

Priority Pathway Design for Emergency Rescue Vehicle Route Planning Algorithms

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ABSTRACT

The response efficiency of urban emergency rescue systems is critical to public safety, and path planning algorithms are key technologies for ensuring the rapid passage of rescue vehicles. Conventional navigation algorithms cannot meet the extreme time-sensitivity requirements and highly disturbed road network characteristics inherent in rescue missions. This paper focuses on optimising priority routes for emergency rescue vehicles. By analysing the dynamic attributes of rescue vehicles under abnormal driving conditions, it dissects the nonlinear coupling mechanism between rescue vehicles and dynamic traffic flow parameters, revealing the formation mechanism of secondary congestion in road networks under forced-priority strategies. Traditional static algorithms exhibit significant response delays to sudden traffic conditions and rely on single-dimensional decision-making. This paper proposes an optimisation method that integrates global path search with localised signal control, introducing a dynamic evasion coordination mechanism for non-emergency vehicles. This provides a theoretical foundation and implementation pathway for building adaptive, innovative emergency transportation systems.

KEYWORDS

Emergency rescue; Vehicle path planning algorithm; Priority passage

1 Introduction

As urban road network structures grow increasingly complex and motor vehicle ownership continues to rise, traffic congestion has become a structural issue affecting urban operational efficiency. Emergency rescue missions demand near-demanding responsiveness from road transportation systems. However, an inherent contradiction exists between limited spatiotemporal resources and the sudden nature of rescue demands, rendering traditional traffic management approaches inadequate for handling high-priority, highly dynamic passage tasks. Most existing path planning frameworks are built upon equilibrium theories designed for routine users. Although regulations grant priority to special vehicles, this privilege often fails to translate into actual travel speed when physical congestion occurs. Emergency rescue path planning is not merely a shortest path search problem but a dynamic optimisation challenge involving multi-agent games and complex constraints. Forced intervention by rescue vehicles disrupts the existing equilibrium of traffic flow. Without intelligent algorithms for global coordination, this can easily trigger cascading network failures, where locally optimal rescue solutions become globally suboptimal for traffic flow. Current research predominantly focuses on isolated algorithmic improvements at single levels, lacking comprehensive integration across macro-level path decision-making, micro-level signal control, and vehicle coordination for avoidance manoeuvres. Deeply exploring priority passage mechanisms in emergency rescue scenarios, analysing traffic flow evolution patterns, and developing optimisation algorithms with real-time responsiveness hold significant academic and practical value for enhancing urban emergency management and ensuring unimpeded access to lifelines.

2 Foundational Scenario for Priority Path Planning of Emergency Response Vehicles

2.1 Special Requirements for Path Planning Under Emergency Vehicle Operation Characteristics

Emergency response vehicles exhibit distinct operational states during critical missions, differing significantly from regular traffic flow. Extremely high speeds and nonlinear trajectories characterise them. This unique operational mode requires rapid spatial displacement within minimal time frames, often necessitating violations of conventional traffic regulations—such as lane crossing, counterflow driving, and excessive speeding. Consequently, path planning mathematical models cannot rely solely on road design speeds or static impedances; they must incorporate considerations of vehicle dynamic limits and road geometric constraints. Large rescue vehicles face hard constraints on turning radius, road load capacity, and clearance height, necessitating algorithms capable of precisely filtering road network micro-physical attributes^[1]. Additionally, the urgency of rescue missions prioritises the reliability of passage. Thus, planned routes must not only minimise theoretical distance but also incorporate fault tolerance to mitigate collision risks from unconventional driving manoeuvres, ensuring the safe and continuous deployment of rescue forces to target areas.

2.2 Mechanism of Dynamic Road Network Traffic Flow Parameters on Path Decision-Making

Urban traffic networks are inherently time-varying, nonlinear, complex fluid systems where instantaneous fluctuations in traffic flow parameters decisively influence emergency vehicle path decisions. When traffic density on a segment approaches critical saturation thresholds, the spatio-temporal distance between vehicles becomes severely compressed, forming highly viscous queued traffic flows. In this state, evasion space for non-emergency vehicles is virtually locked out. If path decisions fail to capture these dynamic characteristics in real time, emergency vehicles are easily guided into seemingly short but impassable congestion deadlocks. Traffic flows exhibit wave propagation effects, where upstream signal interruptions or downstream accident disturbances propagate as shock waves across the network. Consequently, path planning mechanisms must be built upon dynamic predictions of parameters like flow rate, speed, and occupancy. Understanding the spatiotemporal evolution logic of congestion enables the identification of flowing green waves with sustained passability at the macro level, rather than relying solely on lagging historical traffic snapshots.

2.3 Current Application Status of Vehicle Path Planning Algorithms in Emergency Response Scenarios

Path planning algorithms currently applied in emergency domains largely follow the logic of classical graph theory. While effective for static or low-dynamic road networks, their limitations become increasingly apparent in highly uncertain emergency scenarios. Mainstream applications typically consider only the average travel time from historical data, neglecting the non-repeatable and transient nature of traffic conditions during emergencies. While some systems incorporate real-time traffic navigation, they lack deep weighting for emergency vehicles' special rights in data fusion processing. Consequently, planned routes may avoid conventional congestion but fall into passive delays caused by mismatched traffic signal phases. Beyond these limitations, existing algorithms predominantly treat emergency vehicles as isolated passive nodes, lacking deep logical interaction with intelligent traffic signal systems. This prevents active coordination between vehicles and road infrastructure^[2]. Such unidirectional path guidance models constrain rescue efficiency improvements, as they are limited by the algorithms' insufficient environmental perception and control capabilities.

3 Challenges in Planning Priority Routes for Emergency Vehicles

3.1 Forced Priority Causes Secondary Congestion Risks in Social Traffic Flow

In implementing priority passage, algorithms often favour forcibly clearing the road ahead. This absolute deprivation of right-of-way inevitably causes severe disruption to social traffic flow. When planning algorithms implement all-red signals or force civilian vehicles to stop, the continuous flow of traffic is abruptly severed, creating high-density localised queues. Such artificially induced traffic interruptions, if occurring at critical network junctions, can easily trigger cascading failures, leading to severe regional paralysis stemming from a single rescue mission. Congestion peaks often fail to dissipate rapidly after emergency vehicles pass, sometimes leading to prolonged recovery periods due to excessive backlogs. Current algorithm designs generally lack quantitative assessments of such negative externalities. By pursuing single-objective optimisation, they overlook system-wide robustness, causing local priority strategies to undermine the network's self-regulating capacity. This results in priority passage costs exceeding the urban transportation system's carrying capacity threshold.

3.2 Traditional Algorithms Exhibit Real-Time Response Latency to Dynamic Emergencies

Emergency rescue missions often occur under conditions of high environmental entropy, where road conditions can change instantaneously due to accident propagation, sudden weather shifts, or temporary traffic controls. However, traditional path planning algorithms inherently suffer from time delays within the closed-loop process of data collection, transmission, computation, and command issuance. Models predominantly rely on data updates from discrete time intervals. When real-world traffic changes occur faster than data refresh rates, the information algorithms on which they depend become obsolete. This disconnect between information and reality can render the planned optimal route impassable by the time the vehicle arrives. Particularly during periods of intense flow variation, such as morning and evening rush hours, even minor computational delays can mean missing the optimal passage window^[3]. Existing algorithm architectures predominantly rely on centralised computation. The latency introduced by massive data processing often renders route solutions merely as references rather than precise tactical instructions for real-time driver guidance, severely limiting the accuracy of rescue operations.

3.3 Complex Decision Dimensions for Optimal Priority Path Selection Under Multi-Objective Constraints

Emergency rescue path planning is fundamentally a highly multidimensional multi-objective optimisation challenge, with its decision-making process facing a complex system of mutually conflicting constraints. Algorithms must not only minimise time costs but also ensure path smoothness for casualty safety, account for the geometric clearance requirements of large vehicles, and minimise disruptions to public traffic. These objectives often involve nonlinear conflicts: wide main roads offer the fastest speeds but cause maximum traffic disruption. In contrast, side roads cause less disruption but may fail to meet strict passage constraints. Mathematically, as the number of road network nodes increases, this problem exhibits exponential growth in computational complexity. Existing algorithms often simplify the model using linear weighting methods when addressing such issues. This approach readily masks inherent contradictions between sub-objectives, leading to flawed decisions in critical dimensions. Rapidly locating optimal solutions within a solution space interwoven with multiple complex and soft constraints represents a significant technical challenge.

4 Optimisation Design of Priority Path Algorithms for Emergency Rescue Vehicles

4.1 Global Priority Path Search Strategy Based on Enhanced Intelligent Algorithms

Addressing the shortcomings of traditional algorithms—prone to local optima and slow convergence—the core of optimisation design lies in establishing an intelligent search strategy with a global perspective. This strategy moves beyond static graph search by integrating the positive feedback of ant colony algorithms with the worldwide optimisation capabilities of genetic algorithms. During the initial algorithmic phase, historical data is used to construct a probabilistic graph model, enabling rapid elimination of invalid regions to reduce the solution space ^[4]. Dynamic volatility factors and pheromone update mechanisms are then incorporated, allowing the algorithm to swiftly respond to minor shifts in traffic flow without rigidly following obsolete pheromone trails. Furthermore, it possesses predictive capabilities: while computing the current optimal solution, it simulates the short-term evolution of traffic flow to anticipate potential congestion nodes along the route. After this dual temporal-spatial search, the algorithm dynamically plans a robust path globally—one that resolves immediate issues while accommodating future uncertainties—ensuring rescue vehicles remain on the path of least resistance.

4.2 Local Priority Passage Design at Intersections Under Signal Coordination

Intersection throughput often represents the micro-bottleneck determining rescue success. Consequently, algorithm optimisation must extend to the underlying logic of signal control systems. This design moves beyond passively waiting for vehicles to trigger sensors, instead dynamically calculating arrival time windows at intersections based on real-time vehicle dynamics parameters. The system preemptively adjusts downstream signal phases using strategies like green wave extension or early red light termination to clear queued vehicles precisely before the emergency vehicle arrives. This control strategy demands extremely high real-time computational capability, requiring the construction of a spatiotemporal resource occupancy model for single intersections to calculate the green light duration needed for precise clearance. Simultaneously, to prevent excessive disruption of lateral traffic flows, the signal recovery mechanism should employ a smooth transition mode. After the emergency vehicle passes, cycle durations are gradually adjusted to distribute delays across subsequent cycles. This ensures absolute priority at the local intersection while preventing a catastrophic decline in overall intersection service levels.

4.3 Dynamic Evasion Coordination Mechanism for Social Vehicles Considering Network Recovery

Relying solely on the unilateral advancement of emergency vehicles cannot overcome physical space constraints. A dynamic evasion coordination mechanism is necessary for social cars. This mechanism addresses the dilemma of having right-of-way but insufficient space by utilising vehicle-to-everything (V2X) technology to send precise tactical evasion instructions to preceding social cars, rather than ambiguous stop signals. The algorithm must construct a micro-level vehicle game model, dynamically evaluating each civilian vehicle's contribution to widening the rescue corridor to form a fluid virtual dedicated lane. Concurrently, this mechanism prioritises the network's self-healing capability—guiding disorganised civilian vehicles back to standard traffic patterns after emergency vehicles pass ^[5]. By establishing this collaborative model, social vehicles are transformed from obstructions into facilitators. This fundamentally mitigates disorderly interference within mixed traffic flows, enabling the harmonious coexistence of rescue operations and public mobility while minimising long-term disruptions to the road network's order.

5 Conclusion

Emergency vehicle priority route planning represents both an advancement in algorithmic technology and a transformation in the logic of urban traffic resource allocation. Through analysing the unique requirements of emergency response scenarios and the characteristics of traffic flow dynamics, this paper reveals that traditional static planning approaches become ineffective when applied to highly dynamic road networks. Relying solely on path search methods is increasingly inadequate for meeting the practical demands of modern emergency response operations. A comprehensive solution must be established that integrates global dynamic search, micro-level signal coordination, and cooperative avoidance by non-emergency vehicles. Algorithmically integrating macro-level decision-making with micro-level control ensures unimpeded access to lifelines while minimising disruptions to the broader transportation system and mitigating secondary congestion risks.

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