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Ethical Architectures and Decision Logics in Sustainable Autonomous Transportation: Normative Foundations, Technical Pathways, and Societal Implications

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ABSTRACT: The rapid development and deployment of autonomous vehicles has transformed road transportation from a predominantly human-centered activity into a complex socio-technical system governed by algorithms, sensors, and learning architectures. This transformation has intensified long-standing ethical questions surrounding road safety, responsibility, harm distribution, and social welfare, while simultaneously introducing novel dilemmas related to machine decision-making, sustainability, and moral accountability. Within this context, ethical decision-making frameworks for autonomous transportation have emerged as a central scholarly and policy concern, particularly in relation to the contrast between rule-based systems grounded in explicit normative prescriptions and learning-based systems driven by data-intensive adaptive models. This article offers an extensive, theory-driven, and critically engaged analysis of ethical decision-making in sustainable autonomous transportation, with particular attention to the comparative strengths, limitations, and societal implications of rule-based and learning-based approaches. Drawing on interdisciplinary literature spanning moral philosophy, criminal law theory, artificial intelligence ethics, traffic safety research, and engineering studies, the article situates autonomous vehicle ethics within broader debates on utilitarianism, deontological constraints, responsibility attribution, and the ethics of risk. The analysis is anchored by recent comparative scholarship examining ethical decision-making in sustainable autonomous transportation, which highlights the tensions between transparency, predictability, adaptability, and moral pluralism in algorithmic systems (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025). Through a qualitative methodological framework that synthesizes normative analysis with interpretive evaluation of empirical and experimental findings, the study elucidates how ethical principles are operationalized, contested, and transformed within autonomous driving architectures. The results emphasize that ethical decision-making in autonomous transportation cannot be reduced to technical optimization problems, but must instead be understood as an evolving moral practice shaped by legal norms, cultural expectations, sustainability goals, and public trust. The discussion advances a critical argument for hybrid ethical architectures that integrate rule-based constraints with learning-based adaptability, while acknowledging persistent limitations related to moral disagreement, data bias, and institutional governance. By offering a comprehensive and deeply elaborated account of ethical decision-making in autonomous transportation, this article contributes to ongoing scholarly efforts to align technological innovation with societal values, environmental sustainability, and the ethical demands of contemporary mobility systems.

Keywords: Autonomous vehicles; ethical decision-making; sustainability; rule-based systems; learning-based systems; transportation ethics; artificial intelligence governance

INTRODUCTION

The The ethical dimensions of road transportation have historically been framed around human behavior, regulatory compliance, and infrastructural design, with moral responsibility largely attributed to individual drivers, manufacturers, and policymakers. Road traffic injuries and fatalities have long constituted a significant global public health challenge, prompting ethical debates about acceptable risk, prevention strategies, and distributive justice in transportation systems (Centers for Disease Control and Prevention, 2019; Fahlquist, 2009). With the emergence of autonomous vehicles, however, the locus of decision-making has increasingly shifted from human agents to algorithmic systems, thereby reconfiguring the ethical landscape of mobility in profound and often unsettling ways (Etzioni and Etzioni, 2017; Evans, 2008). Autonomous transportation systems are no longer merely tools that extend human agency; they are increasingly autonomous

moral actors in the sense that they make decisions with morally salient consequences, including decisions that may involve harm, life preservation, and trade-offs between competing values.

This transformation has occurred alongside growing societal commitments to sustainability, environmental responsibility, and the reduction of traffic-related harm. Sustainable autonomous transportation is frequently promoted as a pathway to safer roads, reduced emissions, and more efficient mobility, yet these promised benefits are inseparable from ethical questions about how autonomous systems prioritize safety, efficiency, and fairness (European Commission, 2018a; European Commission, 2018b). The ethical design of autonomous vehicles thus occupies a critical intersection between environmental ethics, technology ethics, and social justice, demanding rigorous theoretical and empirical scrutiny.

A central axis of contemporary debate concerns the ethical architectures underpinning autonomous vehicle decision-making, particularly the distinction between rule-based systems and learning-based systems. Rule-based systems rely on explicitly encoded norms, constraints, and decision rules, often inspired by legal standards or moral principles such as the minimization of harm or adherence to traffic laws. Learning-based systems, by contrast, employ machine learning techniques that infer decision policies from large datasets, simulations, or reinforcement learning environments, enabling adaptive behavior but often at the cost of transparency and predictability (Awad et al., 2018; Fraichard and Kuffner, 2012). This distinction has significant ethical implications, as it shapes how moral values are represented, interpreted, and enacted within autonomous vehicles.

Recent scholarship has emphasized that ethical decision-making in autonomous transportation cannot be adequately addressed by technical optimization alone, but requires engagement with normative theory, legal reasoning, and societal values. Comparative analyses of rule-based and learning-based systems have highlighted trade-offs between explainability and adaptability, as well as tensions between universal ethical rules and context-sensitive moral judgments (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025). These tensions are further complicated by empirical findings suggesting that human moral intuitions in traffic dilemmas are themselves diverse, context-dependent, and often inconsistent, raising questions about which moral standards autonomous vehicles should emulate or enforce (Faulhaber et al., 2019; Awad et al., 2018).

The introduction of autonomous vehicles also reopens longstanding philosophical debates about moral responsibility and agency. If an autonomous vehicle causes harm, responsibility may be distributed across designers, programmers, manufacturers, regulators, and users, challenging traditional frameworks of criminal and civil liability (Coca-Vila, 2018; Widen, n.d.). From an ethical perspective, this diffusion of responsibility risks creating moral gaps in which harmful outcomes are insufficiently accounted for or remedied, undermining public trust and ethical legitimacy (De George, 1999; Etter et al., 2019).

Despite a rapidly expanding literature, significant gaps remain in our understanding of how ethical decision-making frameworks can be coherently integrated into sustainable autonomous transportation systems. Much existing research focuses on isolated dilemmas, such as trolley-style scenarios, without adequately situating these cases within broader ethical, legal, and environmental contexts (Foot, 1967; Lawlor, 2021). Other studies prioritize technical safety metrics or probabilistic risk assessment while neglecting the normative assumptions embedded within these approaches (Fraichard and Asama, 2004; Benenson et al., 2008). Moreover, comparative analyses of rule-based and learning-based systems often remain at a high level of abstraction, failing to engage deeply with the philosophical foundations and societal implications of these architectures.

This article seeks to address these gaps by offering a comprehensive, theory-driven examination of ethical decision-making in sustainable autonomous transportation. By synthesizing insights from moral philosophy,

AI ethics, traffic safety research, and legal theory, the study develops a nuanced understanding of how ethical principles are operationalized within autonomous vehicle systems and how different decision-making architectures shape moral outcomes. The analysis is anchored by recent comparative scholarship on rule-based and learning-based systems, which serves as a focal point for broader theoretical elaboration and critical discussion (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025).

The central argument advanced in this article is that neither rule-based nor learning-based systems, in isolation, can adequately address the ethical demands of sustainable autonomous transportation. Rule-based systems offer transparency, predictability, and alignment with legal norms, but struggle with moral pluralism and contextual complexity. Learning-based systems provide adaptability and empirical grounding, yet risk opacity, bias, and misalignment with societal values. A sustainable and ethically robust approach to autonomous transportation therefore requires hybrid architectures, institutional oversight, and ongoing ethical deliberation informed by public engagement and interdisciplinary scholarship (Etzioni and Etzioni, 2017; European Commission, 2018a).

In developing this argument, the article proceeds through a detailed methodological exposition, an interpretive analysis of findings grounded in existing literature, and an extensive discussion that situates these findings within broader ethical and societal debates. Throughout, emphasis is placed on the inseparability of ethical decision-making from sustainability goals, legal accountability, and social trust. By engaging deeply with both normative theory and empirical research, this study aims to contribute to the development of autonomous transportation systems that are not only technically sophisticated, but also ethically legitimate and socially responsible (Fahlquist, 2009; Evans, 2008).

METHODOLOGY

The methodological framework adopted in this study is qualitative, interpretive, and interdisciplinary, reflecting the inherently normative and socio-technical nature of ethical decision-making in autonomous transportation. Rather than relying on experimental testing or quantitative modeling, the methodology is designed to synthesize, analyze, and critically evaluate existing theoretical, empirical, and legal scholarship in order to generate a coherent and comprehensive account of ethical architectures in autonomous vehicles (De George, 1999; Etzioni and Etzioni, 2017). This approach is particularly well-suited to examining ethical questions that cannot be resolved through empirical measurement alone, but require normative reasoning, conceptual clarification, and contextual interpretation.

At the core of the methodological design is a comparative analytical strategy that examines rule-based and learning-based decision-making systems as ideal-typical ethical architectures. These categories are not treated as mutually exclusive or exhaustive, but as heuristic constructs that facilitate systematic comparison of underlying assumptions, strengths, and limitations (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025). By analyzing how ethical principles are encoded, interpreted, and enacted within each architecture, the study aims to illuminate broader ethical tensions and design trade-offs.

The first methodological component involves an extensive literature synthesis across multiple disciplinary domains. Sources include moral philosophy texts addressing utilitarianism, deontological ethics, and the doctrine of double effect (Foot, 1967; Lawlor, 2021), legal scholarship on criminal responsibility and justification in autonomous vehicle contexts (Coca-Vila, 2018; Widen, n.d.), empirical studies on human moral decision-making in traffic dilemmas (Faulhaber et al., 2019; Awad et al., 2018), and engineering research on safety, collision avoidance, and motion planning (Fraichard and Asama, 2004; Benenson et al.,

2008). This integrative review is conducted not as a summary exercise, but as a critical dialogue in which competing perspectives are juxtaposed and interrogated.

A second methodological element consists of interpretive analysis of policy and regulatory documents related to autonomous transportation and traffic safety. Reports from governmental and supranational bodies provide insight into how ethical considerations are translated into governance frameworks and design guidelines (European Commission, 2018a; European Commission, 2018b). These documents are analyzed to identify implicit ethical assumptions, normative priorities, and areas of ambiguity or contestation, thereby situating technical decision-making within broader institutional contexts.

The third component involves conceptual analysis of ethical dilemmas commonly discussed in the autonomous vehicle literature, including unavoidable collision scenarios and risk distribution problems. Drawing on philosophical tools such as thought experiments and counterfactual reasoning, the study examines how different ethical architectures respond to these dilemmas and what this reveals about their moral commitments (Evans, 2008; Fahlquist, 2009). This analysis is informed by empirical findings on human moral intuitions, but does not assume that popular intuitions should be directly encoded into machine behavior (Awad et al., 2018).

Throughout the methodological process, reflexivity is maintained regarding the limitations and normative assumptions of the study itself. The reliance on existing literature means that the analysis is shaped by the availability, scope, and biases of published research, particularly the predominance of Western philosophical frameworks and high-income country contexts (Centers for Disease Control and Prevention, 2019; D'Elia and Newstead, 2015). Moreover, the qualitative and interpretive nature of the methodology precludes definitive claims about empirical effectiveness or public acceptance, instead emphasizing theoretical coherence and ethical plausibility.

Despite these limitations, the methodological approach offers significant strengths. By integrating diverse strands of scholarship, it enables a holistic understanding of ethical decision-making in autonomous transportation that transcends disciplinary silos. The comparative focus on rule-based and learning-based systems provides a structured lens through which complex ethical issues can be systematically explored, while the emphasis on sustainability ensures that ethical analysis remains attentive to long-term societal and environmental impacts (Fahlquist, 2009; European Commission, 2018a).

In adopting this methodology, the study aligns with broader trends in technology ethics that emphasize the need for interdisciplinary, reflective, and normatively engaged research. Ethical decision-making in autonomous transportation is not a problem that can be solved through technical ingenuity alone; it requires ongoing dialogue between engineers, philosophers, policymakers, and the public. The methodological framework employed here is intended to contribute to that dialogue by offering a rigorously argued, deeply contextualized, and ethically informed analysis (Etter et al., 2019; Etzioni and Etzioni, 2017).

RESULTS

The interpretive analysis conducted in this study yields a set of interrelated findings that illuminate the ethical dynamics of rule-based and learning-based decision-making systems in sustainable autonomous transportation. These findings do not take the form of statistical results or experimental measurements, but rather emerge from a systematic synthesis of theoretical arguments, empirical observations, and policy analyses present in the existing literature (Evans, 2008; Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025). As such, the results are best understood as analytical insights into how ethical principles are operationalized and contested

within autonomous vehicle architectures.

One central finding concerns the ethical clarity and normative determinacy associated with rule-based systems. Rule-based architectures typically encode explicit constraints and priorities, such as compliance with traffic laws, minimization of harm, or protection of vulnerable road users. This explicitness facilitates transparency and explainability, enabling designers, regulators, and users to understand and scrutinize the ethical logic guiding vehicle behavior (Lawlor, 2021; Coca-Vila, 2018). From an ethical perspective, this clarity aligns with deontological traditions that emphasize rule-following, rights protection, and moral accountability. However, the analysis also reveals that this determinacy can become a liability in complex or novel scenarios where rigid rules fail to capture morally relevant contextual factors (Foot, 1967; Fahlquist, 2009).

A second finding highlights the adaptive strengths and ethical ambiguities of learning-based systems. Learning-based architectures, particularly those employing reinforcement learning or deep neural networks, are capable of adjusting behavior based on accumulated experience and probabilistic prediction. This adaptability enables nuanced responses to dynamic traffic environments and may enhance overall safety outcomes under conditions of uncertainty (Fraichard and Kuffner, 2012; Benenson et al., 2008). Ethically, such adaptability resonates with consequentialist approaches that prioritize outcomes and aggregate welfare. Yet the analysis underscores that learning-based systems often lack transparent moral reasoning, making it difficult to ascertain why particular decisions are made or to ensure alignment with societal values (Awad et al., 2018; Etzioni and Etzioni, 2017).

The comparative analysis further reveals a persistent tension between individual-level ethics and system-level sustainability goals. Rule-based systems tend to focus on immediate, localized decisions, such as obeying traffic signals or avoiding collisions, whereas learning-based systems are often optimized for long-term performance metrics, including efficiency, safety rates, and environmental impact (European Commission, 2018a; Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025). This divergence raises ethical questions about whether autonomous vehicles should prioritize individual rights and protections over aggregate benefits, or whether sustainability objectives justify trade-offs that may disadvantage particular individuals or groups (Fahlquist, 2009; Evans, 2008).

Another significant finding relates to the role of human moral intuitions in shaping ethical design. Empirical studies indicate that human responses to traffic dilemmas often reflect utilitarian tendencies, such as favoring the greatest number of lives saved, but also exhibit context sensitivity and moral inconsistency (Faulhaber et al., 2019; Awad et al., 2018). The analysis suggests that neither rule-based nor learning-based systems can straightforwardly replicate human moral judgment without encountering ethical and practical difficulties. Encoding popular intuitions into rule-based systems risks entrenching moral biases, while training learning-based systems on human behavior data may perpetuate ethically problematic patterns (Etter et al., 2019; De George, 1999).

The results also highlight the ethical significance of responsibility attribution in autonomous transportation. Rule-based systems, by virtue of their explicit design logic, may facilitate clearer lines of responsibility between designers, manufacturers, and operators, supporting legal and moral accountability (Coca-Vila, 2018; Widen, n.d.). Learning-based systems, in contrast, complicate responsibility attribution due to their emergent and probabilistic behavior, raising concerns about moral hazard and accountability gaps (Widen, n.d.; Etzioni and Etzioni, 2017). This finding underscores the importance of governance frameworks that address not only technical performance, but also ethical responsibility and public trust.

Finally, the analysis reveals that sustainability functions as both a normative goal and an ethical constraint

within autonomous transportation. While autonomous vehicles are often promoted as environmentally beneficial and socially efficient, these benefits depend on ethical design choices that shape traffic patterns, energy consumption, and accessibility (European Commission, 2018b; D'Elia and Newstead, 2015). The results suggest that ethical decision-making architectures must be evaluated not only in terms of immediate safety outcomes, but also in relation to their long-term contributions to sustainable mobility and social equity (Fahlquist, 2009; Centers for Disease Control and Prevention, 2019).

Collectively, these findings indicate that ethical decision-making in sustainable autonomous transportation is characterized by deep normative trade-offs that cannot be resolved through singular design paradigms. Rule-based and learning-based systems each embody distinct ethical commitments and vulnerabilities, and their comparative evaluation reveals the need for integrative approaches that acknowledge moral complexity and societal pluralism (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025; Etzioni and Etzioni, 2017).

DISCUSSION

The findings of this study invite an extensive and critical discussion of the ethical, philosophical, and societal implications of decision-making architectures in sustainable autonomous transportation. At the heart of this discussion lies the recognition that autonomous vehicles are not merely technical artifacts, but moral and political actors embedded within complex social systems (Evans, 2008; Fahlquist, 2009). The ethical evaluation of rule-based and learning-based systems therefore demands engagement with foundational questions about moral theory, responsibility, governance, and the role of technology in shaping collective futures.

One of the most salient theoretical implications concerns the enduring tension between deontological and consequentialist ethics in autonomous vehicle design. Rule-based systems are often implicitly grounded in deontological commitments, emphasizing adherence to rules, protection of rights, and avoidance of intentional harm (Foot, 1967; Lawlor, 2021). This alignment offers moral reassurance by mirroring legal norms and everyday moral expectations, yet it also exposes limitations when rigid rules produce outcomes that appear ethically counterintuitive or socially suboptimal (Coca-Vila, 2018; Evans, 2008). Learning-based systems, by contrast, resonate with consequentialist reasoning, seeking to optimize outcomes across time and populations, but risk violating deeply held moral intuitions about fairness, dignity, and individual worth (Awad et al., 2018; Faulhaber et al., 2019).

The discussion thus reveals that ethical decision-making in autonomous transportation cannot be resolved by selecting a single moral theory as definitive. Moral pluralism, as a descriptive feature of contemporary societies, implies that autonomous vehicles will inevitably operate within environments characterized by competing values and contested norms (Etzioni and Etzioni, 2017; Etter et al., 2019). From this perspective, the comparative analysis underscores the ethical inadequacy of monolithic decision architectures and supports arguments for hybrid systems that integrate rule-based constraints with learning-based adaptability (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025).

A further dimension of the discussion concerns transparency and explainability as ethical requirements. Rule-based systems are often praised for their interpretability, which supports accountability and public trust (Lawlor, 2021; De George, 1999). Learning-based systems, while technically powerful, frequently operate as opaque "black boxes," raising concerns about inscrutable decision-making and democratic oversight (Etzioni and Etzioni, 2017; Awad et al., 2018). The ethical significance of transparency extends beyond technical comprehension to encompass the ability of affected parties to contest, critique, and influence the norms

governing autonomous systems (European Commission, 2018a).

The issue of responsibility attribution emerges as another central theme. As autonomous vehicles assume greater decision-making autonomy, traditional models of responsibility rooted in individual agency become increasingly strained (Coca-Vila, 2018; Widen, n.d.). The diffusion of responsibility across designers, manufacturers, data providers, and regulators risks creating moral and legal vacuums in which harmful outcomes are insufficiently addressed (Etter et al., 2019; De George, 1999). The discussion suggests that ethical decision-making architectures must be accompanied by institutional arrangements that clearly allocate responsibility and provide mechanisms for redress, learning, and ethical revision.

Sustainability adds an additional layer of ethical complexity. While autonomous vehicles are often framed as tools for reducing emissions and improving traffic efficiency, these outcomes are contingent on broader systemic factors, including urban planning, energy infrastructure, and patterns of use (European Commission, 2018b; D'Elia and Newstead, 2015). Ethical decision-making systems that prioritize short-term efficiency may inadvertently exacerbate long-term environmental or social harms, such as increased vehicle miles traveled or unequal access to mobility (Fahlquist, 2009; Centers for Disease Control and Prevention, 2019). The discussion thus emphasizes the need to embed sustainability considerations directly into ethical architectures, rather than treating them as external constraints.

Another critical issue concerns the use of empirical data and human behavior as ethical benchmarks. Learning-based systems often rely on large datasets derived from human driving behavior or simulated moral judgments (Awad et al., 2018; Faulhaber et al., 2019). While such data can enhance realism and adaptability, it also risks encoding existing biases, inequities, and ethically problematic practices into autonomous systems (Etter et al., 2019; De George, 1999). The discussion therefore cautions against uncritical reliance on empirical moral intuitions and advocates for normative oversight that evaluates data-driven decisions against articulated ethical principles (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025).

The limitations identified in this study further inform the discussion. The reliance on existing literature means that ethical analysis may lag behind rapid technological developments, and that emerging forms of autonomous mobility, such as shared or networked systems, may introduce new ethical challenges not fully captured here (European Commission, 2018a; Fraichard and Asama, 2004). Additionally, the predominance of Western ethical frameworks highlights the need for more inclusive, cross-cultural research that reflects global diversity in moral values and mobility contexts (Centers for Disease Control and Prevention, 2019; Fahlquist, 2009).

Future research directions emerge naturally from this discussion. Scholars are encouraged to explore participatory approaches to ethical design that involve diverse stakeholders in shaping decision-making norms (Etzioni and Etzioni, 2017; Etter et al., 2019). Comparative empirical studies examining public responses to different ethical architectures could further inform design choices and governance frameworks (Awad et al., 2018; Faulhaber et al., 2019). Moreover, interdisciplinary collaboration between ethicists, engineers, and policymakers remains essential for translating ethical insights into practical design and regulation (European Commission, 2018b; De George, 1999).

In sum, the discussion reinforces the central argument that ethical decision-making in sustainable autonomous transportation is an ongoing, contested, and inherently social process. Rule-based and learning-based systems each contribute valuable capabilities, but neither offers a complete ethical solution in isolation. The challenge moving forward lies in cultivating ethical architectures and institutional frameworks that are responsive to moral pluralism, accountable to the public, and aligned with long-term sustainability goals (Ethical Decision-

Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025; Fahlquist, 2009).

CONCLUSION

Ethical decision-making in sustainable autonomous transportation represents one of the most consequential moral challenges of contemporary technological development. As autonomous vehicles transition from experimental prototypes to integral components of everyday mobility, the ethical architectures guiding their behavior will shape not only safety outcomes, but also societal trust, environmental sustainability, and conceptions of responsibility (Evans, 2008; European Commission, 2018a). This article has offered a comprehensive and deeply elaborated analysis of ethical decision-making frameworks, focusing on the comparative evaluation of rule-based and learning-based systems within a broader socio-ethical context.

The analysis has demonstrated that rule-based systems provide normative clarity, transparency, and alignment with legal and deontological principles, yet struggle with contextual flexibility and moral pluralism (Lawlor, 2021; Coca-Vila, 2018). Learning-based systems offer adaptability and outcome-oriented optimization, but raise concerns about opacity, bias, and accountability (Awad et al., 2018; Etzioni and Etzioni, 2017). Neither approach, taken alone, adequately satisfies the ethical demands of sustainable autonomous transportation.

By integrating insights from moral philosophy, legal theory, empirical research, and policy analysis, the study has argued for hybrid ethical architectures supported by robust governance frameworks and ongoing ethical deliberation (Ethical Decision-Making In Sustainable Autonomous Transportation: A Comparative Study Of Rule-Based And Learning-Based Systems, 2025; Fahlquist, 2009). Such approaches acknowledge moral complexity, respect societal values, and align technological innovation with sustainability goals.

Ultimately, the ethical evaluation of autonomous transportation is not a finite task, but a continuing responsibility that evolves alongside technological and social change. Addressing this responsibility requires sustained interdisciplinary engagement, public participation, and a commitment to embedding ethical reflection at the core of autonomous system design and deployment (De George, 1999; Etter et al., 2019).

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