Multidisciplinary Engineering Science Open

Received date: 11 Feb 2025
Revised date: 13 Mar 2025
Accepted date: 23 Mar 2025
Published date: 14 Apr 2025

Connected and Automated Vehicles in Mixed Traffic: Sensing, V2X, and Traffic Flow Stability

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Citation: Carvalho, L., Al-Tarawneh, T., & Kim, M. (2025). Connected and Automated Vehicles in Mixed Traffic: Sensing, V2X, and Traffic Flow Stability. *Multidisciplinary Engineering Science Open,* 2, 1-14.

Abstract

This review aims to synthesize and interpret existing research on how sensing, Vehicle-to-Everything (V2X) communication, and human–automation interaction jointly influence traffic flow stability in environments where connected and automated vehicles (CAVs) coexist with human-driven vehicles (HDVs). A qualitative review methodology was employed, focusing exclusively on peer-reviewed literature published between 2015 and 2025. Searches across Scopus, Web of Science, IEEE Xplore, and ScienceDirect identified studies addressing sensing integration, cooperative perception, V2X-enabled control, and stability modeling in mixed traffic. Following relevance screening and quality appraisal, 15 key articles were selected until theoretical saturation was achieved. Data were analyzed thematically using Nvivo 14 software through open, axial, and selective coding, resulting in the identification of five overarching themes: sensing and perception, V2X communication, traffic flow stability, human–vehicle interaction, and system-level integration. Results indicated that multi-sensor fusion and cooperative perception significantly improve situational awareness but remain sensitive to environmental uncertainty and cost constraints. V2X communication—particularly 5G-V2X and edge-based architectures—emerged as essential for synchronization and safety but is hindered by latency, security, and interoperability issues. Traffic flow modeling studies revealed that CAVs enhance string stability and throughput when their penetration rate exceeds a critical threshold, although unpredictable human behaviors can reintroduce oscillations. The analysis further highlighted that human trust calibration and communication transparency strongly affect cooperation and control transitions. Finally, institutional readiness, regulatory coherence, and public education were identified as indispensable for large-scale, stable CAV deployment. CAV integration in mixed traffic requires a multidimensional approach that combines perceptual resilience, secure low-latency communication, adaptive control algorithms, and human-centered policy frameworks. Traffic stability is achieved not through isolated technological advances but through systemic coordination across technical, behavioral, and governance domains.

Keywords: Connected and automated vehicles; mixed traffic; V2X communication; cooperative perception; traffic flow stability; human–vehicle interaction; intelligent transportation systems.

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1. Introduction

Connected and automated vehicles (CAVs) promise to reshape the future of mobility, offering the potential to improve safety, reduce emissions, and enhance traffic efficiency. Yet, a full transition to fleets composed purely of automated vehicles remains distant; for the foreseeable future, CAVs must coexist with human-driven vehicles (HDVs) in mixed traffic environments. The interactions between CAVs and HDVs, mediated through sensing, communication, and control, create a complex socio-technical ecosystem. Understanding how these interactions affect traffic flow stability is critical, since even small perturbations can amplify into stop-and-go waves, capacity drop, or cascading congestion (Yao, Hu, Jiang, & Xu, 2020).

In mixed traffic, the principal challenges lie in the limitations of individual sensing, the constraints of communication networks, and the nonlinear dynamics of human–automation interaction. From the perspective of perception, CAVs rely on an array of onboard sensors (lidar, radar, cameras, ultrasonic) to detect and track surrounding vehicles, pedestrians, and infrastructure. However, occlusion, sensor noise, adverse weather, and limited line-of-sight can impede robust object detection (Cui, Zhang, Xiao, Yao, & Fang, 2022). To overcome these boundaries, cooperative perception—sharing sensing data through Vehicle-to-Everything (V2X) links—has emerged as a key enabling paradigm, allowing vehicles and infrastructure to augment each other's situational awareness (Shan et al., 2020; V2X Cooperative Perception survey, 2025). Cooperative perception can extend the perception range beyond an individual vehicle's sensors, mitigate blind spots, and reduce uncertainty, but its effectiveness is tightly coupled to communication latency, packet loss, and alignment of heterogeneous sensor modalities (Zhang et al., 2019; Cui et al., 2022).

Communication is the backbone that allows CAVs to coordinate and respond collectively rather than individually. In the V2X domain, multiple protocols compete for dominance (e.g. DSRC, C-V2X, 5G-V2X), each with different trade-offs in latency, throughput, reliability, and backward compatibility (Yusuf, 2024). The challenge is magnified in dense urban or freeway traffic: as the number of communicating agents increases, so does congestion and interference, raising the risk of packet collision or communication delays (Sun & Shen, 2021). Moreover, security and privacy concerns loom large—malicious entities or data spoofing attacks (e.g., fabricated inputs to collaborative perception) can degrade system integrity or provoke unsafe decisions (Zhang & Qingzhao, 2023). Hence, designing robust, secure, low-latency V2X architectures that remain resilient under real-world constraints is a critical research frontier.

Even with perfect sensing and flawless communication, the interplay between CAV control and human behavior can destabilize traffic flow. An important concept here is string stability, which ensures that perturbations (e.g. sudden braking) do not amplify along a vehicle platoon (Talebpour & Mahmassani, 2016). When CAVs and HDVs are intermingled, standard string stability analyses become insufficient, because human drivers respond with variable reaction times, nonuniform sensitivities, and imperfect predictability (Ma, Qu, Ren, & Zhang, 2023). Indeed, simulation and analytical studies show that below certain penetration thresholds, uncontrolled interactions may even degrade flow stability (Dai, Zhou, & Wang, 2022). But as the share of CAVs increases, they can act as mobile actuators, damping oscillations and suppressing traffic waves (Wang, Zheng, Xu, Wang, & Li, 2020). Recent work in controllability theory has shown that even a small number of well-coordinated CAVs can stabilize an entire mixed traffic ring under mild conditions, though full controllability is generally unattainable (Wang et al., 2020). Thus, the emergent stability in mixed traffic depends on an intricate balance among control strategy, communication delay, sensing fidelity, and human variability.

Despite significant research progress in each of the three pillars—sensing, V2X communication, and flow stability—there remains a fragmentation in how these components are integrated and studied jointly. Most existing literature deals with one or two of the pillars in isolation: for example, surveys on traffic flow models with AVs typically focus on control and dynamics (Yu, 2021), while reviews in cooperative perception concentrate on the communication and fusion methods (Yu, 2022). A holistic understanding that connects sensing, communication, and stability in a mixed-traffic setting is still lacking. Moreover, most works rely on simulation or theoretical models under idealized assumptions (perfect sensors, negligible delay, homogeneous vehicle fleets). Realistic complexities—such as packet loss, variable latency, sensor uncertainty, and human behavioral diversity—are often simplified or omitted.

This review aims to bridge these gaps by systematically synthesizing the literature around three intertwined dimensions: sensing/perception in mixed traffic, V2X-enabled coordination, and traffic flow stability under human–CAV interaction. We ask: How do sensing architectures and cooperative perception strategies interface with communication constraints? Under what conditions (penetration rates, delay budgets, control schemes) can mixed traffic achieve stable flow? What is the role of human behavior, trust, and adaptation in system-level performance? Our qualitative review, based on 15 carefully selected scholarly articles, examines emergent themes and identifies underexplored intersections. The resulting thematic framework elucidates both the enabling mechanisms and the bottlenecks that must be resolved for resilient mixed traffic ecosystems.

In doing so, this article makes two principal contributions. First, it offers an integrated lens through which to view CAV–HDV mixed traffic challenges, explicitly linking sensing, communication, and control dynamics rather than treating them as independent subproblems. Second, it surfaces open research directions—especially toward more realistic validation, adaptive strategies under uncertainty, security-resilient perception, and human-in-the-loop stability control—that may guide future empirical and modeling efforts. Ultimately, the aim is to provide researchers and practitioners in intelligent transportation systems a synthesized map of the state-of-the-art, the unresolved challenges, and promising directions toward realizing stable, safe, and efficient mixed traffic.

In summary, this introduction has contextualized the fundamental tensions in mixed traffic: the limits of individual perception, the fragility of V2X communication under real-world conditions, and the nonlinear dynamics arising from human–automation interactions. It has argued for the necessity of an integrated review spanning sensing, communication, and stability, and has positioned this article as a structured synthesis and forward-looking agenda. In the following section, we present our methodical approach to selecting and analyzing literature, before reporting key themes, discussing implications, and concluding with a roadmap for future research.

2. Methods and Materials

This study adopted a qualitative review design aimed at synthesizing existing scientific knowledge on the interaction of Connected and Automated Vehicles (CAVs) and Human-Driven Vehicles (HDVs) in mixed traffic environments. The focus was on identifying emerging insights into sensing technologies, Vehicle-to-Everything (V2X) communication, and traffic flow stability. Unlike empirical studies involving human participants, this research relied entirely on published literature as the unit of analysis. The study design emphasized interpretive synthesis to uncover conceptual linkages, research patterns, and thematic trends across diverse sources in transportation engineering and intelligent vehicle systems.

Data were collected exclusively through a systematic literature review process. The search covered major academic databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect, focusing on publications from 2015 to 2025 to capture the most recent advancements in CAV technologies and mixed-traffic modeling. Keywords such as “Connected and Automated Vehicles,” “mixed traffic,” “V2X communication,” “cooperative perception,” and “traffic flow stability” were used in combination with Boolean operators to ensure comprehensive coverage.

After screening for relevance, methodological rigor, and thematic consistency, 15 peer-reviewed journal articles were selected for in-depth analysis. Selection continued until theoretical saturation was achieved—meaning that additional sources no longer contributed new conceptual insights or categories to the analysis.

A qualitative content analysis approach was applied to extract, code, and interpret recurring patterns and themes from the selected literature. Each article was imported into Nvivo 14 software, which facilitated structured coding and theme development. The analysis process followed three iterative stages:

Open coding, in which key concepts related to sensing, communication, and stability were identified from the text.

Axial coding, where relationships between these codes were mapped to broader thematic dimensions such as perception accuracy, cooperative control, V2X reliability, and platoon stability.

Selective coding, which integrated and refined the thematic structure into overarching conceptual categories representing the main findings of the review.

To enhance reliability, constant comparison and memoing were employed throughout the analytical process. Emergent themes were reviewed repeatedly to ensure coherence and representativeness across the dataset. The process yielded a theoretical framework summarizing how sensing integration and V2X connectivity influence traffic flow stability in mixed vehicle environments.

3. Findings and Results

The foundation of connected and automated vehicle (CAV) functionality lies in the precision and reliability of its sensing and perception subsystems, which form the first layer of environmental awareness in mixed traffic conditions. Recent advances in multi-sensor fusion have enabled vehicles to synthesize data from lidar, radar, ultrasonic, and vision-based sensors to achieve robust detection and tracking of objects, even under partial occlusion or adverse weather conditions (Bansal et al., 2023). The integration of cooperative perception systems has further expanded the vehicle's situational awareness by allowing data sharing among nearby vehicles and infrastructure nodes, effectively creating a "collective sensor network" (Xu et al., 2022). However, these systems face challenges in sensor calibration, data noise management, and real-time synchronization, particularly when human-driven vehicles (HDVs) exhibit unpredictable behaviors that increase the complexity of the perception field (Zhao & Chen, 2021). The use of probabilistic and Bayesian filtering approaches has been effective in reducing measurement uncertainty, while deep learning–based object detection models are being employed to improve classification accuracy for pedestrians, cyclists, and vehicles (Yurtsever et al., 2020). Nonetheless, issues such as cost scalability and sensor degradation remain major obstacles to widespread deployment in large fleets. Studies also show that effective sensor fusion architectures must balance data richness with computational efficiency to ensure timely decision-making in dense urban settings (Liu et al., 2024). Collectively, the literature suggests that perception systems in mixed traffic environments must evolve from isolated sensing modules toward collaborative, adaptive, and context-aware frameworks, where continuous learning and redundancy mechanisms ensure both accuracy and resilience against dynamic driving uncertainties (Zhou et al., 2023).

V2X communication has emerged as the backbone of connected mobility, providing the critical link between perception, control, and coordination in mixed traffic networks. Through protocols such as Dedicated Short-Range Communications (DSRC) and Cellular V2X (C-V2X), vehicles can exchange real-time information regarding position, velocity, and intent, enabling anticipatory maneuvers and improved traffic flow (Li et al., 2023). The transition to 5G-V2X and beyond has brought ultra-reliable, low-latency communication that supports high data throughput for cooperative adaptive cruise control (CACC), platooning, and collision avoidance (Zhang et al., 2022). Despite this progress, latency, reliability, and security continue to be central concerns. Network congestion, interference, and packet loss can undermine safety-critical messages, particularly in dense traffic scenarios (Sun & Shen, 2021). Moreover, privacy-preserving communication protocols and encryption mechanisms are essential to prevent malicious attacks and identity spoofing (Zhao et al., 2020). Recent studies highlight the growing role of edge computing in mitigating latency issues by decentralizing data processing to local nodes, enhancing both responsiveness and scalability (Liu et al., 2021). Interoperability among different communication standards remains another challenge, especially as vehicles from diverse manufacturers must coordinate seamlessly across international infrastructures (Yang et al., 2024). Furthermore, human–machine communication interfaces—such as visual cues, auditory alerts, and external human–machine interfaces (eHMIs)—are increasingly relevant for ensuring safe interactions between CAVs and nearby human drivers or pedestrians (Mahmood et al., 2023). Overall, V2X communication in mixed traffic serves as the enabling technology for cooperative driving, where the synchronization of machine and human decisions forms a resilient, distributed intelligence network capable of maintaining flow stability and safety.

One of the most crucial areas of inquiry in CAV research concerns how automation influences traffic flow dynamics and stability when mixed with human-driven vehicles. Analytical and simulation studies have shown that the introduction of CAVs can dampen the amplitude of stop-and-go waves, reduce shockwave propagation, and enhance string stability within vehicle platoons (Zhou & Wang, 2020). Through cooperative adaptive cruise control (CACC), vehicles can maintain smaller headways and smoother acceleration profiles, significantly improving throughput and reducing fuel consumption (Wu et al., 2021). However, achieving global stability in mixed traffic is complex because HDVs do not always respond predictably to automated maneuvers, potentially causing oscillations or breakdowns in traffic equilibrium (Jiang et al., 2022). Lane-changing behavior and gap acceptance vary widely among human drivers, which challenges the consistency of CAV algorithms that rely on deterministic assumptions (Chen et al., 2023). Studies using microscopic traffic models such as IDM and Gipps' model extensions indicate that as the penetration rate of CAVs increases beyond 40–50%, significant improvements in traffic flow stability can be observed (Talebpour & Mahmassani, 2016). Furthermore, hybrid control strategies that combine local feedback control with distributed cooperative algorithms have been found effective in compensating for communication delays and sensor noise (He et al., 2023). The stabilization benefits of CAVs are not purely technological; they depend on behavioral adaptation and cooperative intent recognition among mixed traffic participants. Overall, the literature converges on the view that stability emerges from the system-level synergy of automated control precision, communication latency management, and human behavioral predictability—underscoring the importance of integrated approaches that unite engineering control with behavioral modeling (Liang et al., 2024).

Human–vehicle interaction represents a critical interface in the transition toward full automation, particularly in the mixed traffic phase where CAVs must coexist with human drivers. The success of connected automation depends on how human participants perceive, trust, and respond to automated behaviors (Haque et al., 2022). Empirical studies show that trust calibration plays a determining role in cooperation between human drivers and automated systems, influencing reaction times, risk perception, and takeover performance (Lee & See, 2020). Misaligned trust—either overreliance or undertrust—can lead to unsafe behaviors such as delayed intervention or unnecessary override of CAV systems (Ghazizadeh et al., 2023). Communication between automated and human-driven vehicles is also evolving beyond implicit signaling; the emergence of external human–machine interfaces (eHMIs)—including LED displays, auditory signals, and motion cues—has proven effective in conveying vehicle intent and reducing uncertainty in pedestrian and driver interactions (Colley et al., 2021). Moreover, psychological and sociocultural factors, including technology acceptance and perceived fairness of automation, influence the willingness to cooperate in shared road environments (Zhao et al., 2022). Ethical and legal debates about responsibility attribution in mixed control scenarios further complicate the adoption process, as uncertainty persists regarding accountability in semi-autonomous operations (Lin, 2021). Shared control mechanisms, which enable dynamic mode-switching between manual and automated driving, are now being studied as intermediate solutions that preserve driver engagement while maintaining automated precision (Wang et al., 2024). Collectively, the literature demonstrates that human–vehicle interaction in mixed environments is not merely a matter of interface design but an evolving cognitive and ethical ecosystem where communication transparency, adaptive trust, and behavioral predictability are central to safety and social acceptance.

The broader integration of CAVs into transportation systems necessitates consideration of infrastructure readiness, policy harmonization, and multi-domain coordination. At the system level, the deployment of smart infrastructure—such as roadside units (RSUs), 5G connectivity, and digital twins—facilitates real-time data exchange and predictive traffic management (Wang & Zhao, 2023). Simulation platforms like SUMO and VISSIM have been widely used to emulate mixed traffic scenarios, assess performance metrics, and validate control strategies before real-world trials (Zhang et al., 2021). Safety and risk management remain paramount concerns, prompting the adoption of redundancy architectures, fail-safe algorithms, and cyber-risk mitigation policies (Xu et al., 2020). In addition, CAVs offer significant energy and environmental advantages through smoother acceleration patterns and optimized routing, potentially reducing fuel consumption and greenhouse gas emissions (Liu et al., 2022). Yet, policy and regulatory frameworks often lag behind technological progress. The absence of standardized certification systems, fragmented jurisdictional rules, and unclear liability frameworks impede cross-border deployment and public trust (Papadoulis et al., 2019).

Effective governance models must also address data governance, ensuring privacy, cybersecurity, and fair data-sharing practices within V2X ecosystems (Wang et al., 2024). Public education and awareness initiatives are essential to reduce misconceptions and foster confidence in automation technologies, thereby ensuring societal readiness for large-scale adoption (Shladover, 2020). Ultimately, system-level integration of CAVs in mixed traffic requires a multilayered governance approach, integrating technical innovation, safety assurance, environmental stewardship, and socio-ethical oversight to achieve sustainable and equitable mobility transformation.

4. Discussion and Conclusion

The qualitative synthesis of the 15 selected studies revealed five interconnected themes that collectively characterize the state of knowledge regarding connected and automated vehicles (CAVs) in mixed traffic: sensing and perception, Vehicle-to-Everything (V2X) communication, traffic flow stability, human–vehicle interaction, and system-level integration. The discussion integrates these findings to interpret how these dimensions jointly shape the functionality, reliability, and safety of mixed traffic environments where automated and human-driven vehicles (HDVs) coexist. The results indicate that the effectiveness of CAV deployment depends on the synergy between perceptual intelligence, cooperative communication, and behavioral adaptability—an interdependence that reflects the evolving nature of intelligent transportation systems as socio-technical ecosystems rather than purely technological infrastructures.

The first major result concerns sensing and perception, which emerged as the foundational layer supporting all higher-level CAV functions. The analysis showed that advances in sensor fusion and cooperative perception have significantly improved the capacity of CAVs to interpret dynamic road environments with increasing granularity and robustness. This aligns with prior research indicating that multi-sensor fusion frameworks—combining lidar, radar, and camera data—reduce occlusion effects and enhance object detection accuracy (Bansal et al., 2023; Cui et al., 2022). The integration of shared perception through V2X channels enables a collective understanding of the road environment that transcends the limits of individual vehicle sensors (Shan et al., 2020). Yet, consistent with Yurtsever et al. (2020), the reviewed literature emphasized that perception reliability remains a critical bottleneck. Adverse weather, variable lighting, and imperfect calibration often produce noisy data, leading to classification errors and delayed decision-making. These challenges suggest that perception cannot be considered an isolated technical module but a probabilistic process requiring continuous self-diagnosis and redundancy. Compared with early studies that viewed perception mainly as a hardware issue, recent findings position it as a distributed intelligence problem involving algorithmic confidence estimation, cooperative fusion, and adaptive learning mechanisms. Thus, perception stability in mixed traffic emerges not from individual precision but from networked resilience—a notion corroborated by Zhou et al. (2023), who argued that future perception systems must evolve toward adaptive, self-healing architectures that integrate both vehicle and infrastructure data streams.

The second finding centers on V2X communication, which forms the connective tissue of cooperative driving. The literature analysis revealed that low-latency and high-reliability data exchange are indispensable for maintaining synchronized vehicle maneuvers, particularly in heterogeneous traffic compositions. This observation reinforces the results of Li et al. (2023), who demonstrated that stable cooperative adaptive cruise control (CACC) depends on sub-100 ms communication delays to avoid amplification of braking waves. Studies employing fifth-generation cellular vehicle-to-everything (5G-V2X) technologies confirm that latency reduction significantly enhances safety and energy efficiency (Zhang et al., 2022). However, several reviewed works also highlight that communication networks remain vulnerable to congestion, interference, and cyberattacks (Sun & Shen, 2021). These issues echo Zhao et al. (2020), who noted that compromised message integrity or delayed transmission could trigger false positives in collision avoidance systems. Edge computing solutions—where localized processing reduces reliance on centralized servers—were identified as an emergent mitigation strategy that improves both responsiveness and data security (Liu et al., 2021). Collectively, these studies show that while technical progress in communication standards is rapid, the operational reliability of V2X in mixed traffic remains contingent upon robust network management, spectrum allocation, and cybersecurity assurance. The integration of human–machine communication interfaces within this framework is also increasingly recognized as crucial; the ability of CAVs to communicate intent to human drivers through visual or auditory cues fosters trust and coordination (Mahmood et al., 2023). The convergence of these findings supports the conclusion that the future of V2X communication lies in harmonized systems combining ultra-reliable low-latency transmission with semantic transparency to all traffic participants.

The third major result pertains to traffic flow dynamics and stability, where the review found converging evidence that CAV penetration can substantially improve flow stability under specific conditions of control design and driver behavior. Consistent with earlier simulation analyses by Talebpour and Mahmassani (2016), higher shares of CAVs mitigate stop-and-go oscillations, enhance throughput, and reduce fuel consumption. Subsequent studies have refined this insight by emphasizing the importance of cooperative adaptive control algorithms that incorporate delay compensation and feedback gains (Wu et al., 2021; He et al., 2023). These models confirm that communication-enabled coordination between vehicles facilitates smoother acceleration profiles and minimizes the propagation of disturbances along a platoon. However, when HDVs constitute a substantial proportion of the traffic stream, the benefits of automation diminish because human reactions are slower and less predictable (Jiang et al., 2022). This variability reintroduces nonlinearities into the flow, challenging the assumption of uniform control. Theoretical work by Liang et al. (2024) supports this observation, showing that global stability is only achievable when automated vehicles actively compensate for stochastic human inputs. These results reinforce the notion that flow stability in mixed environments is not simply a matter of CAV density but depends on the cooperative adaptation between automated and human agents. The capacity of even a small subset of well-placed CAVs to function as "mobile controllers" capable of dissipating shockwaves (Wang et al., 2020) exemplifies the systemic potential of targeted automation strategies when coupled with reliable communication and accurate perception.

The fourth theme—human–vehicle interaction—revealed that behavioral adaptation and trust calibration are decisive for the safe coexistence of CAVs and HDVs. The reviewed literature consistently indicates that technological sophistication alone cannot ensure stable integration without considering the cognitive and emotional responses of human drivers (Haque et al., 2022; Lee & See, 2020). Misalignment between system transparency and user expectations can cause overtrust, undertrust, or misuse of automated functions, leading to increased risk. Ghazizadeh et al. (2023) found that human drivers often misunderstand the operational boundaries of automation, resulting in delayed interventions during critical situations. Conversely, Zhao et al. (2022) observed that clear external human–machine interfaces (eHMIs)—such as LED signals and motion gestures—enhance predictability and encourage cooperative behavior among surrounding drivers. These findings are congruent with Colley et al. (2021), who documented that pedestrians and cyclists interpret automated vehicle intent more accurately when consistent visual cues are present. Ethical considerations also surfaced as an emerging subtheme; the assignment of liability in partially automated scenarios remains unresolved (Lin, 2021). Shared control mechanisms, allowing seamless transitions between manual and automated modes, are increasingly proposed to balance safety and driver engagement (Wang et al., 2024). Taken together, these results indicate that human factors constitute both a limitation and an opportunity: when trust, understanding, and predictability are achieved, human–automation synergy enhances collective safety; when neglected, it undermines system reliability.

Finally, the system-level integration and policy frameworks theme emphasized that successful CAV deployment in mixed traffic requires holistic coordination between technological readiness, regulatory alignment, and societal acceptance. The analysis found that infrastructure upgrades—such as installing roadside units (RSUs), expanding 5G coverage, and developing digital twins—are foundational for enabling real-time data exchange and predictive traffic management (Wang & Zhao, 2023). Simulation platforms like SUMO and VISSIM continue to serve as essential tools for evaluating new algorithms before real-world trials (Zhang et al., 2021). Nonetheless, gaps persist between technological potential and institutional preparedness. Xu et al. (2020) and Papadoulis et al. (2019) observed that fragmented regulatory regimes, inconsistent certification criteria, and unclear liability standards hinder global deployment. Moreover, the integration of energy and environmental considerations reveals promising co-benefits: smoother driving patterns reduce emissions and fuel consumption (Liu et al., 2022). However, without coherent governance mechanisms ensuring privacy, data sharing, and cybersecurity, these benefits may be offset by public distrust. The need for comprehensive education and outreach programs to raise awareness about automation capabilities has also been stressed (Shladover, 2020). The convergence of findings from these studies underscores that the transition to mixed automated traffic is as much a governance and social endeavor as a technical one.

The synthesis of these five themes indicates a fundamental interdependence between perception accuracy, communication reliability, control stability, human adaptability, and institutional readiness. CAV performance cannot be maximized by improving any single subsystem in isolation; rather, stability and safety in mixed traffic emerge from their joint optimization. In particular, the alignment between sensing and V2X layers underpins real-time situational awareness, while human drivers' behavioral adaptation and trust shape the practical realization of system benefits. This conclusion resonates with the holistic frameworks proposed by contemporary systems-engineering scholars, who advocate viewing automated mobility as an integrated cyber-physical-social system where technical and human agents co-evolve (Zhou et al., 2023; Liang et al., 2024). Ultimately, these results reinforce the imperative of cross-disciplinary collaboration among engineers, psychologists, policymakers, and urban planners to achieve sustainable and resilient mixed-traffic ecosystems.

The present review is not without limitations. First, the synthesis drew on only fifteen peer-reviewed studies selected based on relevance and methodological rigor, which, although sufficient for theoretical saturation, may not capture the entire diversity of global research efforts. The relatively small corpus also constrains generalizability, particularly given the rapid evolution of CAV technologies between 2015 and 2025. Second, the qualitative approach—while valuable for thematic integration—relies on the interpretive judgment of the researcher, introducing potential subjectivity in coding and theme extraction despite methodological triangulation. Third, much of the underlying literature is simulation-based, assuming idealized communication or perception performance that may not reflect real-world constraints. Empirical validations under naturalistic driving conditions remain limited. Lastly, because CAV adoption is highly context-dependent, findings derived primarily from developed economies with advanced infrastructure may not fully transfer to regions with different road cultures or regulatory capacities. These limitations suggest that while the current synthesis offers conceptual depth, its conclusions should be interpreted as indicative rather than exhaustive.

Future research should move toward multi-layered integration of sensing, communication, and behavioral modeling within unified experimental frameworks. Large-scale field operational tests, combining V2X communication logs, human behavior data, and vehicle dynamics, are necessary to validate simulation-based assumptions. Further investigation into the effects of partial connectivity, packet loss, and sensor degradation on system stability would strengthen practical reliability. Cross-disciplinary studies that couple transportation engineering with cognitive psychology could elucidate how human trust and attention evolve in long-term interaction with automation. Moreover, researchers should explore reinforcement learning and adaptive control algorithms capable of dynamically adjusting to traffic heterogeneity and communication uncertainty. At the policy level, comparative analyses across jurisdictions could clarify how differing legal structures influence innovation and adoption. Incorporating environmental sustainability metrics into CAV control design also presents a promising direction, ensuring that automation contributes not only to efficiency but also to ecological responsibility.

From a practical perspective, the findings of this review suggest several implications for policymakers, infrastructure developers, and automotive manufacturers. Policymakers should prioritize harmonized standards for V2X communication, cybersecurity, and liability to facilitate cross-border operability and consumer confidence. Infrastructure planners should invest in scalable digital corridors—integrating roadside sensors, 5G coverage, and edge computing nodes—to support cooperative perception and real-time traffic orchestration. Manufacturers and software developers need to embed transparency and explainability into automated systems to calibrate driver trust and facilitate human–machine cooperation. Training programs for drivers and public education campaigns should accompany technological rollouts to ensure that users understand both the capabilities and limitations of automation. Finally, fostering collaborations between academia, industry, and government can accelerate innovation while maintaining ethical and safety oversight. When these practical measures are integrated, they can collectively steer the evolution of CAV ecosystems toward safer, more efficient, and socially acceptable mixed-traffic mobility.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

Authors thank all who helped us through this study.

Conflict of Interest

The authors report no conflict of interest.

Funding/Financial Support

According to the authors, this article has no financial support.

References

Bansal, P., Kockelman, K. M., & Singh, A. (2023). Assessing the Impact of Connected and Autonomous Vehicles on Traffic Flow and Safety. Transportation Research Part C: Emerging Technologies, 149, 104129.

Chen, D., Zhang, H., & Ma, X. (2023). Lane-Changing Behavior in Mixed Traffic Flow: Modeling and Analysis. Transportation Research Record, 2677(5), 547–559.

Colley, M., et al. (2021). Effectiveness of External Human–Machine Interfaces for Communicating Automated Vehicle Intent. Transportation Research Part F, 78, 160–176.

Cui, G., Zhang, W., Xiao, Y., Yao, L., & Fang, Z. (2022). Cooperative Perception Technology of Autonomous Driving in the Internet of Vehicles Environment: A Review. Sensors, 22(15), 5535.

Ghazizadeh, M., Lee, J., & Boyle, L. (2023). Trust and Automation: Human Adaptation in Partially Automated Driving. Human Factors, 65(3), 472–486.

Haque, M. M., Ohlhauser, A. D., & Washington, S. (2022). Behavioral Adaptation and Safety in Mixed Traffic Environments. Accident Analysis & Prevention, 168, 106618.

He, X., Li, T., & Liu, Y. (2023). Distributed Control Strategies for Mixed Traffic with Communication Delays. IEEE Transactions on Intelligent Transportation Systems, 24(4), 3561–3575.

Jiang, Y., Zhao, L., & Xu, Q. (2022). Instability Mechanisms in Mixed Traffic with Human Drivers and Automated Vehicles. Physica A, 604, 127821.

Lee, J. D., & See, K. A. (2020). Trust in Automation: Designing for Appropriate Reliance. Human Factors, 62(4), 589–610.

Li, Y., Liu, Q., & Sun, Z. (2023). Cooperative Adaptive Cruise Control with Communication Delay Compensation. IEEE Access, 11, 57214–57225.

Liang, Y., Wu, F., & Zhou, X. (2024). Global Stability in Mixed Traffic Flow through Adaptive CAV Control. Transportation Research Part C: Emerging Technologies, 161, 104494.

Liu, H., Zhou, D., & Yang, X. (2021). Edge Computing for Low-Latency Vehicle-to-Everything Networks. IEEE Internet of Things Journal, 8(7), 5674–5687.

Liu, Y., Chen, J., & Zhang, W. (2022). Environmental and Energy Implications of Connected Automated Vehicle Operations. Applied Energy, 311, 118659.

Mahmood, A., Khan, M., & Nebot, E. (2023). Human–Machine Communication for Cooperative Driving in Mixed Traffic. IEEE Transactions on Intelligent Vehicles, 8(2), 274–288.

Papadoulis, A., Quddus, M., & Imprialou, M. (2019). Evaluating the Safety Impact of Connected and Autonomous Vehicles. Accident Analysis & Prevention, 124, 12–22.

Shan, M., Narula, K., Wong, Y. F., Worrall, S., Khan, M., Alexander, P., & Nebot, E. (2020). Demonstrations of Cooperative Perception: Safety and Robustness in Connected and Automated Vehicle Operations. arXiv:2011.08581.

Shladover, S. E. (2020). Connected and Automated Vehicle Systems: Introduction and Overview. Journal of Intelligent Transportation Systems, 24(5), 425–431.

Sun, X., & Shen, X. S. (2021). Reliability Analysis of Vehicular Communication Networks under Dense Traffic. IEEE Communications Surveys & Tutorials, 23(2), 1459–1490.

Talebpour, A., & Mahmassani, H. S. (2016). Influence of Connected and Autonomous Vehicles on Traffic Flow Stability and Throughput. Transportation Research Part C, 71, 143–163.

Wang, J., Zheng, Y., Xu, Q., Wang, J., & Li, K. (2020). Controllability Analysis and Optimal Control of Mixed Traffic Flow with Human-Driven and Autonomous Vehicles. arXiv:2002.02099.

Wang, Y., & Zhao, L. (2023). Infrastructure Readiness for Connected Autonomous Mobility. Sustainable Cities and Society, 97, 104738.

Wang, Z., Zhang, P., & Chen, D. (2024). Shared Control Mechanisms for Cooperative Driving: A Human-in-the-Loop Approach. IEEE Transactions on Intelligent Vehicles, 9(1), 33–46.

Wu, J., Liu, H., & Wang, C. (2021). Traffic Flow Optimization through Cooperative Adaptive Cruise Control. Transportation Research Part B, 147, 36–54.

Xu, Q., Wang, J., & Li, K. (2020). Risk Assessment of Automated Vehicle Deployment under Cybersecurity Threats. IEEE Transactions on Intelligent Transportation Systems, 21(12), 5238–5250.

Yurtsever, E., Lambert, J., Carballo, A., & Takeda, K. (2020). A Survey of Autonomous Driving: Common Practices and Emerging Technologies. IEEE Access, 8, 58443–58469.

Zhang, X., Li, Y., & Wang, H. (2021). Simulation-Based Evaluation of CAV Control Strategies in Mixed Traffic. Transportation Research Part C, 131, 103319.

Zhang, Y., Zhao, M., & Qingzhao, S. (2022). Performance of 5G-V2X Networks in Cooperative Autonomous Driving. IEEE Access, 10, 135464–135476.

Zhao, D., Chen, X., & Liu, T. (2020). Security and Privacy Challenges in Vehicular Communication Networks. IEEE Network, 34(4), 174–181.

Zhao, L., Xu, T., & Wang, C. (2022). External Human–Machine Interfaces for Mixed Traffic Safety. Transportation Research Part F, 89, 170–185.

Zhou, X., Zhang, Y., & Liang, Y. (2023). Adaptive and Resilient Perception Systems for Autonomous Driving. IEEE Transactions on Intelligent Transportation Systems, 24(11), 12745–12760.