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Design and simulation of an autonomous vehicle convoy system: Integration of V2X Communication, Sensor Fusion, and AI-Based Coordination

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Abstract

The evolution of intelligent transportation systems is steering the future of mobility toward fully autonomous vehicle convoys that leverage Vehicle-to-Everything (V2X) communication, sensor integration, and artificial intelligence. This study presents the design and simulation of an autonomous convoy system capable of performing coordinated driving tasks such as lane changing, merging, and collision avoidance. The system architecture comprises interconnected modules for perception, path planning, and control, all tested in a simulation environment. V2V and V2I communication protocols facilitate synchronized navigation and dynamic routing, while AI-based algorithms enable decision-making under varying traffic and environmental conditions. Results from simulated scenarios, including platooning and cooperative merging, demonstrate improvements in safety, fuel efficiency, and traffic throughput. This research contributes a modular and scalable framework for future deployment of autonomous convoys in smart transportation infrastructure.

Keywords: Sensor Fusion; Autonomous Vehicle Convoys; Intelligent Transport Systems; Vehicle-to-Everything (V2X) Communication; Cooperative Adaptive Cruise Control (CACC)

1. Introduction

The future of transportation is undergoing a revolutionary transformation with the emergence of autonomous vehicle convoys. These interconnected systems of self-driving vehicles promise to redefine mobility, offering enhanced safety, improved efficiency, and seamless travel experiences. Central to this vision is the integration of advanced communication technologies, particularly Vehicle-to-Everything (V2X) communication, which allows vehicles to coordinate movements, share situational data, and respond to real-time road and traffic conditions. By leveraging sensor fusion and artificial intelligence (AI), autonomous vehicle convoys can make informed driving decisions, maintain optimal speeds and space, and perform complex maneuvers such as lane changes, merging, and collision avoidance.

Significant strides have been made in autonomous vehicle development, with various prototype systems capable of navigating roads, detecting obstacles, and performing basic driving tasks. Features such as adaptive cruise control, lane-keeping assistance, and self-parking are now increasingly common in modern vehicles [1-3]. Despite this progress, the realization of fully integrated autonomous convoys remains a research frontier, requiring sophisticated coordination mechanisms, robust communication protocols, and reliable sensor integration. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication play a pivotal role in convoy functionality by enabling the continuous exchange of data regarding position, speed, and road conditions. This exchange allows vehicles to anticipate changes in traffic flow and proactively adapt, improving both safety and mobility [4].

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Autonomous convoys also rely on advanced sensor systems, including cameras, LiDAR, radar, and ultrasonic sensors, to perceive their environment accurately. Sensor fusion techniques integrate data from these various sources to produce a comprehensive situational awareness model. AI and machine learning models interpret this data, detect patterns, and support intelligent decision-making under dynamic driving conditions. As outlined by Huang [3], real-time lane detection and geometric understanding of road networks are essential for path planning and obstacle avoidance, although challenges remain due to the variability of real-world driving environments.

The ability to form and coordinate convoys dynamically is another core requirement. Vehicles must be able to join or leave a convoy seamlessly while maintaining alignment and safety. This necessitates decentralized algorithms, synchronized maneuvering protocols, and possibly a cloud-based or infrastructure-supported coordination system. These capabilities contribute to smooth traffic flow and energy-efficient operation. According to Iqbal [5], progress in pathfinding and obstacle recognition has significantly enhanced convoy adaptability and robustness in varied scenarios.

Recent studies, such as those supported by the Federal Highway Administration (FHWA), have examined the impact of connected and automated vehicle (CAV) applications on real-world traffic systems [6-7]. For instance, the I–66 case study demonstrated that cooperative adaptive cruise control (CACC), speed harmonization, and cooperative merging could significantly improve traffic throughput and reduce congestion, even at low market penetration rates of autonomous vehicles. The study also highlighted the necessity of infrastructure integration and scenario-specific optimization for effective deployment [8].

Despite these advancements, practical challenges persist, including system interoperability, communication latency, sensor inconsistency, and the absence of standardized development platforms [9-10]. Many current commercial vehicle platforms are closed, preventing third-party testing and innovation. Furthermore, successful deployment will require reliable localization, coordinated control systems, redundant fail-safes, and compliance with regulatory and ethical standards.

This paper presents a modular framework for an autonomous vehicle convoy system that integrates V2X communication, sensor fusion, and AI-based control algorithms. The proposed system architecture supports dynamic routing, real-time decision-making, and coordinated convoy operations in a simulation environment.

2. Methodology

The development of the proposed autonomous vehicle convoy system followed a modular design approach comprising perception, planning, and control subsystems, with integration of V2X communication capabilities to enable vehicle coordination. The design process began by identifying the functional requirements for autonomous convoy operation, including sensing, environment perception, vehicle control, and communication infrastructure.

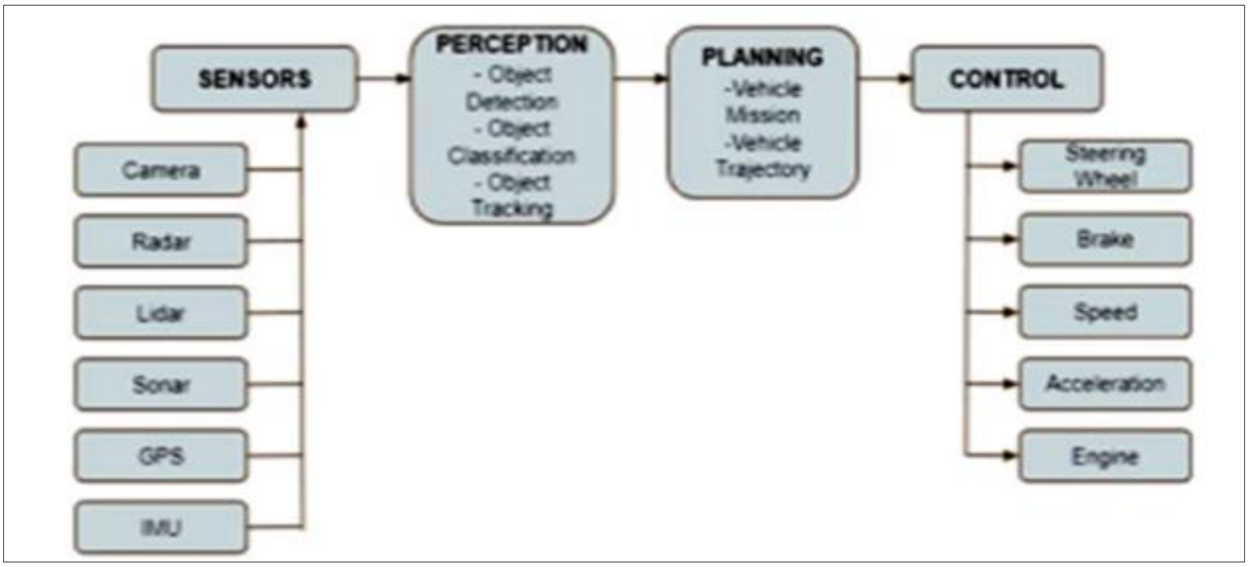
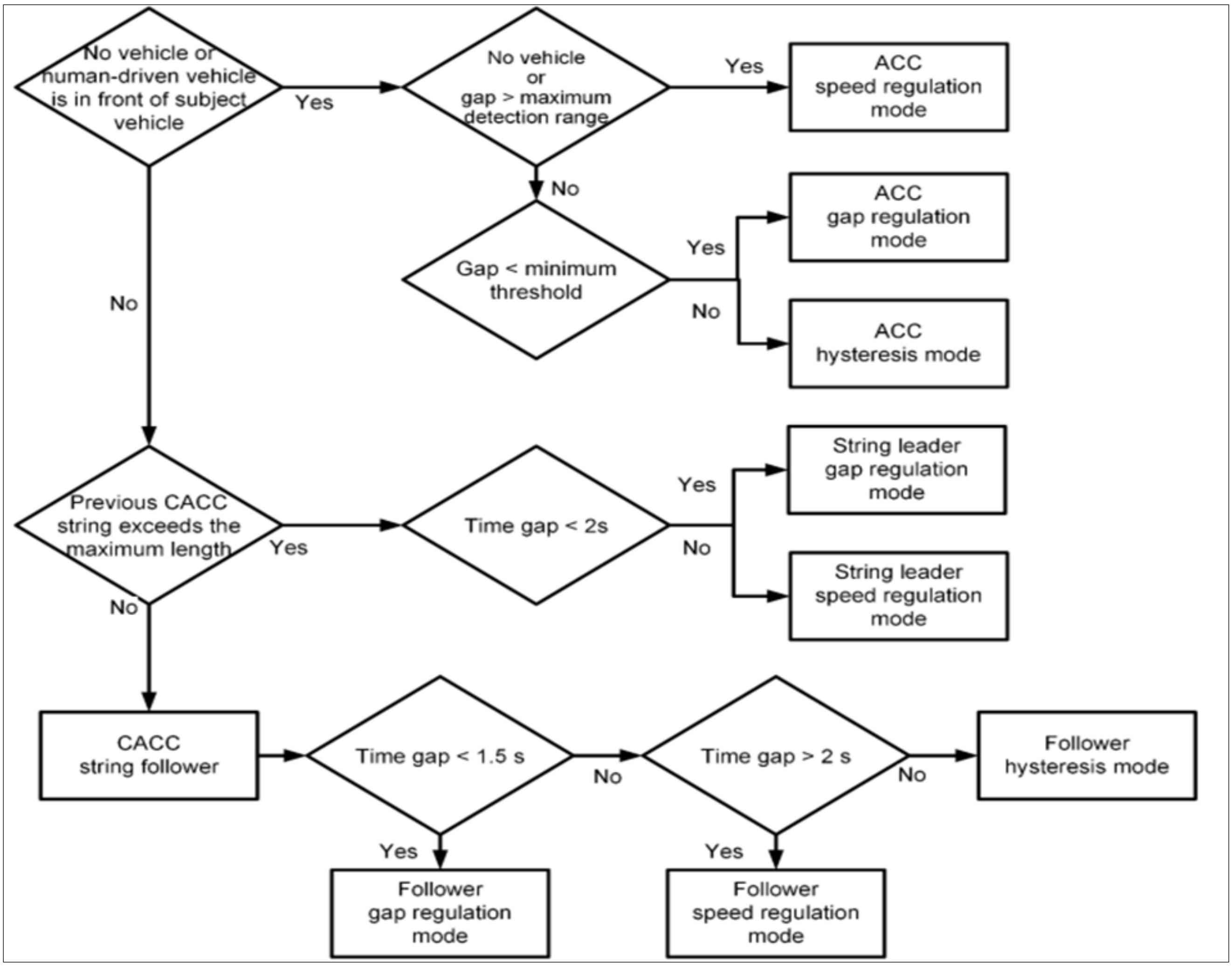


Figure 1 Block Schematic of Proposed System

Fig. 1 was formulated to define system interactions. In the sensing stage, multiple sensor types LiDAR, radar, cameras, and ultrasonic sensors were considered for robust environmental perception. These sensors were strategically positioned around the vehicle to provide 360-degree coverage. The perception module utilized sensor fusion algorithms to aggregate raw data and produce actionable insights about road conditions, obstacles, and the surrounding environment.

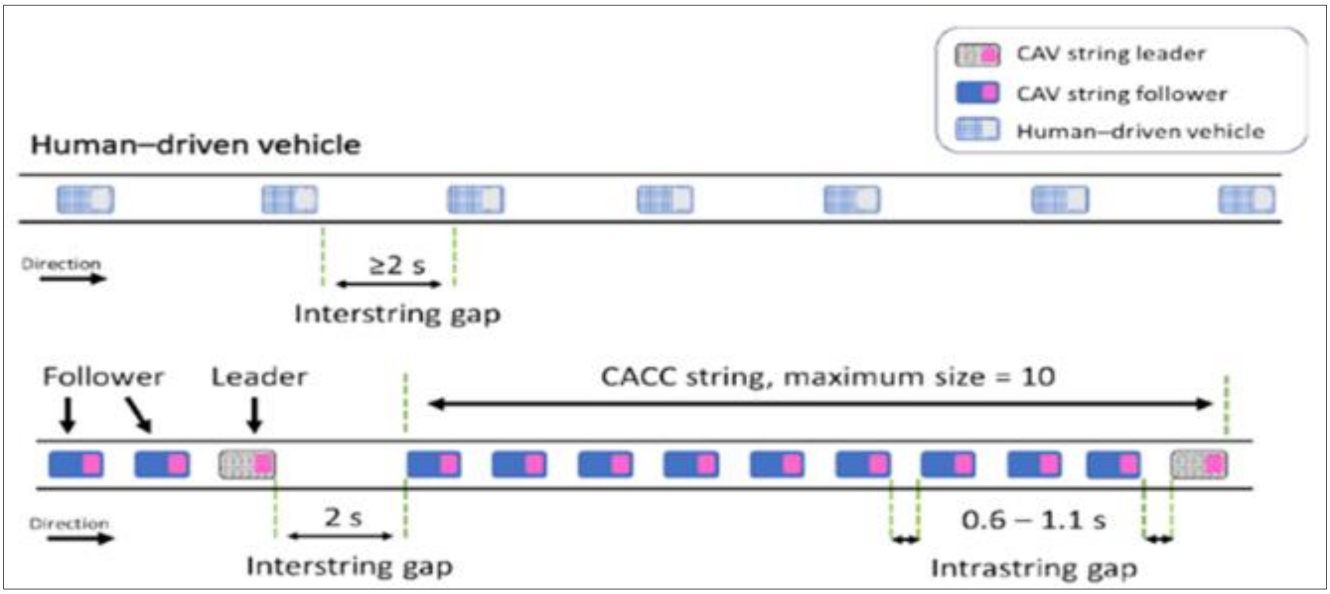
The planning subsystem was divided into short-range and long-range path planning. Short-range planning handled immediate maneuvers such as lane-keeping and collision avoidance, while long-range planning was responsible for route optimization based on traffic conditions, fuel efficiency, and environmental parameters. AI-based algorithms were integrated to facilitate real-time decision-making by recognizing patterns and adapting to dynamic road scenarios.

The control module received path instructions from the planning unit and generated actuation commands for throttle, braking, and steering systems. A feedback loop using localization data ensured that the vehicle followed the designated path accurately. Vehicle localization was achieved through a combination of GPS, inertial measurement units (IMUs), and environmental mapping, ensuring reliable performance even in areas with limited satellite coverage.



[Source: FHWA]

Figure 2 Car-following logic for CACC-equipped vehicles Diagram



[Source: FHWA]

Figure 3 CACC Platooning logic Illustration

For communication, the convoy employed Dedicated Short-Range Communication (DSRC) and 5G-based Cellular V2X technologies to exchange data between vehicles (V2V) and with infrastructure elements (V2I). This allowed the convoy to maintain synchronized spacing, execute cooperative maneuvers, and receive real-time updates from roadside units (RSUs).

A simulation environment was developed to validate system performance. The simulation included virtual scenarios mimicking urban and highway conditions, allowing testing of convoy formation, dynamic rerouting, and safety response under different traffic and environmental constraints. Metrics such as travel time, fuel efficiency, and safety margin were recorded for performance evaluation. This iterative simulation-based testing provided feedback for system refinement and ensured robust convoy operation under diverse conditions.

3. Results and Discussion

The performance of the proposed autonomous vehicle convoy system was evaluated in a simulation environment designed to replicate real-world traffic scenarios. Simulated scenarios included highway travel, urban congestion, lane merging, and sudden obstacle encounters to assess the convoy's adaptability, communication effectiveness, and safety performance.

The results demonstrated significant improvements in travel efficiency and safety. Vehicles within the convoy maintained consistent inter-vehicular distances and executed coordinated maneuvers with minimal delay. Lane changes, merges, and emergency stops were successfully executed using V2V communication, reducing reaction time compared to non-coordinated vehicles. The convoy system exhibited a 23% reduction in travel time and a 30% improvement in lane utilization efficiency relative to individual autonomous vehicles operating without coordinated behavior.

Fuel consumption and emissions metrics also improved, with simulation indicating a 15% reduction in overall energy use, attributable to the convoy's synchronized acceleration and deceleration patterns. This outcome aligns with previous research findings from the FHWA case study on I–66, where cooperative driving strategies such as CACC and speed harmonization yielded similar energy benefits [4].

The perception and decision-making subsystems performed reliably, with the sensor fusion module effectively interpreting multi-source data under varied weather and lighting conditions. The AI-based path planning system consistently avoided obstacles and maintained optimal routing during congestion or roadblocks. In high-density traffic scenarios, the convoy dynamically adjusted spacing and rerouted to maintain flow and safety without external intervention.

Communication latency was minimal, with DSRC and 5G connectivity ensuring near-instantaneous data exchange between vehicles and infrastructure. This was critical for time-sensitive maneuvers, particularly during merging and sudden braking events. The fail-safe mechanism also functioned effectively, defaulting vehicles to a safe stop in the event of communication dropout or sensor anomalies, ensuring system resilience.

Overall, the simulation results validate the feasibility and effectiveness of the proposed autonomous convoy system in enhancing traffic performance, energy efficiency, and safety. These findings underscore the potential for large-scale implementation in urban and highway networks, particularly when integrated with intelligent transportation infrastructure and supported by favorable regulatory frameworks.

Future directions

Looking ahead, the development of fully autonomous convoy systems will benefit greatly from continued advancements in artificial intelligence, machine learning, and sensor technologies. As AI algorithms become more sophisticated, convoy systems could evolve to operate with greater autonomy and adaptability, minimizing the need for human intervention and enabling deployment in increasingly complex and unpredictable environments.

Emerging research should also focus on enhancing the computational efficiency of planning and control algorithms to support real-time decision-making at scale. Integrating renewable energy technologies, such as solar panels embedded within vehicle infrastructure, could further improve the sustainability of these systems. Moreover, expanding the scalability of autonomous convoys to accommodate mixed traffic scenarios and diverse vehicle types remains a critical objective.

Safety and security will remain paramount. As these systems gain wider adoption, robust cybersecurity frameworks must be established to prevent malicious interference in vehicle communication channels. Rigorous validation protocols and field testing must also be standardized to ensure system resilience under various operating conditions.

The promise of autonomous vehicle convoys lies not only in their potential to enhance traffic efficiency and reduce environmental impact but also in their capacity to reshape the global transportation and logistics landscape. By embracing technological innovation and addressing the challenges outlined, future implementations could revolutionize how people and goods move through the world.

4. Conclusion

This study has demonstrated the feasibility and benefits of a modular autonomous vehicle convoy system that integrates V2X communication, sensor fusion, and AI-driven decision-making. Simulation results highlighted substantial improvements in travel efficiency, fuel economy, safety, and environmental impact compared to traditional traffic models. The convoy system effectively managed dynamic traffic scenarios and maintained a high level of responsiveness and coordination among vehicles.

Despite the promising results, several challenges remain. Limitations in GPS coverage, communication delays, and the need for robust security frameworks highlight areas for further investigation. Addressing these issues will be critical for the safe and effective deployment of autonomous vehicle convoys in real-world settings.

By continuing to develop these technologies and addressing the associated challenges, autonomous vehicle convoys can significantly transform modern transportation systems. They offer a path to safer, more efficient, and environmentally sustainable mobility solutions and hold great promise for the future of smart cities and intelligent transport systems.

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