IRSHAD
Uzbek Journal of Law and Digital Policy |
Volume: 3, Issue: 5
2025

Emerging Regulatory Countermeasures for Sensor Spoofing in Autonomous Vehicles

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Abstract

This research explores how regulators and policymakers address the rising threat of sensor spoofing in autonomous vehicles. It highlights the growing importance of cybersecurity and accountability in the safe deployment of self-driving technologies. The study aims to examine existing legal and regulatory frameworks, identify gaps in current governance, and propose practical approaches for improvement. Using a qualitative research method based on doctrinal and document analysis, the study reviewed official laws, international standards, and peer-reviewed literature. The results show that current policies emphasize general cybersecurity but lack specific rules for spoofing, creating inconsistencies across countries. The analysis suggests that stronger coordination, clearer liability frameworks, and proactive legal design are needed to ensure safety and trust in autonomous systems. The study concludes by recommending global harmonization of standards and further research on ethical and legal implications of emerging vehicle technologies.

Keywords: Sensor Spoofing, Autonomous Vehicles, Cybersecurity, Regulation, Accountability, Liability, Governance, Policy

APA Citation:

Allahrakha, N. (2025). Emerging Regulatory Countermeasures for Sensor Spoofing in Autonomous Vehicles. *Uzbek Journal of Law and Digital Policy, 3*(5), 1–19. https://doi.org/10.59022/ujldp.375

I. Introduction

Imagine an autonomous car suddenly swerving to avoid a wall that doesn't exist. This is not a software glitch. It's a sensor spoofing attack. Sensor spoofing happens when false signals deceive the sensors that guide autonomous systems, such as LiDAR, cameras, GPS, and radar (Jakobsen et al., 2023). These attacks can trick vehicles into seeing fake objects or misjudging their location, leading to serious accidents. As the world moves toward self-driving cars and other autonomous technologies, the risk of such cyber-physical attacks grows. What makes this issue urgent is that current laws and standards are still catching up with these fast-evolving threats. Governments and international bodies are now working to create new regulations to ensure that autonomous vehicles are both safe and secure.

Autonomous vehicles rely on a network of sensors to understand their surroundings and make driving decisions without human control. These sensors, such as GPS, cameras, LiDAR, and radar, were designed to improve safety and efficiency, but they have also created new risks (Matos et al., 2024). Over the past decade, researchers have shown that these systems can be tricked through sensor spoofing, where attackers send false signals to mislead the vehicle. While technical studies have explored ways to detect or prevent spoofing, less attention has been given to how laws and regulations can address it. Existing rules for vehicle safety and cybersecurity were not created with such complex, AI-driven systems in mind.

Although autonomous vehicles are becoming more advanced, they remain highly vulnerable to sensor spoofing attacks that can manipulate their perception of the environment. These attacks can cause accidents, property damage, and loss of public trust in autonomous technology. We already know that technical solutions, such as sensor fusion and encryption, can reduce some risks, but they cannot fully prevent spoofing or assign legal responsibility when attacks occur. The real challenge lies in the lack of clear and comprehensive regulations to govern these threats. Current laws focus mainly on general cybersecurity or traditional vehicle safety, leaving many questions unanswered. Who is accountable if a spoofing attack leads to an accident the manufacturer, the software provider, or the vehicle owner?

Recent studies show growing awareness of sensor spoofing as a serious threat to autonomous vehicles. Research has shown that LiDAR and GPS spoofing can create false detections and navigation errors, proving that physical-layer attacks can easily bypass existing protections. Other experiments show that GPS spoofing can mislead drones and vehicles, revealing that even secure communication systems cannot fully prevent these attacks (Hu et al., 2024). Many of these studies rely on simulations and hardware testing to show vulnerabilities, but they rarely connect their findings to regulatory or legal measures. Technical research focuses on detection algorithms, sensor fusion, and encryption, yet lacks policy integration, leaving a major gap in how governments can set

and enforce protection standards (Ali et al., 2025).

Some research discusses governance and accountability in autonomous systems, stressing the need for clearer legal responsibility for cyber-physical risks (Pande & Taeihagh, 2023). Other studies emphasize building security and privacy into autonomous design to strengthen user trust and compliance (Alelyani, 2024). However, most of this literature remains fragmented and limited to specific countries, offering no global framework for addressing spoofing threats. The existing studies confirm the technical risks of sensor spoofing but do not fully explain how policy and regulation can evolve to manage these challenges effectively (Tzoannos et al., 2024).

The existing literature provides strong technical evidence on how sensor spoofing can mislead autonomous systems, but it offers little understanding of how regulations should address these risks. Most studies focus on detection methods and system resilience, showing technical strength but ignoring the policy and legal aspects that determine accountability and enforcement. Few researchers have analyzed how current or emerging laws respond to spoofing or how international standards can create unified protection measures. There is also limited data on how governments balance innovation with safety when designing regulations for autonomous vehicles. The lack of comparative studies across different countries and sectors further weakens the policy perspective. The objective of this research is

- To examine how existing national and international regulations address the issue of sensor spoofing in autonomous vehicles.
- To identify gaps and weaknesses in current legal and policy frameworks related to the security and accountability of autonomous vehicle systems.
- To analyze emerging regulatory countermeasures and propose recommendations for developing proactive, harmonized, and effective policies to prevent and manage sensor spoofing attacks.

How are regulators and policymakers responding to the growing threat of sensor spoofing to ensure the safe, secure, and accountable operation of autonomous vehicles?

This study is important because it addresses a growing security risk that could affect the future of autonomous transportation. As vehicles become more dependent on sensors and artificial intelligence, the threat of sensor spoofing poses serious safety, legal, and ethical challenges. The research is significant because it connects the technical problem of spoofing with the regulatory and policy responses needed to manage it. The study contributes new knowledge about how governments can build safer and more accountable autonomous systems. It also provides practical guidance for policymakers, manufacturers, and researchers on creating stronger rules and preventive measures. The rationale for this study is to fill the gap between technology and regulation, ensuring that innovation in autonomous vehicles is matched by effective protection against cyber-physical attacks, ultimately improving public safety, trust, and global policy coordination.

II. Methodology

This study uses a qualitative research design based on document analysis. The qualitative approach is suitable because the research focuses on understanding policies, laws, and standards rather than numerical data. The document analysis method allows a detailed review of existing regulations, legal frameworks, and scholarly literature related to sensor spoofing and autonomous vehicle security. The study examines secondary sources such as peer-reviewed journal articles, government reports, and official policy documents to explore how regulatory countermeasures are being developed globally.

The target population for this research includes national and international laws, standards, and regulatory frameworks concerning autonomous vehicle cybersecurity and sensor spoofing. The sample consists of selected legal instruments and policies from regions with active autonomous vehicle regulation, such as the Automated Vehicles Act 2024 (UK), Dubai Law No. 9 of 2023, and relevant UNECE and ISO standards. Sampling is purposive, focusing on the most recent and influential documents that illustrate emerging regulatory trends.

Data is collected from publicly available and credible sources. Legal texts are obtained from official government portals (e.g., GOV.UK, UAE official gazette, UNECE website), while academic literature is gathered from peer-reviewed databases such as Scopus, Google Scholar, and ResearchGate. The inclusion criteria require that all materials are published within the last five years to ensure the information is current and relevant. No primary data or human participants are involved in this study. The main instruments are document analysis checklists that record key information about each source such as publication year, author credentials, research focus, and regulatory implications. Legal and regulatory texts are analyzed directly from official websites to ensure authenticity. Scholarly articles are selected from law and technology journals and verified through peer-review status and citation frequency.

To ensure validity, only credible, peer-reviewed, and up-to-date sources are used. Each source is assessed for relevance, author expertise (such as academic researchers or government officials), and supporting evidence. The reliability of findings is strengthened by cross-referencing information across multiple sources and citing all references accurately to acknowledge original contributions. The materials used are scientific and unbiased, ensuring that the conclusions drawn are based on verified and trustworthy information. The collected data is analyzed using qualitative content analysis and doctrinal legal analysis. Document analysis involves systematically identifying themes, patterns, and trends within laws, policies, and literature. The doctrinal approach focuses on interpreting legal documents to understand how they address sensor spoofing and what gaps remain. The findings are synthesized to identify best practices and propose recommendations for future regulatory development.

This research uses data that is publicly available and does not involve human

participants, ensuring minimal ethical risk. All information derived from external sources is properly cited to respect intellectual property and academic integrity. The researcher declares no conflict of interest, and the study is conducted solely for academic purposes. For potential future surveys, ethical principles such as informed consent, voluntary participation, anonymity, and confidentiality would be strictly followed. Limitations include the reliance on secondary data, which may restrict access to the latest unpublished regulatory developments. Regional variations in policy implementation may also limit the generalizability of findings.

Delimitations are set by focusing only on autonomous vehicle regulations and sensor spoofing, excluding other types of cyber-physical attacks or unrelated AI regulations. The time frame is limited to publications and laws, and the geographic scope includes the UK, UAE, EU, and selected international frameworks. This research assumes that all selected sources are accurate, authentic, and representative of current regulatory developments. It also assumes that policymakers and international bodies are making genuine efforts to address sensor spoofing risks. Finally, it assumes that findings from analyzed documents can be generalized to inform future policy and academic discussions on autonomous vehicle cybersecurity regulation.

III. Results

This study explored how governments and international organizations are developing regulatory countermeasures to protect autonomous vehicles from sensor spoofing attacks. Using qualitative document analysis, the research reviewed recent laws, international standards, and peer-reviewed articles to identify current progress and remaining gaps. The main question guiding the research was: How are regulators and policymakers responding to the growing threat of sensor spoofing to ensure the safe, secure, and accountable operation of autonomous vehicles? The analysis revealed that while several nations and institutions have started addressing cybersecurity in autonomous systems, specific measures against sensor spoofing remain limited.

The analysis found that most existing regulations focus broadly on cybersecurity but rarely mention sensor spoofing specifically. The UNECE Regulation No. 155 sets cybersecurity management requirements for vehicle manufacturers, encouraging threat analysis that indirectly includes spoofing. The ISO/SAE 21434 standard also emphasizes risk management and secure design principles, pushing for “security-by-design” approaches. National laws, such as the Automated Vehicles Act 2024 (UK) and Dubai Law No. 9 of 2023, include provisions for safety certification and data protection, but none explicitly define spoofing as a regulatory category (Benyahya et al., 2023).

A key finding of this research is that regulators are increasingly recognizing sensor spoofing as part of the broader cybersecurity challenge in autonomous technology. International bodies like the UNECE and ISO are taking the lead in setting baseline standards that influence national laws. These frameworks encourage vehicle

manufacturers to integrate continuous monitoring, secure communication, and threat detection systems. Another important discovery is that liability and accountability remain unclear. Most legal systems still struggle to define who is responsible in case of a spoofing-related accident whether it is the vehicle owner, manufacturer, or software provider. This uncertainty hinders the creation of effective enforcement mechanisms. The results confirm that while technical defenses are improving, legal clarity and coordinated regulatory enforcement lag behind technological progress (Margaret et al., 2024).

An interesting finding is the growing cooperation between governments and private industry in shaping cybersecurity policy for autonomous vehicles. Several countries now consult technology firms and automotive manufacturers before drafting laws, aiming to balance safety with innovation. Another notable trend is the rise of "cyber resilience" as a guiding principle focusing not just on preventing attacks but also on ensuring systems can detect and recover from them. This concept is being discussed in new European and Asian policy drafts. Additionally, the analysis found that countries with strong data protection frameworks, such as the EU's GDPR, are more proactive in addressing sensor-related vulnerabilities. This shows how broader privacy and data security laws indirectly support efforts to mitigate spoofing risks (Verma et al., 2025).

The results show that the regulation of sensor spoofing in autonomous vehicles is still developing. International standards like ISO/SAE 21434 and UN Regulation No. 155 provide foundational guidance but lack direct enforcement mechanisms. National regulations, such as those in the UK and UAE, are beginning to incorporate cybersecurity principles but remain general. Academic studies highlight that awareness of spoofing is growing, yet most laws are reactive rather than preventive. The findings also emphasize that accountability frameworks and cross-border cooperation are essential for progress (Lingras & Basu, 2025).

One unexpected finding is that several countries without autonomous vehicle deployment programs are already developing cybersecurity regulations that could apply to sensor spoofing. This suggests that governments are preparing in advance, learning from early adopters like the UK and UAE. Another surprising observation is that while many academic studies call for stricter laws, some industry experts warn that overregulation could slow innovation. This highlights a tension between technological freedom and safety control. Additionally, the study found that insurance and liability discussions are emerging faster than expected, with insurers beginning to demand cybersecurity certifications before covering autonomous vehicles. This market-driven pressure could accelerate regulatory action more than legislation alone (Lin et al., 2025).

The research question asked how regulators and policymakers are responding to the threat of sensor spoofing in autonomous vehicles. The findings show that responses are emerging but remain uneven and indirect. Regulators are incorporating cybersecurity standards that indirectly address spoofing, but few have enacted specific anti-spoofing

laws. Policymakers are beginning to emphasize resilience and accountability, reflecting a shift toward proactive governance. International organizations such as the UNECE and ISO are playing key roles in harmonizing standards across borders, yet enforcement remains national and inconsistent. Therefore, while progress is visible, stronger coordination, clearer legal definitions, and unified international policies are still needed to ensure the safe and secure operation of autonomous vehicles against sensor spoofing threats.

IV. Discussion

A. Sensor Spoofing in Autonomous System

Sensor spoofing is a type of cyber-physical attack where false data is sent to confuse or mislead the sensors of autonomous vehicles. These sensors, including LiDAR, radar, cameras, and GPS, collect real-time information to help vehicles make safe driving decisions (Giannaros et al., 2023). Attackers exploit the trust these systems have in their data by sending fake signals that mimic real objects or locations. This manipulation can cause a vehicle to brake suddenly, change lanes unnecessarily, or even crash. The main danger lies in the system's inability to distinguish real signals from fake ones. As autonomous vehicles rely heavily on sensor data, such spoofing attacks threaten both passenger safety and public confidence.

Sensor spoofing can occur in several ways, depending on the type of sensor targeted. In LiDAR spoofing, attackers use lasers to create artificial reflections, producing phantom obstacles that deceive the vehicle. GPS spoofing involves broadcasting false satellite signals, causing the vehicle to misjudge its position or route. Camera spoofing uses lights, projections, or patterned images to blind or confuse computer vision systems, while radar spoofing generates fake wave reflections to mimic other vehicles or barriers. Each technique exploits the sensor's reliance on physical signals, making detection difficult. These attacks can be performed remotely and often require minimal equipment. The diversity of spoofing methods makes it challenging to create universal protection standards (Wang et al., 2024).

Sensor spoofing poses serious safety and operational risks for autonomous vehicles and broader transportation systems. A spoofed signal can cause a vehicle to make incorrect driving decisions, such as emergency braking, steering away from imaginary obstacles, or failing to detect real dangers (Sakhai et al., 2025). This can lead to traffic accidents, disruptions, and damage to surrounding infrastructure. On a larger scale, coordinated spoofing attacks could disrupt entire networks of autonomous vehicles or delivery drones, creating public safety hazards. Beyond physical harm, such incidents undermine trust in automated systems and delay public adoption. Companies may face financial losses, reputational damage, and legal disputes following a spoofing incident. The growing dependence on sensors for real-time decision-making increases the potential damage from such attacks.

While technical research focuses on improving sensors and developing spoof detection algorithms, regulatory and ethical perspectives are equally important. A purely technical solution cannot prevent all attacks, especially as spoofing techniques evolve. Governments need to create standards that ensure vehicles are designed with built-in resilience and accountability mechanisms. Public awareness and education are also essential, as users must understand how spoofing can affect autonomous safety. Moreover, researchers must share knowledge across disciplines to build integrated solutions that combine technology, policy, and law. Understanding sensor spoofing as both a technological and societal issue provides the foundation for developing strong regulatory countermeasures.

B. Legal and Regulatory Landscape

The regulation of autonomous vehicles is still developing in most parts of the world. Many countries have begun to create laws to manage safety, testing, and operation, but few focus directly on sensor spoofing (Schellekens, 2016). The current legal landscape is shaped by general cybersecurity and vehicle safety rules rather than specific anti-spoofing measures. Governments and international bodies are trying to catch up with the fast growth of autonomous technologies. Several policies now include basic cybersecurity requirements, such as protecting data and ensuring system reliability. However, these policies often lack clear standards for handling attacks on sensors. As a result, the responsibility for preventing spoofing largely falls on manufacturers and engineers.

International organizations have introduced several frameworks to improve vehicle cybersecurity and resilience. The UNECE Regulation No. 155 is one of the most important global standards, requiring manufacturers to create cybersecurity management systems for vehicles. This includes identifying, assessing, and mitigating risks such as spoofing and hacking. Similarly, ISO/SAE 21434 provides detailed guidance for implementing cybersecurity principles throughout the vehicle's lifecycle. Although these frameworks do not specifically mention "sensor spoofing," they address it indirectly by promoting risk-based thinking and secure design. These international efforts are vital because they encourage countries to adopt harmonized rules, ensuring that vehicles meet similar safety standards across borders. However, since the implementation of these standards depends on national governments, differences still exist in how strictly they are applied or enforced in practice. Several countries have started creating their own regulations for autonomous vehicle operation (Kifor & Popescu, 2024).

The Automated Vehicles Act 2024 in the United Kingdom is one example, introducing a clear approval process to ensure that autonomous cars can operate safely without human control. It also includes cybersecurity requirements as part of vehicle authorization. In the United Arab Emirates, Dubai Law No. 9 of 2023 regulates autonomous vehicle testing and deployment, emphasizing safety, innovation, and risk

management. Meanwhile, the European Union relies on a combination of data protection laws, such as the GDPR, and vehicle safety directives to manage cybersecurity. In the United States, regulations vary by state, with the NHTSA providing voluntary guidelines rather than binding laws. These examples show that while progress is being made, national approaches remain diverse, making global harmonization difficult and creating gaps in cross-border safety and accountability.

Recent trends in regulation show a shift toward proactive governance, but there are still limitations. Many countries now require cybersecurity certification for autonomous vehicles before they are approved for use. There is also a growing emphasis on collaboration between government agencies, industry experts, and researchers to design effective policies. However, the absence of detailed rules for detecting and preventing spoofing attacks remains a major weakness. Most laws still focus on traditional cybersecurity threats, such as data theft or system hacking, rather than sensor manipulation. Another limitation is the slow pace of regulatory updates compared to the rapid advancement of autonomous technologies. This creates a lag between innovation and law enforcement.

C. Challenges in Current Regulatory Frameworks

One of the biggest gaps in the current regulatory framework is the lack of clear and specific laws on sensor spoofing. Most existing rules focus on general cybersecurity, such as protecting vehicle software and data systems, but they do not address sensor manipulation directly. This means that when a spoofing incident occurs, it is often unclear who is legally responsible, the manufacturer, the software provider, or the operator. Without precise definitions, enforcement becomes difficult. Courts and regulators struggle to classify spoofing as a distinct type of cybercrime in the context of autonomous vehicles (Elendu et al., 2024). This gap leaves both companies and consumers without clear legal protection. As a result, there is a need for specific legislation that recognizes spoofing as a unique threat and sets penalties, response protocols, and safety standards to reduce its impact on autonomous systems.

Another challenge is the inconsistency of rules across countries. Each nation has its own approach to regulating autonomous vehicles and cybersecurity. For example, some countries have strict testing laws and cybersecurity audits, while others only provide voluntary guidelines. This difference creates confusion for manufacturers who sell vehicles globally. A car approved in one country may not meet the safety or cybersecurity requirements of another. There is also no global agreement on how to share data or respond to cross-border spoofing attacks(El-Rewini et al., 2020). These inconsistencies slow down innovation and make international cooperation harder. A lack of coordination between countries means that attackers can exploit weak jurisdictions. A harmonized global framework would help ensure that autonomous vehicles meet uniform security standards everywhere, improving safety and public confidence. However,

achieving such agreement requires significant political and technical collaboration.

Many legislatures do not have enough technical expertise to fully understand sensor spoofing and its effects. As a result, legal frameworks often lag behind technological advances. Technical experts develop complex systems and defense mechanisms, but these are not always translated into legal or regulatory language. This disconnect makes it hard for regulations to keep pace with innovation. Moreover, without detailed technical knowledge, laws may be too broad or too narrow, failing to address real risks (Kollarova et al., 2023). For instance, while some policies mandate cybersecurity audits, they do not require specific tests for sensor spoofing resistance. This oversight weakens overall vehicle safety. To close this gap, governments need to include engineers, cybersecurity professionals, and academic researchers in the policy-making process. Collaborative, multidisciplinary efforts can help ensure that laws reflect current technological realities and future developments.

Even when laws exist, enforcing them can be difficult. Many countries lack the infrastructure or expertise to monitor and verify whether autonomous vehicles meet cybersecurity standards. There are also challenges in investigating spoofing incidents because they often leave few traces and can be conducted remotely. Establishing accountability is another major issue. If a spoofing attack causes an accident, determining who is at fault. The hacker, the manufacturer, or the system operator becomes complex. Current legal systems are not designed to handle such distributed responsibility. Furthermore, there is no universal protocol for reporting spoofing incidents, which limits data collection and analysis. Without consistent enforcement and accountability measures, regulations cannot effectively deter attacks.

D. Emerging Regulatory Countermeasures and Global Initiatives

Developing an effective policy framework for spoofing mitigation requires a proactive approach rather than a reactive one. Most current laws respond only after an attack occurs, focusing on liability and punishment. However, proactive policies emphasize prevention through design, testing, and certification. Governments can introduce mandatory cybersecurity risk assessments for all autonomous systems before they are approved for public use. These assessments should include specific tests for spoofing resistance in sensors such as LiDAR, radar, GPS, and cameras (Meng et al., 2022). Proactive measures also include periodic system updates, threat simulations, and transparency in reporting vulnerabilities. Such forward-looking policies would shift the focus from merely reacting to attacks to preventing them altogether.

One of the most important elements of a strong policy framework is the integration of international technical standards into national laws. Standards such as ISO/SAE 21434 and UNECE UN R155 already provide detailed guidelines on vehicle cybersecurity and risk management. However, many of these standards remain voluntary, which limits their effectiveness. Governments should make compliance with such standards a legal

requirement for manufacturers and developers of autonomous vehicles. This integration would help align technical innovation with legal accountability (Schepis et al., 2023). It would also create consistency across different countries, making cross-border operations and trade smoother. Additionally, regulators should regularly update these standards in collaboration with technical experts to reflect emerging threats.

Effective regulation for spoofing mitigation depends heavily on collaboration between governments, industry, and researchers. No single organization can address the problem alone. Governments can establish public-private partnerships that encourage the exchange of information about spoofing incidents, vulnerabilities, and best practices (Burbank et al., 2024). For example, creating national or regional databases for reporting sensor attacks could help track trends and develop common defense strategies. International cooperation is equally important, as spoofing attacks can cross borders easily. Organizations like the United Nations, International Telecommunication Union (ITU), and International Civil Aviation Organization (ICAO) can play a central role in coordinating global efforts. Encouraging open communication among countries and industries helps reduce duplication of efforts and improves overall preparedness.

A comprehensive policy framework must clearly define accountability in cases of sensor spoofing. Current systems often lack clarity on who bears responsibility when an autonomous vehicle is compromised (Taeihagh & Lim, 2019). Future policies should establish clear rules for liability, ensuring that all parties involved from manufacturers to operators are held accountable for maintaining cybersecurity standards. Introducing certification schemes and periodic audits can ensure continuous compliance. Moreover, insurance frameworks should adapt to include cyber-physical risks, offering protection against spoofing-related damages. Legal systems should also define procedures for evidence collection, investigation, and prosecution of spoofing crimes.

E. Liability, Accountability, and Ethical Implications

Determining legal responsibility in the case of a spoofing attack is one of the most difficult challenges for regulators. When a sensor spoofing incident causes an accident, it is not always clear who should be held accountable (Huszár & Adhikarla, 2021). The vehicle manufacturer, the software developer, the owner, or the attacker. Traditional traffic and product liability laws were designed for human drivers, not autonomous systems that rely on sensors and artificial intelligence. As a result, current laws often fail to assign responsibility properly when a vehicle act based on false sensor data. Some countries are exploring “shared liability” models, where responsibility is distributed among different stakeholders. However, this approach still lacks clear boundaries. To ensure fairness and accountability, legal systems must update definitions of negligence and fault to include software performance, algorithmic decisions, and cybersecurity preparedness against spoofing threats.

Autonomous vehicles make real-time decisions without human input, which raises

questions about accountability. If a spoofing attack tricks a car into swerving or braking incorrectly, the decision-making process is not based on human error but on manipulated data. This creates a gap in accountability because no single human directly caused the action (Kidmose, 2025). Policymakers and legal scholars argue that manufacturers should be accountable for ensuring that vehicles have adequate fail-safe systems to handle spoofing attempts. Transparent algorithm design and system logs can also help trace how decisions were made during an incident. By introducing auditing requirements and digital evidence preservation, regulators can improve post-incident investigations. Clear accountability not only supports justice but also motivates companies to maintain high ethical and technical standards. Autonomous decision-making must therefore be guided by rules that prioritize safety, explainability, and responsible system design.

The ethical implications of spoofing attacks extend beyond technical or legal questions. They involve human values such as safety, responsibility, and trust. As vehicles gain more autonomy, humans lose direct control over decision-making in critical situations (Al-Na'amneh et al., 2025). This shift creates ethical dilemmas about how much freedom should be given to machines and when human oversight must intervene. A spoofing attack that deceives a vehicle into harming people challenges public confidence in automation. Ethical frameworks should require manufacturers to design systems that prioritize human life and transparency over efficiency or cost-saving. Policies should also include guidelines for human supervision, even in self-driving modes, to ensure a backup level of judgment.

Liability frameworks are gradually evolving to address the new risks posed by artificial intelligence and sensor spoofing. Many governments are studying models that combine strict product liability with cybersecurity compliance requirements. For example, if a manufacturer fails to include anti-spoofing measures or ignores known vulnerabilities, they could be held legally responsible for resulting damages. Insurance systems are also adapting by creating new categories for autonomous vehicle risks, including cyber manipulation and software failure (López González et al., 2024). International organizations such as the European Commission and ISO are encouraging "ethics-by-design" principles, ensuring that AI systems are not only technically reliable but also morally aligned with human welfare.

F. Implications

The results of this study show that existing theories of cybersecurity and risk management in autonomous systems are too broad and do not fully address sensor spoofing as a unique threat. Traditional models focus mainly on network security and software vulnerabilities, leaving physical signal deception largely unexplored. This research challenges those frameworks by highlighting how sensor spoofing blurs the boundary between physical and digital security. It shows that protection strategies must evolve from traditional IT-based thinking toward cyber-physical resilience. The findings

also suggest that regulation cannot rely only on technical standards but must integrate accountability, ethics, and transparency. This insight pushes researchers and policymakers to rethink how safety, responsibility, and human oversight are defined in automated systems.

The outcomes have both positive and negative implications for global governance and innovation. On the positive side, international standards such as ISO/SAE 21434 and UN Regulation No. 155 create a foundation for harmonized safety rules, improving trust in autonomous technology. The increased collaboration between regulators and manufacturers encourages innovation while ensuring safer deployment. However, the lack of clear legal accountability can slow adoption and increase uncertainty for investors and consumers. Overly broad or inconsistent rules may also discourage smaller companies from developing new technologies. If laws become too restrictive, they could limit progress; if too flexible, they could expose societies to greater risks. Therefore, careful policy design is needed to protect both technological growth and public safety.

The results also have significant influence on future policy and practical implementation. They show the importance of integrating cybersecurity certification and risk assessments into national vehicle approval systems. Policymakers can use these findings to create stronger frameworks that require “security-by-design” principles and continuous system monitoring. The evidence supports policies that promote information sharing between governments and private industry, helping to detect threats earlier and respond faster. Insurance companies, regulators, and manufacturers can use this research to shape practical guidelines for compliance and liability management. In practice, these findings can lead to the development of testing protocols, international safety audits, and legal updates that clearly define sensor spoofing as a distinct offense.

The current legal frameworks face several challenges that must be addressed to make these findings useful in the real world. Most countries still rely on outdated traffic and product laws that were designed for human drivers. There is little global coordination, leading to inconsistent standards and gaps in enforcement. Many governments lack technical expertise to evaluate spoofing risks, and cross-border data sharing is limited. These weaknesses make it difficult to respond effectively to global threats. Applying the research in practice requires joint efforts among policymakers, cybersecurity experts, and international organizations. New policies should include mandatory resilience testing, clearer definitions of liability, and improved investigation protocols. If implemented well, these approaches can create safer, more transparent, and trustworthy autonomous systems that benefit society as a whole.

The findings also open opportunities for long-term improvements and cooperation. Governments, automakers, and technology developers can benefit from better understanding the link between sensor spoofing and regulatory readiness. The research can help insurance firms design new products and motivate companies to strengthen

cyber-physical defenses. It can also inform training programs for engineers, lawyers, and regulators to improve interdisciplinary knowledge. Real-world applications include the creation of certification centers, international reporting databases, and updated vehicle approval systems. These actions can reduce the frequency and impact of spoofing attacks. However, there are limits to this research, as rapid technological change can quickly make regulations outdated.

G. Recommendations

Regulators should establish independent testing centers to assess sensor integrity before a vehicle enters the market. These centers could simulate spoofing scenarios to ensure that systems can resist false signals. Governments can also introduce licensing requirements for companies that develop or integrate sensor technologies, ensuring compliance with safety benchmarks. Collaboration between national agencies and international organizations would make these measures consistent across borders. Industry partnerships can support real-time information sharing about detected threats, helping reduce response time after an attack. Educational programs and technical workshops for both lawmakers and engineers can close the knowledge gap between regulation and innovation.

Current regulatory frameworks must evolve from theory into flexible systems that can adapt to real-world threats. Laws should not only define accountability but also guide manufacturers in maintaining secure, traceable, and auditable vehicle systems. Introducing mandatory software updates and regular cybersecurity audits would make rules enforceable rather than symbolic. Legal models should include shared accountability contracts that define responsibilities among automakers, software suppliers, and operators. Integrating risk monitoring tools into vehicle certification processes would allow ongoing oversight rather than one-time approval. Authorities could also establish digital registries of certified vehicles to track compliance and quickly identify security lapses.

This research faced practical challenges that limit how widely its findings can be applied. Access to official regulatory data was sometimes restricted, and not all countries publish details of their ongoing policy development. The study relied mainly on publicly available documents, which may not include confidential or emerging initiatives. The absence of interviews or surveys with policymakers and engineers limits the understanding of real implementation difficulties. Technological advances also move faster than regulatory processes, meaning that some recent developments may already be beyond the study's scope. Expanding the range of sources, including government reports, technical evaluations, and industry databases, would improve accuracy.

Further exploration should focus on how governments and private sectors can jointly design enforceable and scalable solutions for spoofing prevention. Future research could examine the impact of insurance policies, risk-based pricing, and public trust on the

adoption of autonomous systems. Investigations may also look at how ethical design principles can become legal requirements within national transportation laws. Comparative analysis of regions such as the European Union, the Middle East, and East Asia could reveal which regulatory approaches most effectively reduce spoofing risks. Collaborating with automotive associations and cybersecurity experts could create a shared global model for compliance and enforcement. Practical experiments, such as simulation testing and prototype auditing, could generate real-time data.

Conclusion

This study examined the growing issue of sensor spoofing and its regulation in autonomous vehicles. As self-driving systems rely heavily on sensors such as LiDAR, radar, GPS, and cameras, spoofing attacks have become a serious threat to safety and public trust. The research focused on how policymakers and regulators are responding to these risks through emerging laws, standards, and global cooperation. This topic is significant because it connects technology, law, and public safety within the larger context of intelligent transportation systems. Addressing spoofing is not just a technical task but also a legal and ethical challenge that affects how societies manage innovation. The increasing use of automation in transportation, industry, and defense highlights the urgent need for strong and adaptive governance.

The findings show that international standards and national regulations are beginning to address cybersecurity, yet few specifically mention spoofing. Frameworks like ISO/SAE 21434 and UNECE Regulation No. 155 promote security-by-design principles but rely on voluntary compliance. Laws in countries such as the United Kingdom and the United Arab Emirates demonstrate progress in certification and data protection but still lack detailed coverage of spoofing attacks. Evidence from academic and policy studies reveals growing awareness among governments but limited harmonization between jurisdictions. This situation reflects an imbalance between technological advancement and legal adaptation. While innovation in sensor and AI technology continues rapidly, legislation remains reactive. Linking technical defenses with regulatory enforcement is therefore essential to achieve sustainable progress.

The importance of these arguments lies in their contribution to bridging gaps between technology, law, and accountability. Recognizing spoofing as a unique cyber-physical threat can reshape how governments design safety regulations for intelligent systems. Integrating technical standards into law encourages both innovation and responsibility. The study reinforces the idea that security cannot depend only on engineering; it must be built into the regulatory process from the start. This approach ensures that autonomous vehicles not only operate efficiently but also withstand malicious interference. Strengthening legal clarity also promotes fairness by defining responsibility among manufacturers, developers, and operators. As autonomous systems

become more common, combining preventive design with enforceable rules becomes the foundation for public safety and technological trust.

The broader outcomes of this research extend to multiple sectors beyond transportation. Autonomous technologies are being introduced in logistics, healthcare, and infrastructure management, all of which face similar vulnerabilities. The study's insights encourage governments to develop comprehensive frameworks that apply across industries. They also suggest that international collaboration can prevent fragmented policies and uneven protection. Global partnerships through organizations like ISO, UNECE, and the International Telecommunication Union can help standardize responses and promote information sharing. The results demonstrate that aligning national interests with global norms is vital for achieving long-term resilience. Creating policies that adapt to new risks will not only strengthen security but also promote responsible innovation. The lessons from autonomous vehicles can therefore guide the governance of future digital ecosystems, where trust, safety, and regulation must advance together.

In practical terms, the study's conclusions can support real-world policy reform and industrial practice. Governments can use these insights to develop clear certification rules for vehicle cybersecurity, including specific provisions for spoofing resistance. Automakers can apply the results to improve testing and auditing processes before vehicles reach the market. Insurance firms can design new coverage models that consider cyber-physical risks, encouraging companies to maintain stronger defenses. Educational institutions and research centers can build training programs to close the gap between engineers and policymakers.

Further study is needed to explore how laws, ethics, and artificial intelligence interact in managing sensor spoofing and related risks. More research should focus on the practical performance of current regulatory models in different regions. Comparing how various countries balance innovation and safety can help identify best practices. Continuous assessment of international standards will ensure that they remain relevant as technology evolves. Collaboration among scholars, policymakers, and industry leaders will be essential for developing realistic, enforceable, and future-oriented policies. Emerging issues such as data sovereignty, cross-border liability, and algorithmic transparency also deserve deeper analysis. Future initiatives should aim to create adaptive legal systems that can evolve with technological change.

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