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Engineering Risk Control and Value Realization Approaches from an Acceptable Risk Perspective: A Case Study of Autonomous Driving Technology

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Abstract

Autonomous driving technology represents the pinnacle of contemporary cutting-edge engineering, and its development process vividly demonstrates the inherent dialectical unity between value creation and risk in engineering activities. This paper adopts "acceptable risk" as the core theoretical framework to comprehensively analyze the positive values of autonomous driving technology across safety, efficiency, economic viability, and social inclusivity, while also detailing its complex risk profile—including technological uncertainties, algorithmic ethical dilemmas, ambiguous liability assignments, and social trust deficits. The study reveals that large-scale adoption of autonomous driving faces significant obstacles due to the lack of consensus on defining acceptable risk thresholds that balance technical rationality, ethical principles, and societal acceptance [1]. Traditional analytical frameworks based solely on technical rationality and cost-benefit considerations have limitations, as risk acceptability is fundamentally a socially constructed process. Therefore, this paper proposes a multi-tiered, collaborative risk governance framework integrating conceptual, technological, and institutional dimensions. It advocates for reconstructing engineering philosophies through "responsibility-driven innovation" and "value-sensitive design," strengthening technical foundations by enhancing algorithm transparency and establishing extreme condition detection systems, and shaping socially acceptable risk boundaries through well-defined regulatory frameworks, clear accountability mechanisms, and sustained public engagement. The conclusion emphasizes that the positive value of autonomous driving and other emerging technologies can only be realized stably and ethically within a responsible innovation environment characterized by continuous risk identification, rigorous evaluation, and transparent societal dialogue.

Keywords: *acceptable risk; engineering ethics; autonomous driving; risk control; algorithmic ethics*

Introduction

We are now at a critical stage of the transportation revolution driven by silicon-based intelligence. Autonomous vehicles are no longer a product of science fiction but have become a strategic priority in global technological competition and industrial layout. For instance, Google Waymo offers commercial Robotaxi services in Phoenix, General Motors Cruise conducts pilot operations in San Francisco, while Chinese companies such as Baidu's "LuoBo KuaiPao" and Pony.ai are also advancing related initiatives in multiple cities [2]. Global capital and policy investments continue to support this technology, reflecting its ambition to reshape future society. Autonomous driving technology promises a vision close to utopia: it could free humans from tedious and hazardous driving tasks and address traffic accidents caused by human error—the primary cause of approximately 1.35 million annual deaths worldwide due to road accidents. Additionally, it has the potential to enhance transportation system efficiency, optimize urban space utilization, improve energy structures, and provide dignified mobility for vulnerable groups such as the elderly and people with disabilities.

However, the path to this future is far from smooth. In 2018, an Uber self-driving test vehicle killed a pedestrian crossing the street while pushing a bicycle during nighttime testing in Tempe, Arizona. Analysis revealed that the vehicle's perception system failed to accurately identify objects, and its safety officer was severely distracted. Beyond such tragedies,

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there have been multiple fatal accidents involving Tesla's Autopilot advanced driver assistance system, along with ongoing academic and public debates about the "trolley problem." These incidents highlight a stark reality: behind the promised benefits of autonomous driving technology lies a complex risk matrix shaped by technological limitations, ethical dilemmas, legal delays, and societal psychology [3]. Consequently, large-scale adoption of autonomous driving faces a fundamental bottleneck. While seemingly simple, this challenge runs deep: To what extent are we as a society willing to accept the risks associated with autonomous technology? The question of "acceptable risk" transcends mere technical feasibility, becoming a critical barrier between engineering design and societal acceptance. "Acceptable risk" is neither a static numerical standard nor something determined solely by experts; it is a dynamic process fraught with value trade-offs, continuously evolving through social negotiation and construction.

1. The theoretical implications of acceptable risk and its evolution and prominence in the field of autonomous driving

1.1 The Ethical Implications of Acceptable Risk and the Limitations of Classic Judgment Models

In both the field of engineering ethics and risk management, "acceptable risk" is a foundational concept. It is defined as a level of risk that exists within specific social, cultural, economic, and technological contexts. Relevant stakeholders must fully understand this risk and are only willing to tolerate it after weighing the risks against potential benefits [4]. It represents both a societal compromise and a collective consensus. This compromise lies between two extremes: one end is the utopian vision of "absolute safety," and the other is a state of complete laissez-faire anarchy. Historically, defining acceptable risk has primarily relied on two classic models.

1.1.1 Technical Rationality Model:

This model relies on a probabilistic risk assessment conducted by an expert system, which precisely calculates both the likelihood of adverse events occurring and the severity of their consequences. These calculations are used to define safety boundaries using quantitative metrics—such as annual mortality rates being commonly employed indicators. However, the model has inherent limitations, particularly its tendency toward oversimplification: it reduces risks to cold numerical values while neglecting their qualitative dimensions. These qualitative aspects include whether a risk is voluntary or involuntary, public perception of fear associated with the risk, controllability of the risk, and fairness in risk distribution. Public perceptions differ significantly between scenarios—voluntary air travel versus involuntary residence near chemical plants—but the PRA model struggles to capture such perceptual variations.

1.1.2 Economicism Model:

This model employs cost-benefit analysis as its core tool, aiming to quantify intangible values such as life, health, and environmental aesthetics into monetary terms. When the calculated total benefits exceed the total costs—including risk costs—the associated risks are deemed acceptable. The primary criticism of this model lies in its ethical tendency toward "objectification," which measures human dignity and the right to life through economic calculations. This approach may lead to utilitarian decisions that prioritize majority welfare at the expense of minority interests, supported by seemingly scientific justifications. Such practices can give rise to serious issues of environmental justice and social equity.

1.2 How Autonomous Driving Technology Redefines and Challenges Acceptable Risk Boundaries

Autonomous driving technology possesses groundbreaking technical characteristics and unique modes of social interaction. It has rendered the traditional concept of "acceptable risk" exceptionally complex and contentious, as evidenced by the following three aspects:

1.2.1 Unprecedented concentration and transfer of risk decision-making authority:

In traditional transportation systems, risk decision-making is highly decentralized. Hundreds of millions of drivers make instantaneous risk decisions in specific contexts based on instinct, experience, and established rules. However, in the era of autonomous driving, a significant portion of these decisions are predetermined during the research and development phase and implemented through algorithmic code. The decision-makers have also shifted—from individual drivers to centralized teams comprising engineers, algorithm designers, and related enterprises. This shift in decision-making authority transforms previously ambiguous decisions that fell within personal ethical considerations into public policy issues requiring clear definition and open debate, as well as engineering specification requirements. Consequently, responsibility has been unprecedentedly centralized and become more explicitly defined.

1.2.2 The Manifestation of Ethical Dilemmas and Compulsory Codification:

The renowned "Trolley Problem" was primarily a tool for philosophical deliberation during the era of human-driven vehicles. However, in the age of autonomous driving, it has become an unavoidable engineering challenge [5]. When accidents are inevitable, how should algorithms make decisions? Should they prioritize protecting passengers inside the vehicle or pedestrians outside? Should they choose to collide with a young person or an elderly individual? Society is compelled to address the task of transforming vague, highly context-dependent moral intuitions [6]. The goal of this transformation is to formulate clear, executable computer instructions. This process of "ethical codification" poses significant challenges to the flexibility of human morality while also demanding a high level of understanding of its complexity.

1.2.3 Paradigm Shift in Safety Expectations and the "Zero-Risk" Paradox:

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While the industry widely regards "statistically outperforming human drivers" as the safety benchmark for autonomous vehicle commercialization, public expectations, media perceptions, and regulatory standards are increasingly shifting toward "zero accidents" or "absolute safety." Society demonstrates markedly different tolerance levels for two types of incidents: those caused by "machine errors" versus those resulting from "human errors," with former cases receiving significantly lower societal acceptance than the latter. This ethical dilemma manifests in a critical aspect: even if autonomous technology reduces global traffic fatalities from 1.35 million to 135,000 annually—a 90% decrease—public attention may focus exclusively on these 135,000 deaths attributed to "cold-blooded algorithms," while overlooking the 1.215 million lives saved. Such cognitive bias profoundly complicates efforts to communicate and define acceptable risk levels.

2. The Value Vision and Complexity Risk Profile of Autonomous Driving Technology

2.1 Multi-dimensional Positive Value Commitment

The value of autonomous driving technology extends beyond merely replacing humans in driving operations; it points toward a future characterized by systematic optimization of the transportation system, which can be analyzed from four dimensions:

2.1.1 Core Values: The Road Safety Revolution: This value proposition is both the most fundamental and the most compelling aspect of autonomous driving technology. Globally, over 90% of traffic accidents stem from human errors, including driver distraction, fatigue while driving, drunk driving, and speeding. By eliminating these accident-prone factors, autonomous driving technology holds the potential to significantly reduce the incidence of traffic accidents at their root cause, mitigate their severity, and ultimately achieve a generational leap in road safety standards.

2.1.2 Derivative Value: From the perspectives of system efficiency and economic momentum, autonomous vehicles can form highly efficient driving formations by leveraging Vehicle-to-Everything (V2X) communication technology and collaborative control methods. Such formation driving helps reduce traffic wave phenomena, significantly alleviating congestion and saving substantial time costs for society. Economically, autonomous driving technology will give rise to a new business model called Mobile as a Service (MaaS). This model will redefine the concept of vehicle ownership and strongly drive advancements across multiple fields—including artificial intelligence, high-precision sensors, high-resolution maps, and cloud computing—collectively forming an advanced industrial ecosystem.

2.1.3 Social Value: Inclusive empowerment and equitable accessibility: Autonomous driving technology can provide mobility support for specific groups—including individuals with visual impairments, physical disabilities, and the elderly or frail—namely those traditionally classified as "non-drivers" in transportation systems. Autonomous vehicles enable them to travel independently, conveniently, and with dignity. Such mobility support not only exemplifies a human-centered approach within technological development but also significantly advances social equity and enhances societal inclusivity.

2.1.4 Environmental and Spatial Value: Green, low-carbon development and urban renewal: Autonomous driving technology shares inherent compatibility with electric vehicle technology. Moreover, autonomous driving can significantly reduce energy consumption and vehicle exhaust emissions by optimizing acceleration, deceleration processes, and route planning. Additionally, shared autonomous vehicle fleets have the potential to greatly enhance vehicle utilization efficiency. Increased vehicle utilization will decrease overall societal demand for parking spaces, thereby freeing up substantial valuable urban land resources. These freed-up resources can be utilized for developing green spaces, public areas, or commercial facilities, ultimately promoting a shift toward more people-oriented urban planning.

2.2 The Comprehensive Risk Landscape of Complexity

In line with the profound value promised by autonomous driving technology, it also entails a range of risks. These risks form a complex and multi-layered risk landscape that can be analyzed across three dimensions: the technological ontology layer, the algorithmic ethics layer, and the societal and institutional layer.

2.2.1 Risks at the Technical Ontology Layer:

The first risk lies in the inherent limitations of sensing systems. Key sensors such as LiDAR, cameras, and millimeter-wave radars are essential for autonomous vehicles. These sensors may experience performance degradation or even failure under extreme weather conditions—including dense fog, heavy rainfall, and reflective snow on roads. Additionally, they can encounter similar issues in rare scenarios, such as when foreign objects suddenly appear on the road. Misidentification between static and moving objects by sensors is a major cause of accidents involving autonomous vehicles. The second risk stems from the "long-tail problem" in decision-making algorithms. While autonomous driving systems can handle 99% of typical road conditions, the remaining 1% consists of numerous complex edge cases. Exhaustively testing all these low-probability scenarios through physical road trials would require an astronomical number of test kilometers—a practically

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impossible task from an engineering perspective. Moreover, algorithms may make decisions that violate human common sense or safety principles in such rare situations. Finally, there is the systemic threat of cybersecurity vulnerabilities. Autonomous vehicles are highly interconnected and rely on software updates to maintain functionality, making them prime targets for hackers. If a vehicle's control system is remotely compromised, a single malfunction could escalate into regional traffic paralysis or even severe public safety incidents.

2.2.2 Risks at the Algorithmic Ethics Level: On one hand, there exists the inevitable ethical dilemma in accident prevention decisions. This dilemma essentially represents a real-world manifestation of the "trolley problem" [7]. Currently, no consensus exists regarding the ethical framework that algorithmic decision-making should follow when accidents are unavoidable—for instance, whether to adhere to utilitarian principles prioritizing overall welfare or to uphold deontological principles enshrining absolute rules like the principle of "no active harm." Additionally, there is no societal agreement on whether users should be permitted to customize algorithmic ethical parameters. On the other hand, there are risks of algorithmic bias and discrimination driven by data-driven approaches. Algorithm training relies on extensive datasets; if these datasets contain inherent social biases—such as insufficient collection of driving behavior data for specific communities or populations, or labeling biases—they may introduce systemic issues during algorithm operation. For example, algorithms might unconsciously replicate or amplify such biases during path planning, risk prediction, or even collision selection processes, ultimately leading to new, systemic forms of social injustice.

2.2.3 Social and Institutional-Level Risks: The first risk is the legal vacuum regarding liability attribution. In applications of Level 3 (conditionally autonomous) and higher-level autonomous driving technologies, the chain of responsibility becomes exceptionally complex in the event of an accident. It is crucial to identify the liable parties—whether it's vehicle users who failed to fulfill monitoring responsibilities, automakers with design flaws, software companies providing fault detection algorithms, or map service providers supplying erroneous data. However, the existing legal framework, which centers on human drivers, faces significant challenges when determining liability in autonomous driving incidents. The second risk involves disputes over data privacy and ownership. Autonomous vehicles function as mobile sensing terminals that continuously collect vast amounts of data during operation, including information about the surrounding environment and personal data of passengers. Multiple issues arise from this data: who holds ownership rights, how usage rights should be defined, how user consent rights can be protected, and how data misuse or leaks can be prevented—all constituting major privacy risks. The third risk pertains to structural impacts on the macroeconomy and employment. As autonomous driving technology scales commercially, it is expected to directly affect the employment of specific groups—particularly millions of professional drivers such as taxi, truck, and bus operators. These impacts may trigger structural fluctuations in the labor market and pose challenges for workforce redistribution. Addressing these issues requires proactive development of corresponding social policies [8].

3. Core Challenges: The Diverse Definition Dilemma of "Acceptable Risks" in Autonomous Driving

The root cause of the difficulty in effectively controlling and managing these risks lies in their "acceptable" boundaries, which exist within a complex, dynamic, and highly contentious definitional dilemma that can be broken down into three core challenges [9]:

3.1 The contradiction between the "long tail" of technical reliability and verifying its economic viability Autonomous driving systems have demonstrated extremely high reliability in the vast majority of conventional scenarios. However, those difficult-to-exhaust "edge cases" collectively constitute what is commonly referred to as the "long-tail problem" within the industry. Conducting physical road tests to verify a system's capability in handling all extreme scenarios would entail time and economic costs that no single company can afford. The impracticality of this verification approach makes it virtually impossible to define "acceptable risks" solely based on statistical significance. We must therefore rely on virtual simulations, theoretical modeling, and limited experimental testing—approaches that themselves introduce new uncertainties.

3.2 The Conflict Between Ethical Algorithmization's "Intuitive Discomfort" and Public Acceptance Even when philosophers, ethicists, and engineers jointly develop a theoretically "ideal" ethical decision-making algorithm that adheres to the utilitarian principle of "minimizing overall harm," public resistance and moral intuition may still arise upon its practical implementation. Emotionally speaking, society finds it difficult to accept machines pre-programmed to "voluntarily target specific groups under certain circumstances" on roads. Such profound concerns about algorithms determining life and death have posed significant obstacles to the social acceptance of all ethical programming initiatives [10].

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3.3 The Cumulative Effect of "Structural Inequity" in Risk-Reward Distribution and the Social Trust Deficit

The risks and benefits associated with autonomous driving technology likely exhibit uneven distribution across different social groups. Tech companies, investors, and high-income individuals may be the first to benefit from the convenience and efficiency offered by this technology. In contrast, professional drivers and low-income communities—often located in areas designated as early testing zones or facing heavier traffic volumes—may bear risks and costs disproportionate to their circumstances. This inherent structural inequality, combined with the persistent public "trust deficit" toward major tech firms stemming from concerns about corporate data monopolies, algorithmic black boxes, and past misconduct, results in a situation where risks deemed "acceptable" by technical experts are often perceived as "unacceptable" socially and politically. Risk assessment has thus evolved beyond mere technical considerations into a political economy issue involving power dynamics, resource allocation, and discourse control.

4. Collaborative Path: Establishing a Risk-Controlled Value Realization Framework

To address the risks and challenges associated with autonomous driving technology while realizing its positive value, it is essential to move beyond a singular linear technological approach and establish a multi-level, collaborative risk governance framework that integrates three core dimensions: concept, technology, and institutional mechanisms. Through mutual support and dynamic adaptation across these dimensions, this framework enables proactive definition, systematic management, and effective communication of acceptable risk boundaries. The specific components are as follows:

4.1 Conceptual Reorientation: Establishing an Engineering Culture of "Responsible Innovation"Redefining the core philosophy forms the fundamental basis of risk governance, requiring the integration of "social responsibility" and "risk prevention at the outset" throughout the entire development process of autonomous vehicle technology to ensure that technological progress aligns with social ethics and public needs.

4.1.1 Practicing "Ethics of Responsibility": Engineers and corporate decision-makers must fundamentally embrace the principle of "ethics of responsibility" advocated by Hans Jonas. This principle requires accountability for the long-term and collective consequences of technological actions, particularly toward distant and vulnerable entities such as future generations and the natural environment. To implement this principle, it is essential to cultivate a forward-looking, risk-aware mindset that anticipates potential risks during the early stages of technology development, rather than responding passively only after risks have materialized.

4.1.2 Incorporating "Value-Sensitive Design": The value-sensitive design methodology—a framework that integrates social values into technological design—must be systematically incorporated throughout the entire development process of autonomous vehicle technology. This requires establishing an interdisciplinary team composed of professionals from multiple fields during the initial design phase, including ethicists, sociologists, and legal experts. The team's core task is to jointly identify key human values such as privacy protection, social equity, decision transparency, and accountability traceability, then translate these values into concrete technical design principles. This ensures that technological design aligns with societal value requirements from the outset, rather than requiring patchwork adjustments after the technology has been developed.

4.2 Technical Governance: Building a "Reliable and Trustworthy" Hardware and Software Foundation Technical governance serves as the foundational tool for risk management. It must address the inherent risk points of autonomous driving technology by enhancing capabilities in risk identification, mitigation, and control through technical optimization, thereby providing an objective technical basis for defining "acceptable risks."

4.2.1 Pursuing algorithmic explainability and transparency: Increasing research investment in explainable AI technologies aims primarily to unlock the "black box" of autonomous driving algorithms, enabling human engineers, regulatory authorities, and even judicial systems to understand, audit, and trace their critical decision-making processes—particularly those that may lead to accidents. Only by achieving algorithmic explainability and transparency can public trust in these technologies be established, which serves as a fundamental prerequisite for their practical implementation.

4.2.2 Establishing a High-Fidelity Simulation and Extreme Testing System: Leveraging digital twin technology, we establish a massive-scale, highly realistic virtual testing environment. This environment simulates driving scenarios spanning millions to billions of kilometers, encompassing complex road conditions, extreme weather, and rare edge cases. It systematically and cost-effectively identifies algorithmic flaws, enables timely fixes,

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addresses the limitations in scenario coverage inherent to real-world road testing, and enhances overall technical reliability.

4.2.3 Implement a gradual and conditional market access mechanism: Regulatory authorities must establish clear, tiered technical maturity standards and safety benchmarks. To enter the market, companies must first demonstrate that their autonomous driving systems achieve the required level of reliability and safety within specific closed areas or defined operational design domains. Only upon meeting this requirement can they obtain authorization to deploy in more complex application scenarios, thereby mitigating risks associated with large-scale technology deployment through a "small-step, rapid-iteration" approach.

4.3 Institutional Framework Development: Building a "dynamically adaptive" governance ecosystem Institutional development serves as the regulatory foundation for risk governance, requiring a flexible and comprehensive institutional framework to balance technological innovation with risk management, thereby resolving conflicts between societal and institutional risks.

4.3.1 Promoting the standardization and legal enforcement of ethical guidelines: We should actively promote the adoption of ethical guidelines for autonomous driving issued by international standardization organizations and industry alliances, and translate them into legally binding technical regulations and national standards. Such translation will provide autonomous vehicle manufacturers with clear, unified design requirements and safety compliance standards, preventing technological confusion caused by ambiguous ethical criteria.

4.3.2 Exploring "Adaptive Governance" and "Regulatory Sandbox": The management approach of government departments needs to enhance institutional flexibility and learning capacity. By establishing a "regulatory sandbox" —which selects specific regions and sets defined conditions while strictly ensuring safety standards—enterprises are permitted to conduct innovative trials of autonomous driving technologies and service models within these boundaries. Regulatory rules are dynamically adjusted based on feedback from the trial process, achieving the principle of "learning through regulation and regulating through learning," thereby encouraging innovation while mitigating risks [11].

5. Conclusion

Autonomous driving technology serves as a precise prism, reflecting the core ethical dilemmas inherent in all cutting-edge disruptive engineering endeavors when pursuing human well-being: How should we exercise prudence in wielding this "double-edged sword" of technological innovation? While actively embracing its significant positive benefits, how can we clearly and responsibly identify, assess, and control the accompanying complexities and uncertainties? This article argues that the key to resolving this dilemma lies in a profound understanding and dynamic management of the engineering's "acceptable risk" boundary.

The development of autonomous driving is not merely a linear process involving technological advancements and cost reductions, but rather an unprecedented real-world experiment in the integration of technology and society. Its ultimate success depends not only on further improvements in LiDAR detection accuracy and breakthroughs in chip computing power, but more fundamentally on our ability to establish and operate a comprehensive, robust, and resilient "social operating system" tailored for it. This system must be grounded in "responsibility ethics" as its core value, guided by "value-sensitive design," supported by "algorithmic transparency" and "extreme testing," and secured by "adaptive governance" and "deep public participation."

The reality demonstrates that the significance of engineers as a professional group has been endowed with a completely new and more profound dimension in terms of social identity and responsibility. They are no longer merely practitioners of physical laws or implementers of technical solutions; rather, they have evolved into architects of social solutions and guardians of ethics who operate within a cross-disciplinary knowledge framework, working with unprecedented precision and thoroughness. Their core mission is to identify and uphold the prudent path toward a safer, more efficient, fairer, and more inclusive future—one that balances instrumental rationality against value rationality, innovative drive against ethical prudence, and commercial interests against public welfare.

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