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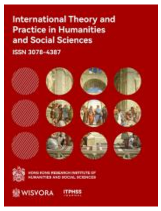

Allocation of liability for driverless cars: Based on legal economics

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Abstract

Autonomous driving disrupts traditional liability frameworks as negligence-based tort law fails multi-actor attribution challenges like algorithm failures or sensor errors. This study proposes a law-and-economics dynamic liability model (DLM), using Kaldor-Hicks efficiency to rebalance accident costs. The DLM mandates manufacturer responsibility in transitional automation (L3-L4) to spur R&D corrections, shifting to risk-pooling via insurance and funds at L5. Algorithm transparency protocols and globally harmonized standards are critical for cost internalization. Empirical validation through Tesla Autopilot cases demonstrates DLM's dual efficacy: compensating victims efficiently while aligning liability costs with manufacturers' control capacities. The framework bridges gaps between innovation incentives and social risk distribution in emerging mobility ecosystems.

1. Introduction

In recent years, with the rapid development of artificial intelligence technology, driverless cars have gradually moved from laboratory tests to market applications, becoming a technological revolution in the field of transportation. By integrating high-precision sensors, complex algorithms and real-time data processing, this technology has shown significant potential to optimize travel efficiency and reduce traffic accidents. However, technological advances have inevitably brought about new legal challenges, the most difficult of which is the allocation of accident liability. While traditional traffic accident liability is centered on driver fault, in a driverless scenario, the autonomous decision-making of vehicles gradually replaces the behavior of human drivers, and the main body of liability is transformed. This profound change makes the existing legal system face great challenges in adapting to the new technology.

The complexity of liability allocation for driverless cars comes not only from the uncertainty of the technology itself, but also from the participation of multiple subjects and the highly intertwined causal chain. In this context, how to reasonably divide the responsibility within the legal framework, which not only provides fair relief for the victims, but also creates a stable social environment for the technological innovation, has become a focus of attention for both academics and practitioners.

This paper takes the perspective of legal economics to explore the optimization path of liability allocation for driverless cars, providing theoretical support and practical inspiration for the improvement of the relevant legal system.

1.1 Legal Dilemma in Liability Allocation

The determination of liability for accidents involving driverless vehicles faces a dilemma that is difficult to resolve under traditional legal principles. In traditional traffic accidents, the driver's behavioral fault is usually the core basis for the attribution of responsibility, while driverless technology relies on algorithms and sensors to make decisions, and the role of the driver has been significantly weakened or even completely replaced. In this context, the allocation of responsibility involves more diversified subjects, including manufacturers, algorithm developers, data service providers, vehicle owners, and infrastructure providers, with blurred boundaries and complex causal chains（Yang, 2021）. This situation has significantly challenged the applicability of the current legal system, specifically manifested in the following two points:

Limitations of the principle of “fault liability” in tort law: traditional tort law takes fault as the core, and realizes relief for victims and deterrence for potential infringers by clarifying the responsibility of actors. However, in a driverless scenario, the main cause of the accident may be the decision-making bias of the algorithm, the hardware failure of the sensor or the error of external data input, and there is often a complex interaction between these factors, which is difficult to recognize through the fault of a single subject.

In 2022, Tesla Autopilot accident, the vehicle was in Autopilot mode and failed to avoid an obstacle in a timely manner. Tesla argued that the driver failed to maintain attention as prompted by the system, while the plaintiffs asserted that the vehicle's algorithm was defective. In the end, it was difficult for the court to clarify the exact proportion of responsibility between the driver and the vehicle system in the accident.

Limitations of the “Defect Determination” Standard in Product Liability Law: Compared to tort law, product liability law emphasizes the manufacturer's liability for damages caused by defective products. However, the core technology of driverless cars lies in algorithms and data services, and the current “defect” standard mainly focuses on hardware equipment, and lacks a clear basis for regulating accidents caused by algorithmic failures or dynamic data services.2021 When the self-driving car accident occurred, the cause of the accident involved a defective sensor design, an algorithmic miscalculation, and a driver's fault. The manufacturer argued that the driver had failed to exercise due care. The manufacturer argued that the driver failed to exercise due care, while the plaintiff argued that the sensor's inability to accurately recognize obstacles constituted a product defect. The difficulty for the court to form a uniform standard on liability attribution highlights the limitations of the current product liability law in a dynamic technological environment.

The above two cases(María Lubomira Kubica,2022) reveal the core challenges in the allocation of liability for driverless cars from different sides. Tort law and product liability law are unable to effectively identify the cause of the accident and protect the rights and interests of the victims in the face of multiple liability subjects and complex causal chains. This legal dilemma calls for further innovation of the system to adapt to the new needs of technological development.

Tort liability for driverless cars is facing unprecedented challenges due to the high complexity of the technology and the participation of multiple subjects. Such technology not only relies on sophisticated hardware devices and complex software systems but also involves data transmission networks and cloud collaboration, which undoubtedly greatly increases the difficulty of liability determination. In the context of traditional tort law, the principle of fault is often regarded as the core criterion of liability attribution, however, in the context of driverless driving, the occurrence of accidents often originates from the joint force of multiple subjects. For example, an accident may be caused by the design flaws of a hardware manufacturer, the failure of an algorithm developer to anticipate a particular driving situation, or even the failure of a data provider to make a prediction. In such a multi-subject situation, the chain of responsibility becomes more and more complicated, and the accurate determination of the real responsibility of the accident depends on highly specialized technical appraisal and cross-disciplinary coordination, which undoubtedly significantly increases the cost of resolving legal disputes.

1.2 Technological-Legal Tension and Research Value

1.2.1 The double tension between technology and law

Driverless technology as a disruptive innovation, demonstrates great potential to reduce human error and improve transportation efficiency. According to research, more than 90% of traffic accidents originate from human error, and driverless cars are expected to significantly reduce the accident rate by eliminating the risk of human operation. However, the complexity and uncertainty of this technology also raises new questions（Xiao, 2022). The system may have decision-making errors when dealing with class bad weather or complex road conditions, and this technological shortcoming directly affects the attribution of responsibility for accidents. The uncertainty of the liability subject also makes the protection of the rights and interests of the victims face difficulties.

1.2.2 Legal Economics for Responsibility Assignment

The core of legal economics lies in measuring the rationality of legal rules through the efficiency criterion, in which the maximization of the overall welfare of society is the core goal of responsibility allocation (Posner, 1973).Legal economics provides a unique analytical framework for the problem of responsibility allocation of driverless cars, the core of which is to realize the optimal allocation of social resources through the design of legal rules. Under this perspective, liability allocation is not only a coordination mechanism for conflict of interest, but also a balancing tool between technological development and social benefits. Specifically, it is a hierarchical division between efficiency goals and equity goals. Efficiency and equity are not diametrically opposed to each other, but complement each other in the responsibility allocation mechanism. A fair distribution of responsibility can enhance public trust in the technology, while an efficient design of rules can reduce the waste of social resources, both of which work together to provide institutional safeguards for the popularization of driverless technology.

1.3 Article originality

Compared with the existing research, this paper pioneers the deep integration of the dynamic framework of law and economics with the characteristics of autonomous driving technology. Traditional legal and economic research (such as the efficiency priority principle of Posner, 1973) mostly focuses on the allocation of responsibilities under static rules, which is difficult to solve the problem of risk weight changes of manufacturers, users, and insurers in different stages of development of autonomous driving technology (L3-L5). For example, in the early stages of technology (L3-L4), increased manufacturer responsibility drives safety investment, but as the technology matures (L5), excessive responsibility inhibits innovation. The phased liability adjustment mechanism proposed in this paper takes “technology maturity” as the core variable of responsibility allocation for the first time by combining the SAE autonomous driving classification standard, which not only makes up for the rigid defect of Xavier's strict liability theory, but also surpasses Kubica's static model of multi-responsibility responsibility definition. At the same time, in view of the fragmentation dilemma of global liability rules, this paper proposes an international black box data mutual recognition agreement based on the Vienna Convention, which solves the problem of cross-border liability determination by standardizing algorithm logs and accident records, and fills the gap of cross-border coordination tools in Calabresi's cost theory. In addition, this paper refines the compensation fund into a three-level structure of technical defects, algorithm misjudgment, and data service failure, and clarifies the shared ratio of the government (20-30%), insurance (20-30%) and enterprises, which is more operable than the fuzzy framework of California's AB 60 bill, and shows the ability to refine the governance of complex technology risks.

2. Legal-Economic Framework: Balancing Efficiency, Innovation, and Equity

As a landmark application in the field of artificial intelligence technology, the rapid progress of driverless cars has not only profoundly changed the mode of operation of the transportation industry, but also posed a severe test to the current legal system. As a core issue in the promotion of driverless technology, the proper solution to the problem of attribution of responsibility requires a delicate balance between the values of efficiency and fairness. From the perspective of legal economics, efficiency value tends to optimize the allocation of resources and stimulate the vitality of technological innovation through a delicate rule structure, thus maximizing the overall welfare of the society; while fairness value focuses on the protection of the rights and interests of disadvantaged groups in the division of responsibility for accidents, and ensures that the victims can obtain just and adequate relief after the accident(Li, 2022). Theoretically, although there is a certain conflict between the two, but through the scientific design of the rules, can also realize the organic integration, for the unmanned driver technology to provide a solid legal support for the steady progress.

2.1 Efficiency-Oriented Rule Design

Efficiency value: optimization of social resources allocation and technological innovation incentives.

Efficiency occupies a primary position in the construction of the responsibility attribution mechanism, the core of which lies in the clarification of the subject of responsibility, the reduction of transaction costs, and the stimulation of the innovation potential of the technical subject. Driverless cars have significantly reduced the incidence of traffic accidents by reducing human driving errors and optimizing traffic flow(Li , 2022). However, the failure of legal rules to precisely define the scope of the rights and responsibilities of the responsible parties will lead to increased uncertainty in the attribution of responsibility for accidents and higher transaction costs, which in turn will weaken the driving force for technology promotion. At the same time, efficiency value requires that the liability attribution mechanism exerts a positive incentive effect on the technology subject. By placing a reasonable burden of responsibility on manufacturers, they can be urged to continuously optimize vehicle sensors, algorithmic logic, and data transmission systems, thus improving the overall safety performance and reliability of driverless technology.

On the contrary, the efficiency-oriented rule design also faces limitations. At a stage of insufficient technological maturity, over-centralization of manufacturers' responsibilities may lead to a surge in their R&D costs and even hinder the pace of technological innovation. Therefore, the realization of the value of efficiency should be compatible with the rationality of responsibility attribution, and the dynamic adjustment mechanism should be used to reduce the burden of responsibility of technical subjects and provide an institutional guarantee for the improvement of the overall efficiency of the society.

Fair value: accident victims' rights and interests of the defense and social justice manifestation

Different from the efficiency value which focuses on the overall welfare of society, the fair value emphasizes that the legal rules should manifest justice when distributing the consequences of accidents, especially focusing on the protection of the rights and interests of vulnerable groups.

Victims of driverless car accidents are often at a disadvantage in terms of information, which makes it difficult for them to gain in-depth insight into the cause of the accident and to bear the high costs of technical appraisal and litigation. Under such circumstances, if the liability rules are excessively tilted to the technical subject, it may lead to the damage to the rights and interests of the victims, and even trigger the public's distrust of the driverless technology. Therefore, the fair value requires that the liability attribution mechanism can fully protect the right to compensation of accident victims, enhance the public's trust in the technology by directly protecting the rights and interests of individuals, and at the same time, promote the harmony and stability of the society by maintaining the justice of liability attribution.

2.2 Fairness as a Social Justice Safeguard

Under the framework of legal economics, value analysis can be divided into first-order value and second-order value. First-order value takes efficiency as the core, and is committed to the optimization of resource allocation and the maximization of social wealth; second-order value focuses on the specific distribution of the results of efficiency and emphasizes fairness and the reasonable distribution of social welfare among different subjects. The allocation of responsibility for driverless cars is a typical scenario for this analytical framework. Due to its technical complexity and multi-object participation, the law needs to achieve a dynamic balance between efficiency and fairness, so as to not only promote technological innovation but also safeguard social justice.

From the perspective of first-order value, efficiency is the primary goal of liability allocation for driverless cars. An efficient liability allocation mechanism can not only reduce legal disputes but also optimize the allocation of social resources by reducing transaction costs and clarifying the subject of liability. Specifically, driverless car technology involves complex hardware and software systems, including sensors, algorithms, and artificial intelligence models, while the liability subject often covers multiple parties such as manufacturers, developers, drivers, and insurance companies. A lack of clarity in the rules for assigning liability can lead to high transaction costs and impede the spread of the technology. In the United States, some states(People's Post and Telegraph,2024) have adopted clear legislation to define the responsibilities of all parties, which effectively reduces the dispute processing time and provides a good legal guarantee for the promotion of driverless car technology. In addition, the efficiency-oriented allocation of responsibility can also incentivize technology research and development. Taking the legislative practice of Germany as an example, the mandatory liability insurance system reduces part of the accident liability pressure for manufacturers, thus incentivizing enterprises to increase their R&D investment in autonomous driving technology.

However, first-order value-oriented liability allocation may also ignore the specific distributional status of efficiency outcomes, thus posing the risk of inequitable distribution, which is at the heart of second-order value concerns. In driverless car accidents, victims are usually in an informationally and economically disadvantaged position, and over shifting the responsibility to users or victims will not only increase their burden but may also trigger social conflicts. In a self-driving accident of Azera Motors, if the cause of the technical defect is ignored and the liability is fully attributed to the driver only in pursuit of efficiency, it may significantly harm their rights and interests and intensify social distrust of the technology. Therefore, the second-order value focuses on protecting the interests of vulnerable groups and enhancing public acceptance of driverless technology through fair distribution rules. By setting up a special fund for compensation, promoting socialized risk sharing, or introducing a punitive compensation mechanism, the law can find a balance between technological innovation and social equity.

The value conflict in the allocation of responsibility for driverless cars is mainly reflected in the opposition between efficiency and justice, as well as the contradiction between individual interests and the overall interests of society(Shu, 2021). In this regard, efficiency-prioritized liability allocation mechanisms may sacrifice the interests of individual victims, while fairness-prioritized system design may increase overall social costs and inhibit technological innovation. In this regard, the law should balance the two through dynamic regulation. Specific measures include the introduction of mandatory liability insurance mechanisms, the concentration of accident compensation on subjects with greater risk-bearing capacity, and the reduction of liability disputes between multiple subjects through technical black box records. Such a legal design can help maintain efficiency as well as balance fairness, providing a stable social foundation for the development of driverless technology.

2.3 Cost-Benefit Analysis: Marginal Cost Perspective

Marginal cost analysis is a core tool of legal economics, which optimizes resource allocation and maximizes overall benefits by comparing the additional costs and benefits of specific behaviors. In driverless car liability allocation, marginal cost analysis can be divided into two levels: marginal accident cost and marginal liability cost.

2.3.1 Marginal Accident Cost Optimization

Marginal accident cost is whether the manufacturer's investment in each unit of technological improvement can effectively reduce accident costs and bring equal or higher benefits to society. Driverless cars, being technology-intensive, require manufacturers to invest significant resources in sensor hardware, algorithm optimization, and redundant system construction. However, there is a significant discrepancy between this investment and the societal benefits of accident reduction, and legal design is needed to regulate the allocation of responsibility in order to incentivize manufacturers to make optimal decisions. Based on the social benefit matching principle, manufacturers' technological improvements can only maximize the efficiency of resource use if the marginal inputs match the social benefits of accident reduction.

Accident rate is a high-value correlate at all stages of liability allocation. In the initial period of driverless cars, the accident rate is high, and the law can encourage manufacturers to invest more resources to improve safety by strengthening their liability(Mu Dan, 2022). When the accident rate decreases to a certain threshold, the cost of further improvements by manufacturers may be much higher than the social benefits of fewer accidents, at which point the marginal burden of technology development should be reduced through a shared responsibility to ensure that manufacturers maintain their R&D incentives.

2.3.2 Marginal Liability Cost Allocation

The marginal liability cost theory emphasizes that the allocation of responsibility must be positively correlated with the energy efficiency of the subject's risk control. Marginal liability cost is whether the behavioral adjustment cost of the liability allocation rule for each subject (manufacturer, driver, pedestrian, and other subjects) is in line with their actual risk-taking ability. The development of driverless cars presents a staged character, and the risk-bearing ability and role positioning of the subjects in different stages are different, so it is necessary to distinguish: L3-L5-other subjects' responsibility allocation rules.

In the L3 stage, the driver still needs to bear the obligation of taking over, and the proportion of responsibility is higher. The law should clarify the driver's operating standards and reaction time requirements in specific situations while imposing supplementary liability on the manufacturer for accidents caused by system design defects. The percentage of liability should be increased accordingly if the manufacturer fails to take over the vehicle due to poor design in the vehicle handover control process.

In L5, the driver's role is gradually replaced by technology, and the manufacturer becomes the subject of liability. The design of legal rules at this stage should focus on the manufacturer's marginal liability costs, i.e., ensuring that the allocation of liability provides incentives to continuously optimize the technology without unduly increasing the burden. Fairness and efficiency in the allocation of liability can be achieved through the introduction of an accident risk classification mechanism, whereby the manufacturer bears more in low-risk scenarios, and a risk-like burden-sharing mechanism is shared by insurance in high-risk scenarios.

2.3.3 Multi-Actor Responsibility Mechanisms

In addition to manufacturers and drivers, other subjects also play an important role in driverless liability allocation. The theory of marginal liability cost emphasizes that the proportion of liability of these subjects should be proportional to the impact of their actions on the occurrence of accidents. The lack of road markings may significantly increase the risk of systematic misjudgments and therefore should have its corresponding risk provision based on the imposition of some liability on infrastructure operators.

2.4 Dynamic Liability Rules under Kaldor-Hicks Efficiency

Kaldor-Hicks Efficiency is one of the core theoretical tools of legal economics for measuring the efficiency of resource allocation, proposed by British economist Nicholas Kaldor and American economist John Hicks. The basic idea is that if a certain resource allocation adjustment can make the total gain of the beneficiary greater than the total loss of the injured party, the adjustment is considered efficient even if no actual compensation is made. The Cardo-Hicks standard, the core theory of legal economics for measuring the effectiveness of resource allocation, proposes that a change in resource allocation is efficient as long as it results in a gain for the beneficiaries that is greater than the loss for the injured parties and is theoretically capable of being compensated.

The central issue in the allocation of liability for driverless cars is how to achieve an efficient allocation of resources between technological development, social risk sharing, and the protection of victims' rights and interests. In this context, the Kaldor-Hicks standard can realize the efficiency of resource allocation through the following three levels:

2.4.1 Balancing Interests in Early-Stage Technology

Analogy with a risk hedging mechanism: Compulsory insurance can reduce the cost of social friction in the early stage of technology promotion by diversifying risks through market-oriented means, but its pricing needs to reflect the actual risk probability to avoid moral hazard(Shavell, 2004). In the early stage of the promotion of driverless car technology, the risk of accidents is high, especially in the L3 and L4 stages, where drivers and manufacturers are exposed to greater risks. At this stage, a reasonably designed risk-sharing mechanism can maximize overall welfare through the principle of Kaldor-Hick's efficiency.

Table 1: Optimization of Risk-Sharing Mechanisms

	Compulsory liability insurance	Specialized Compensation Fund
Application Principle	Compulsory liability insurance transfers accident risks to insurance companies through market-based means and prices accident risks with the help of big data.	Driverless car accidents can involve high levels of liability, especially if systemic technical flaws or algorithmic failures lead to large-scale accidents. The

	This mechanism effectively reduces the direct pressure on drivers and manufacturers to compensate for accidents, while ensuring that victims are compensated in a timely manner.	establishment of a compensation fund co-funded by multiple parties could be effective in spreading these high-risk costs. The main body of the special fund includes: 1) Technical defect accidents: manufacturers (50%), insurance companies (30%), and governments (20%) 2) Algorithms misjudge large-scale accidents: technology providers (40%), governments (30%), insurance (20%), and users (10%) 3) External data service failures: data service providers (60%), car companies (20%), fund income (20%)
Beneficiaries	1. Manufacturers and drivers reduce financial uncertainty by paying a fixed insurance premium and transferring the risk of potentially high compensation to the insurance company. 2. The insurance company spreads the risk through the scale effect and profits from it.	Victims can receive prompt compensation through compensation funds, reducing the cost of litigation and time. Manufacturers, drivers and insurers are under less pressure to pay compensation for a single accident due to the cost-sharing mechanism. .
Injured parties	In the short term insurance costs may raise operating costs for drivers and manufacturers. However, the gains are sufficient to compensate for potential losses: 1. The increase in insurance rates is less than	In the short term, manufacturers, insurers, and governments need to pay additional fund costs. However, through the scale effect of the fund, the total expenditures of these entities are reduced and the gains compensate for the losses. In

	the probabilistic cost of high compensation. 2. the overall welfare of society is increased by the efficiency of post-accident compensation. .	the long run, the compensation fund systematically reduces the main expenditure through the scale effect and risk hedging mechanism: the centralized capital pool uses the law of large numbers to share the occasional risk and reduce the financial pressure of a single enterprise; Advance compensation shortens the compensation cycle for victims, and accident data aggregation facilitates technology iteration; It forces enterprises to internalize risk costs and drives technology optimization and insurance.

The Kaldor-Hicks standard emphasizes that resource allocation adjustments should prioritize whether gains are sufficient to cover losses. In the dynamic rules of unmanned liability allocation, this principle is reflected through the flexible adjustment of the proportion of liability.

Table 2: Liability Allocation at Different Technology Maturity Levels

	Early stages of technology (stages L3-L4): centralization of responsibility allocation	Technological maturity (stage L5): decentralization of responsibility allocation
Matrix	Autonomous driving technology in the L3 and L4 stages is not yet mature enough for drivers to remain partially responsible for taking over, but due to the complexity of the system, manufacturers are responsible for a higher percentage of accidents.	Driverless technology at the L5 stage is approaching maturity, and the technological risk to the manufacturer is significantly reduced. At this point, decentralizing some of the liability to other entities (e.g., insurance companies or the government) can improve the fairness and efficiency of the rules.
Beneficiaries	Driverless technology at the L5 stage is approaching maturity, and the	Manufacturers release more resources for continuous innovation as a result of

	technological risk to the manufacturer is significantly reduced. At this point, decentralizing some of the liability to other entities (e.g., insurance companies or the government) can improve the fairness and efficiency of the rules.	lower liability ratios. Society as a whole benefit from lower accident rates and more efficient compensation.
Injured parties	Manufacturers face short-term cost increases due to increased liability ratios. However, the long-term societal benefits of technological advances (e.g., lower accident rates and increased public acceptance) far outweigh the losses, which is in line with the Kaldor-Hicks criteria.	Governments and insurance companies incur additional expenses as a result of burden-sharing. However, by optimizing the sharing ratio through market mechanisms, the benefits are still sufficient to cover potential losses.

Efficiency gains in resource internalization mechanisms

Table 3 Optimization of the efficiency of the risk-sharing mechanism:

	Data Transparency	Synergizing the division of labor among multiple actors
Beneficiaries	Legal and regulatory agencies reduce the cost of liability determination due to information transparency. Victims and manufacturers reduce litigation costs and compensation disputes due to rapid liability determination	Manufacturers release more resources for continuous innovation as a result of lower liability ratios. Society as a whole benefits from lower accident rates and more efficient compensation.
Injured parties	Manufacturers may experience increased compliance costs as a result of data disclosure. This is more than compensated for by cost savings from fewer disputes.	There may be a cost of collaboration for each actor, but the benefits of collaboration (e.g., reduced accident losses and societal costs) far outweigh the burdens..

The Kaldor-Hicks efficiency standard is an important theoretical tool in the field of legal economics, which focuses on the maximization of net social welfare and provides a clear analytical framework for the allocation of responsibility for driverless cars. However, the practical application of the standard faces complex conflicts and dynamic game problems among the subjects of interest, and needs to be adjusted and optimized in specific contexts.

2.5 Stage-Adaptive Liability Allocation

The promotion of driverless cars requires a balance between short-term social costs and long-term efficiency gains. The core of this issue lies in how to incentivize technological innovation through a liability allocation mechanism while avoiding excessive social burdens at a stage when the technology is not yet mature.

Incentivizing Innovation in Early Stages, the immaturity of driverless technology brings with it a higher risk of accidents and legal uncertainty. At this stage, appropriately concentrating responsibility on technology developers can help promote technology improvement. For example, Japan implemented a mandatory liability insurance system in the early stages of driverless trials to ensure that accident victims could obtain compensation quickly while sharing some of the compensation pressure on developers through insurance. Such a system design reduces social distrust of the new technology while also creating space for further development.

Long-Term Efficiency through Dynamic Risk Transfer, the social benefits of driverless technology are obvious, including reducing traffic accidents, improving transportation efficiency, and reducing environmental pollution. However, the realization of these long-term benefits is dependent on the continued innovation drive of developers and widespread social acceptance. Being too harsh on developers may trigger an increase in the cost of technology development and even lead to the withdrawal of some potential markets. Therefore, there is a legal need to reasonably shift a portion of the risk to users and insurance organizations by establishing a mechanism for transferring and dispersing responsibility. For example, Germany has stipulated in its driverless technology legislation that manufacturers are strictly liable for product defects, but uncontrollable risks are dispersed through technical defects insurance, which not only maintains fairness but also paves the way for the commercial application of the technology.

In the dynamic adjustment of liability allocation, the law needs to take into account the stage-by-stage characteristics of technology development. Concentrating liability on technology developers at the early stage helps to rapidly accumulate technological trust, while a reasonable transfer of liability at the mature stage can promote the popularization of technology and the efficient allocation of resources. By dynamically optimizing the liability allocation model, the law can find a suitable balance between efficiency and fairness, and promote the healthy development of driverless technology.

2.6 Net Social Benefit Optimization Framework

Maximizing the net social benefit is the core purpose of legal economics. When exploring the issue of responsibility allocation for driverless cars, the design of a set of dynamic responsibility allocation mechanisms needs to deeply integrate the cost-benefit analysis, the prudent consideration of opportunity cost, and the cooperation between the responsible subjects.

Cost-benefit analysis constitutes the cornerstone of an optimal responsibility allocation framework. In the liability framework of driverless cars, the core is to compare the marginal accident cost with the marginal liability cost. Marginal costs for technology developers in terms of algorithmic refinement and sensor optimization diminish as the technology matures, while the social benefits of fewer accidents in the system are a visual representation of the marginal benefits. By defining the basic scope of responsibility of manufacturers, the law incentivizes them to reduce the accident rate, which in turn leads to an increase in overall performance.

At the same time, opportunity cost analysis provides further guidance for adjusting the allocation of responsibility. Imposing excessive liability on the developer of the technology may lead to a surge in R&D costs and the risk of the technology being withdrawn from the market; on the other hand, placing all the blame on the victim or the insurance company may erode the foundation of the public's trust in the technology(Zhang Jianwen, 2018). France's legislation on liability allocation for driverless technology has skillfully found a balance between incentives for developers and protection of the public interest by adjusting the proportion of liability between manufacturers and insurance organizations in phases.

In addition, the practical application of dynamic liability allocation needs to be closely combined with the maturity of the technology and the complexity of accident scenarios. In L3 autonomous driving, given that the driver still needs to retain some control over the vehicle, a mixed allocation of liability between the driver and the manufacturer is more reasonable. As we move to the L5 level of fully autonomous driving, the model where the manufacturer assumes full responsibility is more in line with the dual standards of efficiency and fairness. This mechanism of flexibly adjusting the allocation of liability according to the stage of technological development not only reduces the room for uncertainty in the application of the law but also significantly enhances the predictability and fairness of the allocation of liability.

3. Internalization of Negative Externalities

3.1 Compensation and Deterrence in Tort Law

From the perspective of economics, the essence of unmanned car infringement is rooted in the existence of negative externalities, which means that the perpetrator fails to fully carry the full picture of the social costs caused by its behavior, and part or even all of the consequences of the damage to be shifted to others or society as a whole. Such externalities often lead to inefficient allocation of resources and a net loss of social welfare. Additionally, the ability of the market mechanism to self-correct for such problems is quite limited. Therefore, the legal system needs to internalize negative externalities through sophisticated rules and liability mechanisms, forcing actors to bear the full costs of their actions, in order to correct misconduct and optimize the pattern of resource allocation. The problem of negative externalities is particularly pronounced in the cutting-edge field of driverless cars. Traffic accidents induced by technological flaws, system failures, or algorithmic deficiencies are all characterized by negative externalities. Victims not only need to bear medical expenses, property damage, and other direct damages but also may face the loss of time, mental damage, and other indirect consequences, if there is no effective intervention of the law, such losses will be transferred to the community as a whole or the victims of the individual to bear, which will result in the imbalance of the risk of technological innovation and the sharing of the cost of the state. Therefore, the internalization of negative externalities with the help of the legal system of tort is not only a key measure to correct the market failure but also an important legal guarantee to promote the sound development of emerging technologies.

3.2 Strict Liability as a Risk Control Tool

In the practical application of driverless cars, the realization path of internalization of externalities mainly relies on the damage compensation mechanism, liability attribution rules, and deterrent provisions of tort law. First of all, the damage compensation mechanism constitutes the cornerstone for coping with the problem of negative externalities. The direct and indirect costs of driverless car accidents, such as medical expenses, property restoration costs, lost wages, and mental damages, need to be clearly compensated through tort law, and incorporated into the cost structure of the responsible subject to ensure that the victims receive adequate relief, while mitigating the net loss of social welfare. In the accident caused by the failure of Tesla's Autopilot system, the U.S. judiciary ruled that the manufacturer should bear high compensation, which not only compensated the victim's economic loss, but also established the responsibility of the enterprise for the technological defects at the legal level, and provided jurisprudential references for the subsequent similar cases.

Second, tort law further strengthens the effectiveness of internalization of externalities through fine-grained liability attribution rules. Given the complexity of driverless cars, liability determination cannot be limited to end-users but should be extended to technology developers, manufacturers, and participants in the supply chain. The advantage of strict liability in technically complex scenarios is that it attributes the internalized risk to the vendor through liability, which is better than the potentially high cost of proof under fault liability(Shavell, 2004). Tort law adopts the principle of strict liability, which ensures that the responsible parties bear full and strict liability for their behavior and product risks. The principle of strict liability will require manufacturers to pay compensation for technical defects caused by neglecting safety testing or algorithm optimization during the R&D and production process, thus effectively curbing the tendency of companies to ignore safety standards in order to reduce costs.

In addition, the deterrence mechanism, as an important auxiliary means of internalizing externalities, can provide a strong legal deterrent to potential infringers by setting high compensation or even punitive damages, thus motivating them to invest more in technology research and development in order to reduce the risk of accidents. In the face of the high liability that may be triggered by driverless cars, companies will be more inclined to strengthen safety performance and optimize algorithmic logic during the product design stage to avoid potential legal costs and reputation loss. Tesla, for example, has upgraded its autopilot system and strengthened its safety features after a number of accidents, and this shift has been driven by the dual pressure of high compensation and public opinion. Such a deterrent mechanism not only accelerates the iterative upgrading of technology but also provides consumers with more solid safety protection.

Finally, while promoting externalities internalization, it is crucial that tort law also needs to balance the relationship between technological innovation and social risk carefully. Driverless cars, as an emerging technology, are in a stage of rapid development and full of uncertainty. While protecting the rights and interests of the victims, tort law should also avoid imposing excessive penalties on enterprises, so as not to inhibit their innovative vitality. Therefore, when setting compensation standards, the law needs to take into account the severity of accidental losses, the degree of fault of the responsible party and the stage of technological development. Through scientific rule design, tort law can provide a stable and flexible legal framework for the prosperous development of the driverless car industry on the basis of safeguarding the legitimate rights and interests of the victims(Ji, 2020).

4. Calabresi's Cost Allocation: A Three-Dimensional Approach

The complexity of the tort liability of driverless cars is rooted in the uncertainty of technology, the intertwining of responsibilities of multiple subjects, and the lack of adaptability of the existing legal system. Drawing on Calabresi's theory of cost allocation, we can explore the optimization path of liability allocation from the three-dimensional perspectives of accident cost, risk avoidance cost and management cost, aiming at minimizing the total cost of society and the fairness of liability allocation.

4.1 Accident Cost Minimization Pathways

The direct losses involved in driverless car accidents cover property damages, medical expenses, and compensation, while the prevention costs focus on the R&D and risk control inputs made by manufacturers and other technological entities. According to traditional tort law, the allocation of liability focuses on the main responsible parties. However, in the context of driverless technology, accidents often originate from multi-party collaborative technology chains, and a single concentration of liability may lead to unfair distribution and may have a curbing effect on technological innovation. For example, if a sensor failure causes an accident, the responsibility may not only be attributed to the hardware manufacturer but also to the software developer or data service provider. Therefore, a multi-level responsibility allocation mechanism should be introduced to share the responsibility based on the actual fault ratio of each subject in the accident chain. If a sensor failure causes a collision, the supplier and manufacturer should share the responsibility according to their technical contribution and degree of fault; if the driver fails to respond to the system's warnings at the L3 level, he or she should share part of the responsibility.

In addition, in order to cope with the changes in the degree of automation, it is recommended that a dynamic liability ratio adjustment mechanism be constructed. As the level of automated driving (L0 to L5) increases, the proportion of the manufacturer's responsibility should be gradually increased: at L3, the driver should take over the vehicle at critical moments, and if he fails to respond to the warning, he has to share the responsibility for the accident; at L5, the driver should be executed by the system, and the manufacturer or the algorithm developer has to bear the full responsibility. This dynamic adjustment mechanism aims to find a balance between incentives for technological innovation and consumer protection.

4.2 Transparency for Risk Reduction

The promotion of driverless technology faces the challenge of consumer risk aversion, which stems from the lack of technological transparency and the uncertainty of accident liability determination. Complex autonomous driving decision-making logic makes it difficult for consumers to trust the performance of vehicles in emergency situations, and the ambiguity of who should be held liable further exacerbates the public's technological skepticism(Yang, 2018). Tesla's multiple Autopilot accidents in 2019 highlight consumers' lack of awareness of the system's safety and accident liability rules, and market acceptance has suffered a setback.

In order to reduce the cost of risk avoidance, the first step is to establish a transparent algorithmic evaluation mechanism, requiring manufacturers to regularly disclose vehicle safety performance data, including the probability of accidents, algorithmic decision-making logic, and the results of scenario-adaptive testing. This not only enhances consumer trust in the technology but also provides data support for accident liability determination. Second, the technology has not yet matured, it is recommended that the government or insurance companies provide risk buffer mechanisms, such as the establishment of a special accident insurance fund, covering the initial due to technical defects due to liability. This mechanism not only protects consumers' rights and interests but also spreads the risk of early technology promotion for manufacturers.

At the same time, the insurance market needs to adjust to the characteristics of driverless technology and develop dynamically priced insurance products. Dynamically adjusting premiums based on vehicle technology upgrades, accident records, and other risk factors not only reflects the actual level of risk but also provides incentives for manufacturers to improve technology. Vehicles with reduced accident rates after technological upgrades can enjoy premium reductions to promote the continuous optimization of safety technology.

4.3 Synergized Management Mechanisms

The process of handling driverless car accidents is often accompanied by high management costs, which are mainly reflected in the complexity of technical identification and responsibility determination. Accident investigation requires reading algorithm logs, sensor data, and driver operation records, which puts high demands on the judicial system. In addition, national laws have not yet been harmonized to determine the liability of driverless accidents, which further pushes up the management costs.

In order to reduce management costs, the first task is to set up a specialized agency to arbitrate driverless accidents. The agency should be composed of technical experts and legal experts, focusing on handling liability disputes in the field of unmanned driving, and completing the liability determination quickly through specialized means, so as to reduce the consumption of judicial resources. Secondly, it is recommended to formulate unified technical appraisal standards and clarify the rules of responsibility attribution. If sensor failure is caused by OTA (online software update), the manufacturer should bear the main responsibility; if the driver fails to respond to vehicle warnings in time, the responsibility should be shared. Standardized rules are designed to improve the efficiency of accident handling and reduce uncertainty in the judicial process.

In addition, strengthening cross-sectoral and international collaboration is key to reducing administrative costs. The global application of driverless technology requires countries to form uniform rules on liability determination. The formulation of international liability standards for driverless vehicles, taking into account the amendments to the Vienna Convention on Road Traffic, can effectively solve the problem of attributing liability for cross-border accidents

5. conclusion

The autonomous vehicle, as a milestone innovation in the field of artificial intelligence, is gradually disrupting traditional transportation models. However, the resulting challenges regarding liability attribution pose a severe test to the existing legal framework. This paper focuses on the perspective of law and economics, deeply analyzing the limitations of traditional tort law and product liability law in addressing complex situations such as algorithmic bias and sensor failure. It proposes a dynamic liability allocation mechanism that integrates efficiency and fairness.

China's autonomous driving technology, propelled by the first-mover advantages of innovators such as Baidu Apollo and XPeng XPILOT, has entered an accelerated phase of commercialization. Yet it confronts a profound regulatory paradox: While technological advancement surges, institutional frameworks lag critically. The existing Road Traffic Safety Law fails to clarify liability attribution for autonomous decision-making algorithms, and decentralized local pilot programs like Beijing and Shenzhen under the Intelligent Connected Vehicle Management Regulations reveal territorial limitations and fragmented regulatory coordination. This creates structural tension between technological iteration and legal adaptation. The academic and practical significance of this study lies in its tripartite paradigm innovation in regulatory design: Firstly, by constructing a SAE Level-based dynamic liability allocation model, the “manufacturer-primary, user-supplementary” logic for L3 autonomy can be systematically integrated into the Automotive Data Security Management Regulations. The proposed Technology Maturity Coefficient (TMC) in Shenzhen's pilot zone enables algorithmic adjustments to liability weights, resolving the paradox between “technological explainability” and “legal accountability”. Then, the novel three-tier risk-sharing mechanism transitions into a national-level accident compensation framework, mobilizing structured capital contributions from the Ministry of Finance (30%), automotive alliances (50%), and insurers (20%). Coupled with Ping An's UBI dynamic pricing trials, this synthesizes a risk-hedging system balancing Kaldor-Hicks efficiency and adaptive efficiency. Anchored in responsive regulatory theory, China's engagement in the Vienna Convention's “Black Box Data Interoperability Standard” technical working group advances the integration of the Bai Dou Temporal-Spatial Protocol (BDS-T) into global accident liability frameworks. This not only dismantles institutional barriers for BYD and NIO’s global expansion but signifies China’s evolution from a “rule-taker” to a “paradigm-setter” in autonomous mobility governance. By deconstructing the equilibrium between negative externality mitigation and innovation incentives, this research provides normative jurisprudential tools to escape China’s “regulatory vacuum trap” while contributing an Eastern-experience-infused legal paradigm to global autonomous driving governance.

In order to cope with the difficulty of attributing liability to driverless cars, countries are working to improve their legal framework. The Artificial Intelligence Liability Act is a useful attempt to clarify the liability boundaries of high-risk technologies, so as to reduce legal disputes arising from the dispersion of liability. In addition, to address the technical bottleneck in the process of liability determination, the future legal system may introduce a dynamic liability ratio mechanism to allocate liability based on the actual degree of fault or the proportion of technological contribution of each party in the accident. This dynamic mechanism can more fairly reflect the multi-causal nature of accidents. At the same time, by promoting the black box recording system, the technical data at the time of the accident can be recorded in real-time and used for subsequent analysis, thus significantly reducing the technical difficulty and transaction cost of liability determination. In addition, the establishment of a specialized compensation fund for driverless car accidents can also provide timely relief for victims in the event of uncertain liability, while sharing risks for technology companies.

At the first-order value dimension, this mechanism emphasizes clarifying responsible parties, reducing transaction costs, and stimulating technological innovation, aiming to optimize the allocation of social resources. It flexibly adjusts liability weights based on the maturity levels of autonomous driving technology (L3 to L5), reinforcing manufacturers' responsibilities in the early stages of technological development to drive iterative upgrades. At the second-order value dimension, it focuses on safeguarding the legitimate rights and interests of vulnerable groups and promoting the realization of social justice, thereby enhancing the public's trust in autonomous driving technology. Once the technology matures, it introduces mandatory insurance and compensation fund mechanisms to effectively disperse potential risks.

While adjusting the legal system, the internalization of negative externalities also needs to balance the incentives for technological innovation and social protection(Ye, 2019). On the one hand, by setting high compensation and strict liability, the law can encourage manufacturers and developers to improve the safety and reliability of their products, thus reducing potential risks; on the other hand, overly stringent liability may inhibit the innovation of technology companies, thus restricting the vigorous development of the industry as a whole. Therefore, when designing liability allocation rules, the law must seek a dynamic balance between sharing the costs of accidents and incentivizing technological innovation.

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