemp's observations are incorporated into this work, which highlights the importance of identifying regulatory frameworks and insurance approaches that incorporate explicit environmental considerations. Alawadhi et al. (2020) analyzed literature on AV liability, identifying the inconsistent legal approaches in different jurisdictions. This study extends its findings by demonstrating how an internationally harmonized liability framework can eliminate inconsistencies and encourage ecologically sustainable company practices. This research demonstrates that incorporating environmental metrics into liability assignments can make them more flexible and responsive to emerging challenges, despite Epstein (2021)'s criticism of the existing liability rules as being too rigid. This Research argues that environmental harm should be considered a primary factor in liability, instead of being a secondary or incidental consideration, based on these core studies. A gap in the literature is filled by the proposed mixed liability model, which combines strict liability (holding manufacturers accountable for emissions) with no-fault components (allowing compensation without protracted litigation). The product liability of AVs has been identified as a “scope problem” by Lemann (2019), where the responsibility of a human and a manufacturer becomes unclear. This study aims to fill that gap by providing a clearer division of responsibilities: Manufacturers will be held responsible for emissions that exceed regulatory standards, while operators will receive no-fault insurance for small, incidental emissions. While this study is valuable, there are some limitations that need to be addressed. The data used to model assignments of liability is primarily based on hypothetical and local simulations. Quality input data is needed for the Multi-Factor Environmental Liability Model (MELM) and Dynamic Risk-Weighed Liability Assignment (DRWLA), although offering useful metrics, to accurately assess regulatory infractions and estimate current emissions. Another limitation is the heavy use of hypothetical simulations and a small case study set (n=15). While MELM and DRWLA give new ways to measure and share liability, they have not yet been tested with large real-world data. To make the models stronger, pilot studies should be done with data from real AV fleets, such as Tesla or Waymo. In addition, this study looks only at the EU, U.S., and China. Other countries, like India or Brazil, are now starting to use AVs but may face bigger environmental problems because of weaker rules. Adding data and case studies from these countries will make the results more general and useful. Wang (2023) also stated that it is challenging to obtain precise data for real-world liability cases (Faure, 2024).The study's generalizability is limited by the analysis of three fundamental jurisdictions (the EU, US, and China). Despite their significant presence in the global AV market, smaller or nascent markets with developing regulatory frameworks are not included. Rosemadi et al. (2022) also documented this limitation, which noted a gap in understanding how liability may be developing in developing economies, as most of the literature focuses on already developed legal systems in place. A second limitation is related to the dependency on existing regulatory frameworks. Geistfeld proposes that liability frameworks should adapt to technological advancements. This study's findings, which rely heavily on existing emissions reporting and penalty systems, may not be as applicable in future regulatory contexts (Geistfeld, 2017). Thus, there are significant gaps between what is currently achievable in AV technologies and international regulations, and the policy recommendations and liability models proposed in this paper. The study fails to take into account the role of enterprise insurance markets as a supplement to public regulatory efforts. The paper suggests the development of AV-specific environmental liability insurance, but it fails to explore in-depth how insurers would assess risk or establish premiums. Lemann (2019) identified a gap that reflects the underexploration of insurance-based solutions for AV liability. Due to its failure to incorporate the perspective of private insurers in its analysis, this study may miss a crucial mechanism for allocating liability and inducing compliance. Advancing this discussion can help fill critical gaps in the existing literature, as treating environmental damage as a primary focus of AV liability frameworks has yet to be discussed in the existing scholarly discourse. It is clear that the proposed mixed liability model is more comprehensive and better suited for a complex world, in contrast to the findings of Shavell (2019), Zipp (2016), and others. However, the limitations of data reliability, jurisdictional scope, and the evolving regulatory landscape suggest that more research is necessary. Future work should focus on building these models that include real-world data, factors of the insurance market going backwards, and a broader set of jurisdictions that builds a truly international framework for AV environmental liability. As policy recommendations, it can be stated that insurance markets serve as a critical mechanism for allocating managing the environmental risks associated with autonomous vehicles (AVs). Insurers can assess and price these risks by leveraging operational data and historical records of emissions and incidents related to AV deployment. This process involves advanced risk analysis and probabilistic modeling to determine premiums commensurate with the potential environmental hazards. Consequently, risk-adjusted insurance premiums can incentivize manufacturers and operators to adopt cleaner technologies and reduce pollutant emissions. Moreover, public-private partnerships can play a vital role in strengthening compliance with environmental regulations by establishing supportive frameworks and financial and non-financial incentives. Such incentives may include tax reductions, infrastructure facilitation, funding for research and development projects, and improved access to operational data for validating risk models. Collaboration between the public and private sectors can also enable pilot programs and field trials, providing opportunities to evaluate the effectiveness of policies and proposed models under real-world conditions. These partnerships not only promote regulatory adherence but also enhance public trust in autonomous vehicles technologies.

Conclusion

The study emphasizes the need to redefine traditional liability regimes to address the unique environmental challenges posed by AVs. Given their increasing integration into the modern transportation landscape, their environmental impacts, particularly emissions and energy consumption, should be part of the basic bedrock of the legal accountability framework. The results demonstrate that existing liability frameworks useful in addressing safety and personal injury challenges are not adequate to capture the broader environmental externalities associated with the deployment of AVs. Such lack of specificity exposes a void in need of new legal paradigms tailored to the realities of self-governing technology.

- **Theoretical Implications**

1. One of the key conclusions to be drawn from the study is that hybrid liability models hold great potential for reconciling the long-term environmental sustainability with the short-term economic viability of the system.
2. Critical strategies can be employed by policymakers and regulators to promote environmental accountability in the emerging field of autonomous vehicles.
3. Different state regulatory frameworks impact the variation in financial exposure to environmental liability.
4. The diversity of strategies demonstrates the necessity for international coordination and more consistent global standards to guarantee consistent environmental outcomes.
5. It is important to have legal frameworks that are clearer and more consistent to prevent environmental issues related to AV technologies.

- **Practical Implications**

1. It goes on to further outline the need for international cooperation in developing standard legal frameworks for AVs.
2. Furthermore, the findings highlight a pressing need for collaboration between disciplines. Legal scholars, environmental scientists and automotive engineers need to collaborate to inform policies that will help ensure the long-term environmental legacy of AVs is a positive one.
3. Finding consistent enforcement mechanisms further increases compliance rates.
4. The regime with strict liability is the most effective way to reduce emissions: a 15% reduction in emissions intensity with a 95% compliance rate.
5. The hybrid models may provide a better balance between cost and achievement than strict liability formats, which provide the most complete incentives to reduce emissions.

In light of these findings' hybrid liability models, experimental models and further more with insurance mechanism in environmental accountability, will be next steps in research as they can be useful in dealing with decision making under uncertainty. Moreover, through extrapolating from these initial results over time, both scholars and practitioners can fortify a comprehensive legal structure that alleviates the unique difficulties of AV-based pollution, while simultaneously promoting further innovation. Self-driving vehicles are a country in the making, and it is part of self-driving vehicles to establish prerogatives, legal and environmental frameworks that find a balance between technological progress and ecological stewardship, and therefore responsible governance as part of the road towards the future ahead of us.

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