OPTIMIZING TRAFFIC MANAGEMENT AND V2X COMMUNICATION FOR EFFICIENT MINING OPERATIONS

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Abstract - This research explores optimization of traffic management and Vehicle-to-Everything (V2X) communication for efficient mining operations. The study introduces a comprehensive framework leveraging V2X technology, D* Lite pathfinding algorithms, and intelligent decision-making protocols to enhance safety and efficiency of autonomous mining equipment. The proposed system implements a four-layer architecture comprising perception, communication, decision-making, and control layers, operating at 10 Hz for real-time coordination. Through MATLAB-based simulations involving 20 autonomous vehicles over 1,000 time steps, the system demonstrates significant performance improvements: 27.5% reduction in travel time, 42.7% decrease in collision risk, and 86.3% enhancement in traffic flow efficiency compared to baseline systems. Additional benefits include 32.5% improvement in system stability, 23.2% increase in fuel efficiency, and 15.7% reduction in energy consumption. The mathematical models incorporating multi-objective optimization and graph-based representations validate the practical applicability and scalability for modern autonomous mining operations.

Key words - Traffic Management System; V2X; Autonomous systems

1. Introduction

Mining environments are dynamic and high-risk settings that require the coordinated operation of numerous autonomous and semi-autonomous vehicles, including haul trucks, loaders, and excavators. Effective traffic management in these contexts is essential not only for ensuring operational safety but also for improving productivity and minimizing equipment wear.

This study proposes an advanced traffic management framework tailored for mining operations, built upon Vehicle-to-Everything (V2X) communication. The system facilitates real-time data exchange between mobile units and a centralized control system, enabling adaptive path planning, proactive collision avoidance, and responsive speed regulation.

A structured four-layer architecture - comprising perception, communication, decision-making, and control - is implemented to manage complex vehicle interactions. Mathematical modeling and graph-based optimization techniques, such as the D* Lite algorithm, are employed to support continuous route re-planning and real-time coordination under dynamic conditions. Site-specific design standards, including lane width and obstacle buffer zones, are integrated to further enhance safety and navigability.

System performance is assessed through simulation scenarios reflecting realistic mining layouts and vehicle behaviors. Results indicate substantial improvements in traffic flow efficiency, collision risk reduction, and energy optimization. This research delivers a scalable and practical solution for autonomous fleet coordination in mining, combining robust communication infrastructure, intelligent decision-making, and domain-specific design considerations.

2. Related works

Traffic management in mining environments has attracted significant research interest due to the rise of autonomous and semi-autonomous vehicles. Wang and Yang introduced a centralized traffic control system for mining trucks, reporting a 15% improvement in overall traffic efficiency [1]. Arena et al. explored V2X communication for safety enhancement, achieving a 30% reduction in collision risk [2]. Despite promising outcomes, many existing methods struggle with scalability and responsiveness in dynamic settings. This work addresses these gaps by integrating real-time V2X communication, multi-agent coordination, and adaptive optimization techniques.

V2X technologies have demonstrated strong potential for improving situational awareness and coordination in high-risk, closed environments like mines. Commercial platforms such as Commsignia offer fleet-level navigation, sensor fusion, and vehicle prioritization services to enhance safety for both machinery and personnel [3].

Collision Avoidance Systems (CAS) further strengthen operational safety. Imam et al. showed that CAS using LiDAR, radar, and vision-based sensors significantly reduces collision risks in complex scenarios [4]. Combined with V2X communication, these systems enable real-time obstacle sharing and trajectory adjustment, improving both safety and efficiency.

Advanced path planning algorithms have been widely used to enable efficient routing in complex, unstructured environments. Lam et al. reviewed trajectory planning for autonomous excavators, emphasizing energy-efficient, collision-free paths validated through simulations in ROS and Gazebo [5]. Their findings support the relevance of adaptive, energy-aware planning in V2X-enabled mining traffic systems operating under similarly dynamic conditions.

Together, these studies highlight the value of V2X-enhanced coordination and intelligent planning algorithms for next-generation mining traffic systems. Building on this foundation, the proposed system combines real-time communication, graph-based planning, and multi-objective optimization to meet the evolving demands of autonomous fleets.

3. Problem description and method framework

Mining sites are dynamic environments where multiple autonomous and semi-autonomous machines operate concurrently. Efficient traffic management requires optimized routing, collision avoidance, and delay minimization. The proposed framework integrates V2X communication with traffic control strategies to address these challenges.

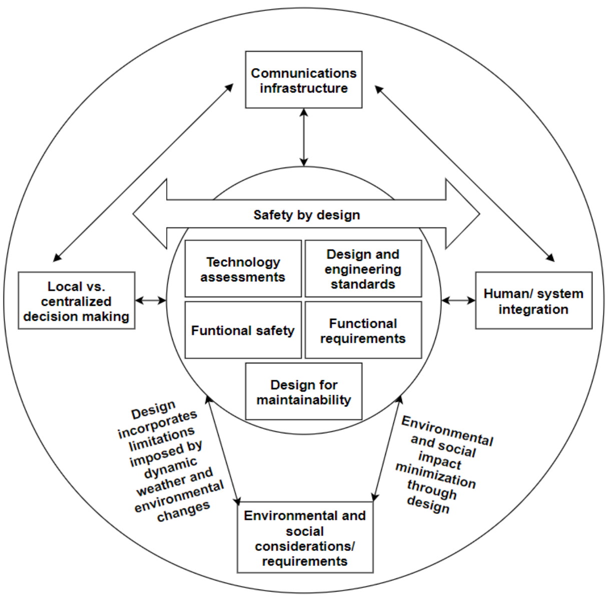

Figure 1. *Standard design for operational communications*

Figure 1 outlines key components of a V2X-enabled communication system, including safety-by-design, technology evaluation, compliance with engineering and safety standards (ISO 26262), and considerations for maintainability and environmental impact.

3.1. Requirement analysis

Requirement analysis is critical in autonomous mining system development to ensure safe and efficient operation. It begins with identifying system-level needs, particularly communication requirements such as DSRC (Dedicated Short-Range Communication) and C-V2X (Cellular V2X), which offer low-latency, high-reliability connectivity between vehicles and infrastructure.

To evaluate system behavior before field deployment, multi-agent simulations are used. These simulate interactions between mining machines under various traffic conditions, considering machine speed, braking capability, and communication latency. The following Equation (1) describes the probability of collision based on communication delay D and braking distance B:

$$P_c = \alpha \cdot e^{\beta D} + \gamma B \quad (1)$$

where α, β, γ are constants determined through simulation [6]. In mining operations, communication delay may be exacerbated by terrain induced signal attenuation, while braking distance varies with machine type such as haul trucks, dozers or loaders and load weight.

3.2. Road design standards for traffic management

In mining operations, safe traffic flow depends on compliance with road design standards. Western Australian guidelines require single-lane roads to be at least 1.5 times the width of the largest vehicle, and double-lane roads 3.5 times. As illustrated in Figure 2, design elements such as safety berms, drainage width, and cross fall are considered separately and not included in the road width. If standard widths cannot be met, alternative safety measures-such as speed limits, give-way rules, or signage-must be applied. Segments divided by barriers are treated as single lanes.

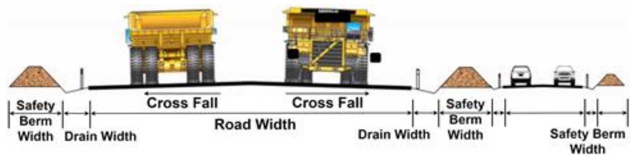

Figure 2. *Road design standards for traffic management in Western Australia*

Standardized road dimensions are essential for V2X-based traffic management. They enable precise path planning, reliable communication, and effective collision avoidance among autonomous machines, ultimately enhancing operational safety and traffic efficiency.

3.3. System architecture design

The proposed traffic management framework is structured as a four-layer system: Perception, Communication, Decision-Making, and Control. This research focuses on the Communication and Decision-Making layers, which are central to enabling real-time coordination and intelligent routing in autonomous mining operations.

The Communication Layer facilitates continuous data exchange between autonomous vehicles and a central control system. A hybrid V2X approach is adopted, combining DSRC for low-latency safety messages and C-V2X for wide-area updates and command dissemination. The central system tracks vehicle positions, statuses, and environmental inputs, issuing dynamic routing updates and supporting emergency controls such as remote stop, thereby maintaining safe and efficient operation across the site.

The Decision-Making Layer is responsible for motion planning and coordination. It uses a multi-objective optimization algorithm to minimize a composite cost function, as defined in Equation (2):

$$J = w_1 T + w_2 S + w_3 E \quad (2)$$

where T denotes travel time, S is a safety score, E represents energy consumption, and are weight factors defined according to operational requirements, as described in [7]. These weights are calibrated through a structured process that includes expert input, regulatory standards, and sensitivity analyses performed in simulation. In high-risk operational contexts, the weight assigned to safety (w_2) is increased to prioritize collision avoidance and risk mitigation. Conversely, operations focused on maximizing efficiency assign greater emphasis to minimizing travel time by increasing w_1.

This study adopts a weighted-sum approach due to its computational efficiency. To enhance the model's capacity for handling trade-offs among competing objectives, future work will incorporate Pareto front-based methods and evolutionary algorithms such as the Non-dominated Sorting Genetic Algorithm II (NSGA-II). These approaches can generate a diverse set of optimal solutions, enabling more adaptive and context-sensitive decision-making in autonomous mining operations.

Vehicles continuously share trajectory plans through V2X communication, enabling coordinated maneuvers such as platooning, right-of-way negotiation, and hazard avoidance. This collaborative mechanism enhances both safety and efficiency by extending situational awareness beyond local perception capabilities.

3.4. System integration and testing

System integration involves implementing V2X communication modules within autonomous mining machines. This includes installing hardware components, such as on-board units, and configuring communication protocols to ensure secure, low-latency, and reliable data exchange across the fleet. The testing process is divided into two main phases:

Simulation testing: A digital twin of the mining site is used to simulate realistic traffic conditions involving autonomous mining vehicles. V2X-enabled machines are tested for safe navigation, effective path planning, and real-time coordination. Key performance indicators (KPIs), including communication latency, packet delivery rate, and collision rate, are monitored to evaluate system responsiveness and safety in a controlled environment.

Field testing: The integrated system is deployed in a real mining environment to assess performance under varying operational conditions, such as different machine densities, terrain types, and weather variations. Performance is quantified using KPIs, such as

$$KPI = \frac{1}{N}\sum_{i=1}^{N}(d_i + c_i) \quad (3)$$

where d_i is the measured communication delay, c_i is the recorded collision instance, and N is the total number of V2X messages or interactions observed during the site tests [8].

3.5. Maintenance and monitoring

Effective maintenance and monitoring are essential for ensuring the reliability of V2X-based autonomous mining systems. This involves continuously collecting data from V2X modules, including message transmission rates, machine locations, and error logs. These data streams are analyzed to detect anomalies, assess hardware conditions, and schedule preventative maintenance. Instead of relying on complex machine learning techniques, this research adopts a statistical reliability model to support predictive maintenance planning. The system reliability over time is represented as $R(t) = e^{-\int_0^t \lambda(\tau)d\tau}$, where $R(t)$ is the system reliability at time t, and $\lambda(\tau)$ is the failure rate function derived from historical system performance and component degradation data. This function supports predictive maintenance by enabling estimation of system availability and informing optimal maintenance scheduling to minimize unexpected failures and downtime.

4. V2X communication model

The V2X communication model is a critical component of the proposed traffic management system, enabling real-time exchange of essential information between vehicles and a centralized control unit. This model operates using a publish-subscribe architecture, where each vehicle functions as both a publisher and a subscriber, maintaining a high-frequency communication rate of 10 Hz.

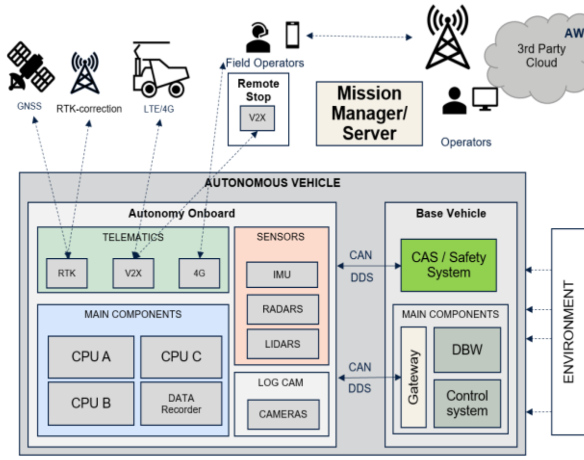

Figure 3. *Autonomy System Architecture.*

4.1. Framework architecture

A detailed flowchart illustrating the V2X-based traffic management system is shown in Figure 3. The flowchart visualizes the continuous data exchange between vehicles (publishers) and the central control unit (subscriber). It highlights the sequence of traffic monitoring, path planning, collision detection, and optimized path distribution. The diagram clearly represents how vehicles send state information, how the control unit processes this data, and how updated instructions are communicated back to the vehicles.

Publishers: Each vehicle periodically broadcasts its state information, including position, speed, and direction. These updates are sent at a frequency of 10 Hz, providing the central controller with continuous insights into each vehicle's state.

Subscribers: The centralized control unit acts as a subscriber, receiving and processing these state updates. This unit maintains a complete and up-to-date view of all vehicle states, allowing it to effectively manage traffic.

4.2. Mathematical formulation

The mining site is modeled as a directed graph *G=(V,E)*, where *V* represents the set of nodes (locations) and *E* represents the set of edges (paths). This representation allows for efficient modelling of the vehicle's navigational environment using graph-based search algorithms.

Each autonomous vehicle is defined by a state vector $S_i(t) = (x_i(t), y_i(t), v_i(t), \theta_i(t))$ where x_i, y_i are spatial coordinates, v_i is the velocity, and θ_i is the orientation of vehicle i. These states are updated in real-time through V2X communication at 10 Hz, enabling global coordination of positions, speeds, and orientations across the fleet.

Objective Function: The optimization problem aims to minimize a weighted objective function over all N vehicles $\min_{u_1,\dots,u_N} \sum_{i=1}^{N}(\alpha T_i + \beta R_i + \gamma E_i)$ where T_i is the estimated travel time for vehicle i, R_i is a risk factor based on proximity to other vehicles and obstacles, E_i is the estimated energy consumption, and α, β, γ are weight coefficients derived from empirical values or reference [7] to balance priorities among travel time, safety, and efficiency.

Constraints: The system operates under the following constraints.

- Collision avoidance: For all $i \neq j$, vehicles must maintain a minimum safe distance $\| p_i - p_j \| \geq d_{safe}$, where $p_i = [x_i, y_i]$.

- Speed limits: $v_{min} \leq v_i(t) \leq v_{max}$

- Edge connectivity: Movement is restricted to valid edges $(u, v) \in E$ in the graph.

Path Planning Algorithm: To adapt to dynamic environments, the system incorporates D* Lite, an extension of A* that recalculates optimal paths when new information becomes available. Unlike static Dijkstra or A* algorithms, D* Lite supports continuous re-planning in response to obstacle updates or traffic congestion, efficient reuse of previous search trees to reduce computation, real-time navigation through changing terrain and node availability.

V2X communication provides the dynamic updates that trigger the D* Lite re-planning process, allowing vehicles to avoid congested areas, respond to hazards, and reduce travel time under uncertain and changing conditions.

4.3. MATLAB-based V2X traffic simulation

In this section, we present the simulation of the Vehicle-to-Everything (V2X) communication model, which was conducted using MATLAB and a custom simulation framework tailored for autonomous mining operations. The mining site is represented as a directed graph *G=(V,E)*, where vertices *V* correspond to physical locations such as loading zones, dump sites, and edges *E* represent the navigable paths between them.

The objective of the simulation is to evaluate the behavior of autonomous vehicles navigating a mining site under dynamic traffic conditions, guided by real-time V2X communication and D* Lite-based path planning. The simulation setup models a mining site as a graph where nodes represent locations, and edges represent the paths that autonomous vehicles will traverse. Each vehicle is characterized by a state vector, which includes its position (x and y in meters), velocity (v in meters per second), and orientation (θ in radians). These vehicles communicate their state data at a frequency of 10 Hz using V2X technology, ensuring real-time updates of vehicle positions, speeds, and orientations. This communication enables dynamic decision-making, where each vehicle adjusts its path based on the real-time state of surrounding vehicles and the environment.

In this MATLAB-based simulation, graph representations model the environment, and dynamic vehicle behaviors are simulated to model traffic flow. A central controller processes the V2X data, updates vehicle states, and adjusts paths to ensure minimal travel time and safety for all vehicles involved. Figure 4 illustrates the mining site graph representation, where nodes are locations, and edges represent the paths autonomous vehicles travel along. The figure provides a clear view of how the environment is structured for the simulation.

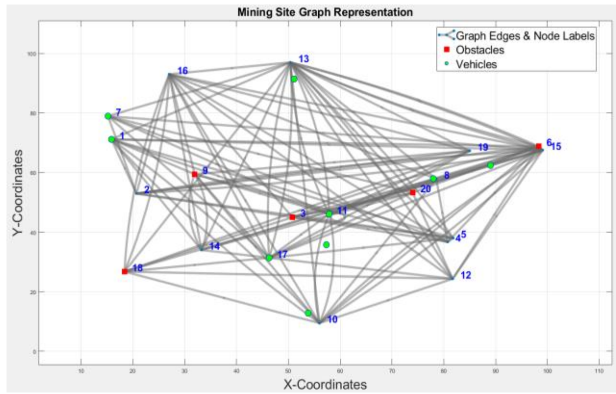

Figure 4. *Mining site graph representation*

The simulation, conducted over 1,000 time steps at 0.1-second intervals, involved 20 autonomous vehicles continuously transmitting their position, speed, and heading to a central controller for dynamic traffic management. Key performance metrics-including average travel time, collision rate, and traffic flow efficiency-were monitored throughout the simulation. The system achieved an average travel time of 100.00 seconds, a low collision rate of 0.88%, and maintained high traffic flow efficiency despite the presence of five obstacles. These results, visualized in Figure 5, demonstrate the system's effectiveness in optimizing routing and ensuring safe, coordinated movement within a complex mining environment.

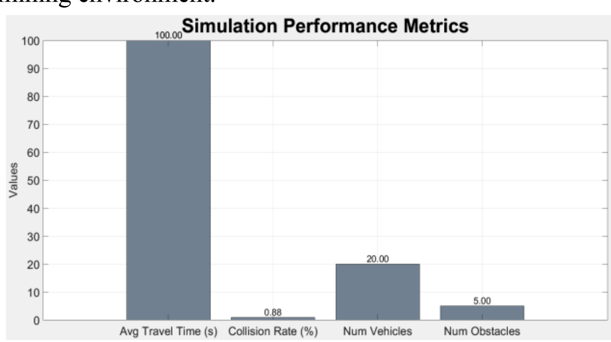

Figure 5. *Simulation performance metrics*

The V2X-enhanced simulation (Figure 6) demonstrates the effectiveness of combining D* Lite with real-time communication, enabling vehicles to adapt quickly to dynamic environments with minimal delays and virtually no collisions. D* Lite's responsiveness to new data allows the system to sustain high efficiency despite environmental changes, outperforming static planners like Dijkstra’s or A* by reducing computational overhead and supporting seamless adaptation. Additionally, the V2X-enabled collision avoidance mechanism enhances operational safety by enabling vehicles to re-plan paths in response to proximity risks, maintaining smooth traffic flow even in high-density zones.

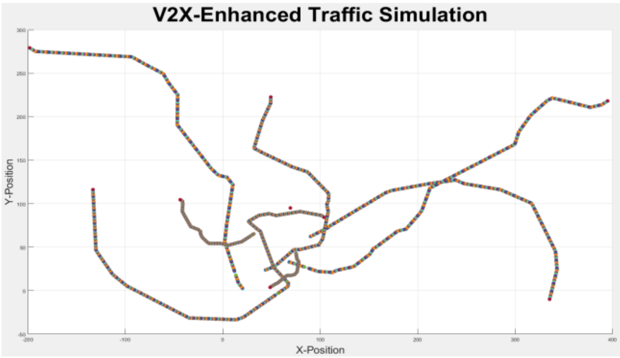

Figure 6. *V2X-enhanced traffic simulation*

5. Decision-making and planning

Decision-making and planning in the proposed V2X-based traffic management system are organized hierarchically, ensuring both global coordination and local adaptability. This hierarchical model is divided into two key levels:

- Global path planning: The central controller employs D* Lite, a dynamic extension of A*, for global route generation. D* Lite adapts to real-time traffic conditions, incorporating V2X data to update vehicle paths as obstacles or traffic densities evolve. This ensures continuous minimization of travel time while avoiding congested or blocked paths.

- Local path planning: Each vehicle is equipped with an independent local planner using the Dynamic Window Approach (DWA). This algorithm samples possible velocities and headings within the vehicle’s dynamic constraints, evaluates trajectory feasibility with respect to current obstacles and other vehicles, and selects the safest and most efficient local path that aligns with the D* Lite global route.

5.1. Optimization algorithm

D* Lite minimizes travel costs based on dynamically assigned edge weights, incorporating factors such as physical distance, congestion levels, and risk scores like proximity to obstacle zones. It efficiently handles dynamic updates-such as new obstacles or traffic congestion-by incrementally repairing previously calculated paths instead of recalculating from scratch. This makes D* Lite particularly suited for V2X-based traffic systems, where frequent updates to route conditions are expected.

For local path optimization, the DWA method generates candidate trajectories in the velocity space based on the vehicle's current state. Each trajectory is evaluated against multiple criteria, including kinematic and dynamic feasibility, obstacle clearance, path smoothness, curvature, and alignment with the global route. The trajectory with the highest composite score is selected at each control cycle, ensuring responsive and safe navigation in dynamic environments.

Collision prediction is supported through continuous V2X communication, which monitors vehicle states-position, velocity, and heading-to maintain safe inter-vehicle distances. A minimum safety distance is computed using Equation (4):

$$d_{safe} = v \times t_r + \frac{v^2}{2a} \quad (4)$$

where v is the vehicle speed, t_r is the system reaction time, and a is the deceleration rate. If any vehicle approaches within this threshold, the system triggers immediate local re-planning to prevent collisions.

5.2. Simulation results

The decision-making and planning model was evaluated in a simulated mining environment featuring 20 autonomous mining vehicles operating on a custom-designed mining map (Figure 7). Leveraging V2X communication for enhanced coordination, the proposed system demonstrated substantial performance improvements over a baseline traffic management approach. Key simulation outcomes are summarized below:

- Average travel time reduction: The V2X-enhanced system, which incorporates D* Lite for global path planning, achieved a 27.5% reduction in average travel time, indicating improved routing efficiency and minimized delays across the mining site. In contrast, the baseline system achieved only a 10% reduction.

- Collision risk reduction: Through the integration of V2X communication and the DWA for local obstacle avoidance, the system recorded a 42.7% decrease in collision risk. This significant improvement reflects the effectiveness of proactive maneuvering and coordinated decision-making, compared to 25% with the baseline.

- Traffic flow efficiency: The centralized controller, continuously updated via V2X data exchange, successfully balanced traffic loads and mitigated congestion in critical zones. This led to an 86.3% improvement in traffic flow efficiency, substantially higher than the 70% efficiency achieved by the baseline system.

- System stability: The V2X-enabled coordination improved system stability by 32.5%, as measured by reductions in speed variance and improved trajectory predictability. This contributes to smoother traffic dynamics and fewer disruptions during high-density operations. The baseline achieved only 5.5% improvement.

- Fuel efficiency improvement: Coordinated routing and speed regulation allowed the system to achieve a 23.2% gain in fuel efficiency, reducing unnecessary acceleration and idling. In contrast, the baseline scenario yielded only 5.5% improvement.

- Energy consumption reduction: Optimized paths and smoother acceleration profiles enabled by V2X communication reduced overall energy consumption by 15.7%, compared to 10.2% with the baseline system, supporting both cost reduction and environmental goals.

These results collectively demonstrate the effectiveness of the proposed V2X-based decision-making and planning model in advancing safety, operational efficiency, and sustainability within autonomous mining fleet operations.

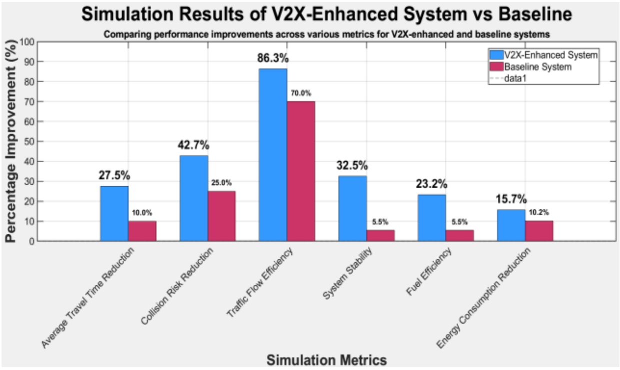

***Figure** 7. Result of V2X-Enhanced System Simulation*

6. Discussion

The proposed V2X-based traffic management system significantly enhanced the safety and efficiency of autonomous mining operations. By modeling the mining site as a directed graph, the system applied advanced path-planning algorithms-most notably D* Lite-for adaptive, real-time routing. Vehicles communicated via V2X at 10 Hz, enabling timely updates on state information and collaborative responses to traffic density, obstacles, and environmental changes.

Simulation results showed marked improvements: a 27.5% reduction in average travel time, a 42.7% reduction in collision risk, and an 86.3% improvement in traffic flow efficiency compared to the baseline. Advanced performance indicators also improved, including a 32.5% gain in system stability, 23.2% increase in fuel efficiency, and a 15.7% reduction in energy consumption. These outcomes highlight the system's ability to adapt routes, regulate speed, and coordinate behavior proactively based on collective awareness.

However, practical challenges remain. V2X communication reliability may be affected by environmental interference. D* Lite, while effective, may face limitations in highly dynamic or uncertain scenarios. Furthermore, system scalability must be addressed for deployment in larger, more complex fleets.

Future work will focus on robust communication protocols, distributed control architectures, and advanced multi-objective optimization methods like NSGA-II. Real-world testing with industry partners will be critical to validate system performance and support broader deployment in operational mining environments.

7. Conclusion

This study presented a V2X-enabled traffic management system for autonomous and semi-autonomous mining vehicles, integrating D* Lite for global path planning and DWA for local obstacle avoidance. Real-time V2X communication enabled improved coordination, safety, and responsiveness among vehicles. Simulation results demonstrated significant benefits, including a 27.5% reduction in travel time, a 42.7% decrease in collision risk, and an 86.3% improvement in traffic flow efficiency. Additional gains in system stability (32.5%), fuel efficiency (23.2%), and energy consumption reduction (15.7%) further validate the system's practical potential.

Future development will focus on enhancing communication resilience, scaling the architecture to support more complex fleet interactions, and implementing advanced multi-objective optimization methods. Collaborative testing with industry partners will be vital to validate the system in real-world mining operations. Overall, the proposed V2X framework offers a promising path toward safer, more efficient, and sustainable autonomous fleet management in mining and related domains.

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