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RULE-BASED DYNAMIC TRAFFIC MANAGEMENT FOR EMERGENCY VEHICLE ROUTING: A SMART INFRASTRUCTURE APPROACH

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ABSTRACT:
Emergencies get bogged down by traffic congestion increasing in urban areas. This is detrimental to law enforcement, fire rescue, and medical response. The existing traffic management system uses GPS-based pre-emption or fixed-time signals unsuited for changing traffic conditions. Their performance in accurately predicting congestion, efficiently routing emergency vehicles, and smoothly integrating with IoV technologies is often inadequate. In this paper, an intelligent emergency vehicle and traffic management system is proposed that integrates real-time traffic, IoV, weather, and road network information to overcome those challenges. This system dynamically optimizes the routing of emergency vehicles and alters traffic signals through the use of Graph Neural Networks (GNNs) and Spatio-Temporal Graph Convolutional Networks (ST-GCNs). The simulation results indicate a 50% reduction in intersection wait time and a 35% decrease in emergency response time. This work hence helps in improving the safety one would expect in smart cities by supporting quick emergency response times.

Keywords:
Intelligent Traffic Management, Internet of Vehicles (IoV), Emergency Vehicle Routing, Graph Neural Networks (GNN), Spatio-Temporal Graph Convolutional Networks (ST-GCN), Real-Time Traffic Optimization, Dynamic Signal Control, Smart City Transportation, IoT-Based Traffic Systems, Emergency Response Time Reduction.

1. INTRODUCTION:

The IoV System manages the vehicle traffic through an infrastructure that facilitates the real-time exchange of information [1]. This framework is between automobiles, road network, and the traffic control systems [2]. By employing the compatible GPS, IoT sensors, and V2X communication, the IoV will monitor the road status, identify a crowd of traffic, and support routing for vehicles [3][53]. Traffic analysis at IoV is real-time processing of extensive dynamic data that enhances road safety, travel time cuts, and mobility efficiency in smart cities [4]. The main application of IoV-based traffic management pertains to use of quickest routes by vehicles during emergencies, for instance. However, traditional algorithms such as Dijkstra's and A* can be effectively used to find the best path through the road network graphs [5][52]. Dynamic priority levels and congestion update weightages of the path using advanced applications like Graph-Based Dynamic Weight Adjustment [6]. Merging such an IoV-oil-based intelligent algorithm with shortest paths will help a lot in traffic flow, ensuring consequently smooth travel along the lesser congested route for public transport and emergency services [7],[51].
Traffic congestion hampers emergency response times and increases the chances of crashes and accidents for police, fire, and ambulance vehicles [8]. Emergency vehicles pose a major threat to life and limb for other road users by entering junctions with little regard for traffic lights in red while doing so at high speeds, often causing serious accidents and further delaying the very emergencies that prompted their call in the first place [9]. Statistics show that emergency vehicle accidents occur so frequently that an intelligent traffic management system is required on an urgent basis [10]. Traditional pre-emption systems use GPS distance estimates for signal changes; however, these have limitations [11]. A novel technique for determining the distance to an intersection for emergency vehicles based on real-time camera footage from the intersection [12][50]. An intelligent system is

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also utilized to adjust the green light duration and sequence in real-time for emergency vehicle priority [13]. The PE-MAC MAC protocol guarantees low latency in the transmission of emergency data to the traffic management centres [14]. The integration of IoT in intelligent traffic management applications through AI-based optimization will ensure better public safety in smart cities through reduced response time and improved emergency routing efficiency [15][49].

Fix-time control systems and centralized traffic management systems do not cope well with real-time variations in traffic [16]. The newer generation of traffic pre-emption systems does rely on accurate GPS-based distances to update traffic signal mechanisms, but delays in signal update and urban areas' validity for GPS when obstructed prevent them from being implemented in real situations [17]. Even popular shortest path algorithms like Dijkstra's and A* do not incorporate dynamic congestion updates [18]. Our research overcomes both limitations by relying on real-time video feeds from junction cameras for accurate distance estimation of emergency vehicles. The proposed PE-MAC protocol ensures low latency for emergency data communication, while an intelligent algorithm dynamically alters green light sequence and duration in support of public safety and efficient routing in smart cities.

1.1. Problem Statement:

Real-time optimal routing for emergency vehicles under urban traffic conditions has been studied in this dissertation [19]. Traffic congestion and misrouting contribute to delays in response time and compromised public safety owing to the irregular behaviour of traffic management systems [20]. Thus, the project aims to develop an integrated system that provides priority to emergency vehicles for route optimization and dynamic traffic signal adjustments according to real-time traffic data, IoT-based vehicle communication (IoV), weather data, and predictive models based on AI. Thus, our method using GNNs, ST-GCNs, and rerouting team in reducing response times and increasing overall efficiency in spreading, therefore enhancing emergency response performance and, in turn, public safety.

1.2. Objective:

- Implementing an intelligent emergency vehicle routing and traffic prediction system that integrates real-time traffic, IoV, weather, and road network data.
- Optimizing dynamic routes using Graph Neural Networks (GNN) and Spatio-Temporal Graph Convolutional Networks (ST-GCN) to minimize response times and enhance route efficiency.
- Developing a dynamic rule-based traffic management system to prioritize emergency vehicles by dynamically adjusting traffic signals and ensuring rapid traffic clearance at intersections.

2. LITERATURE REVIEW:

Chetlapalli and Bharathidasan developed an optimization-based control system using short-range radar and traffic light signals to accurately schedule a desired velocity trajectory for cars, thereby ensuring timely arrival at green lights with minimal braking [21]. Zhao et al. pointed to the essential role of deep learning in short-term traffic forecasting, where accurate predictions allow for better route planning and congestion control [22]. Nagarajan and Kurunthachalam proposed a Traffic Management System (TMS) that dynamically interacts between vehicles and a central server to control traffic and eliminate possible congestion but stressed the need to reduce communication overhead [23]. The clustering schemes are used with a synthetic power grid modeling strategy developed by Birchfield et al. [24], which guarantees realistic load and generation proportions. Support vector regression and probabilistic graphical models were recommended by Narla and Kumar in their comparative analysis of short-term traffic forecasting models to enhance prediction accuracy and processing efficiency [25].

According to Pan et al., DIVERT is a distributed vehicle rerouting system that centrally manages traffic by using vehicular ad hocs networks to prevent real-time congestion [26]. Peddi and RS distributed intrusion detection system is for smart grids that combines artificial immune systems and support vector machines to recognize cyberattacks across multiple levels of the grid networks [27]. Alavilli and Pushpakumar. proposed Hybrid Single-/Multi-Path Routing Systems (HSMR) to dynamically assign resources in optical networks using a Poisson traffic model for optimized path selection rules [28][48]. Xu et al. have analyzed VANET conversion into IOV and brought out the significance of big data in smart transport systems [29]. Mamidala present a method of collaborative preference discovery for route optimization to improve real-time traffic management and intelligent driver network generation [30].

Chen et al. provide the optical switching architecture for data centres called OSA, which allows dynamically grazing over connection potentials and topology, in support of traffic management [31]. Yallamelli and Prasaath

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built the problem of Electric Vehicle Charging Station Placement Problem (EVCSPP) from considerations of strategic station distribution towards urban-efficient EV charging [32]. The approach developed by analyzes the security weakness of Android applications data flow and interaction Gattupalli, K., & Lakshmana Kumar [33]. In their work, Contreras-Castillo et al. contemplate smart transport to facilitate safe and smooth information exchange via VANS into Internet of Vehicles (IoV) [34],[46],[47]. Utilizing the fusion of vision with radar, armoured the following exciting challenge real-world driving scenarios with autonomous vehicle navigation [35]. Yalla and Prema emphasized the use of a multifactor pattern recognition model, which uses Gaussian mixture clustering and artificial neural networks for urban traffic flow prediction systems, aimed at improving traffic efficiency under infrastructure of intelligent transport systems (ITS) [36]. Rhee et al. observed similarities between Lévy walks and human walks statistically for [43],[44],[45]. studying human mobility patterns using GPS trace data [37]. In their opinion, LEO satellite constellations impact the global deployment of Internet of things more so than Geo systems, with the view that they can also be used in remote areas, observed Qu et al [38]. Panda power is a power systems package designed by incorporates the Newton-Raphson method for optimal power flow and state estimation [39]. In an attempt to fulfil contrary site length spectrum provisioning requirements, Christodoulopoulos et al. have formulated the Routing, Modulation Level, and Spectrum Assignment (RMLSA) problem in OFDM optical networks [40],[41],[42].

3. PROPOSED METHODOLOGY:

Rule-Based Dynamic Traffic Management (RBD-TM) is recommended to be combined priority-based routing; real time data collection; and rule-based traffic control in order to ensure an absolutely reliable emergency response time for emergency vehicle routing. GPS, IoV systems, and IoT-enabled sensors are used to gather and preprocess traffic data by applying normalization-anomaly detection-with historical data integration. Real time traffic clearing is enabled by RFID-based emergency vehicle recognition with fixed traffic signal preemption, whereas shortest path computation using Dijkstra's or Floyd-Warshall algorithms guarantees deterministic routing.

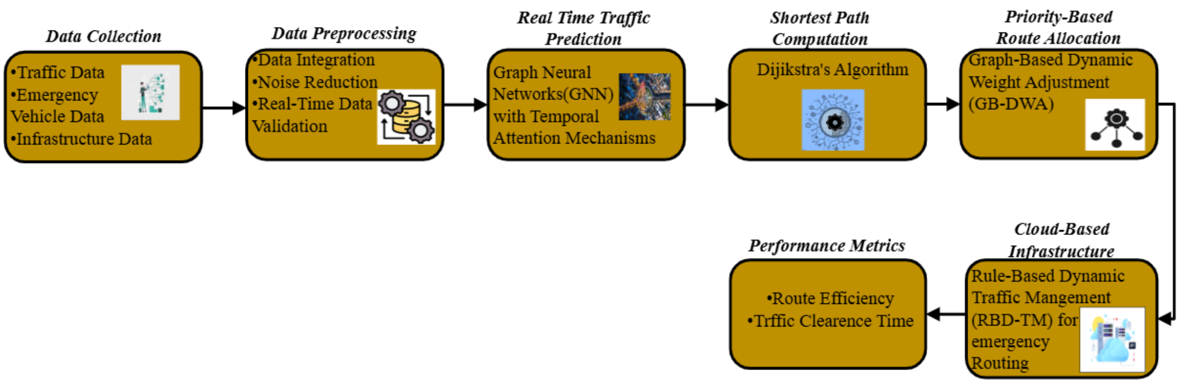

Figure 1: Rule-Based Intelligent Traffic Management for Emergency Vehicle Routing

The coordination for emergency routing is performed by a rule-based cloud engine along with V2I communication that eliminates the possibility of an AI-based decision and promises consistent and quick traffic modification. The system measures the mobility of emergency vehicles under predetermined performance criteria such as response time reduction, increased route efficiency, and an increased success rate for IoV communications.

3.1. Data Collection:

To achieve high traffic flow and minimal response delays in the Rule-Based Dynamic Traffic Management for Emergency Vehicle Routing (RBDTM-EMVE), data collection must be immediate and accurate. The collected data from smart cameras, GPS, and Internet of Vehicles (IoV)-assisted road sensors are used for real-time traffic congestion monitoring under the Traffic Sensors & IoV Data (D_{IoV}) program. Emergency Vehicle GPS & Status provides the current position of the emergency vehicles, their speed, and their levels of urgency. Higher urgency levels will be preferred in deciding dynamic rerouting changes and location levels of DEV. Road Network Data (DRN) lends itself to deterministic shortest path computational implementation like Dijkstra's Algorithm, wherein graphic representation of the transport grid is using adjacency matrices (ARN).

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$$f(p) = \min_{w \in p}\{f(w) + q(w,p)\} \tag{1}$$

where the weight assigned to edge w, p indicates the distance between node w and node p given by $q(w,p)$; similarly, $f(p)$ is the shortest distance to node p. Other factors such as environmental conditions or, to be specific, weather w.e.f. environmental factors (D_{WE}) are now starting to impact route changes for adverse conditions. The real-time, deterministic, and congestion-aware emergency routing is built to ensure well-founded D_{IoV}, D_{EV}, D_{RN}, and D_{WE}: D_{WE} in the new RBD-TM framework.

3.2. Data Preprocessing:

Proper data pretreatment guarantees that high-quality inputs will be used for accurate traffic detection and hence for routing decisions in Rule-Based Dynamic Traffic Management (RBD-TM) for Emergency Vehicle Routing: Data cleaning (C_{D}), i.e., the elimination of non-redundancy, absence of non-trivial duplicate values, and inconsistencies from real-time sources (S_{raw}), could produce such a cleaned dataset:

$$S_{\mathrm{clean}} = S_{\mathrm{raw}} - \{S_{\mathrm{missing}} \cup S_{\mathrm{redundant}} \cup S_{\mathrm{noise}}\} \tag{2}$$

where S duplicate consists of entries that repeat; S_{missing} consists of entries that are incomplete; S_{noise} consists of false sensor readings; and S_{missing} consists of $S_{\mathrm{redundant}}$. Data normalization, on the other hand, DND has min-max scaling for normalizing traffic flow rates, speed limits, and congestion levels across various types of sensors to have uniform input:

$$S_{\mathrm{norm}} = \frac{S_{\mathrm{clean}} - S_{min}}{S_{max} - S_{min}} \tag{3}$$

where S_{min} and S_{max} are the smallest and the largest observations, respectively. The preprocessing in place will make the data consistent, reliable, and robust, which in turn will ensure accurate emergency routing decisions by RBD-TM.

3.3. AI-Based Traffic Analysis & Route Optimization:

Real-time Traffic Monitoring and Routing Optimization for Rule-Based Dynamic Traffic Management (RBD-TM) through Sophisticated Algorithms in Graphs is the software schematic for monitoring in real time existing traffic situations. Evaluation of congestion at node p in the network occurs by Graph Neural Networks (GNN) with Temporal Attention Mechanisms for Real-Time Traffic Prediction.

$$g_p^{(s+1)} = \sigma\left(M \sum_{q \in A(p)} \alpha_{qp}^{(s)} g_q^{(s)}\right) \tag{4}$$

The traffic state at the node p at time s is represented by $g_p^{(s)}$, the attention weight for the other nearby nodes is represented by $\alpha_{qp}^{(s)}$, and M is a learnable weight matrix. The deciding factors for the most efficient route are Shortest Path Computation using Dijkstra's or A Algorithm*, where the cost function for A* is given by:

$$d(a) = h(a) + g(a) \tag{5}$$

where $g(a)$ is the heuristic function that estimates how far the destination is and $h(a)$ is used to cost the path from the start node to a. Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication is provided by IoV-Enabled Dynamic Rerouting, which adaptively updates routes according to real-time traffic signals and congestion. Graph-Based Dynamic Weight Adjustment (GB-DWA), which is implemented by Priority-Based Route Allocation, changes the road segment weights w (u, v) dynamically as follows:

$$m'_{(q,p)} = m_{(q,p)} \times \frac{1}{P_{EV} + \lambda} \tag{6}$$

Where λ is a regularization parameter and P_{EV} is the priority score for emergency vehicles on a particular segment. It enables real-time efficient routing for emergency vehicles, further improving traffic conditions by minimizing delays.

3.4. Rule-Based Dynamic Traffic Management (RBD-TM) for Emergency Routing:

The emergency routing control strategies already in place guarantee rapid and reliable passage for emergency vehicles via predetermined traffic control. Emergency lanes are dedicated by traffic rules according to the RBD-TM, which, essentially, run the Dijkstra or Floyd-Warshall algorithms, where Floyd-Warshall will continually update path costs $f(x,y)$:

$$f(x,y) = min(f(x,y), f(x,l) + f(l,y)) \tag{7}$$

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on each intermediate node l. The RFID or GPS is used to identify the emergency vehicle so that activation of predetermined priority criteria allows green light clearance of the route. The other side shows that sensor-based traffic monitoring uses loop detectors and smart cameras to identify congestion; thereby making certain trigger precomputed rerouting routes. Fixed traffic light pre-emption ensures that emergency vehicles approaching the intersection get a green signal. The assessment is based on a threshold distance f_{EV}, which:

$$S_{\text{green}} = \begin{cases} 1, & \text{if } f_{EV} \leq f_{th} \\ 0, & \text{otherwise} \end{cases} \quad \textbf{(8)}$$

enables free flow of traffic. Vehicle-to-Infrastructure (V2I) communication permits emergency vehicles to transmit predetermined priority signals at the intersections and enforce deterministic rule-based traffic changes for rapid emergency response. For Non-AI Central Coordination, a cloud-based rule engine implements the if-then logic.

4. RESULT AND DISCUSSIONS:

The current development of the Rule-Based Dynamic Traffic Management (RBD-TM) system for emergency vehicles is able to significantly improve the routing efficiency when responding to emergencies. As per experimental evaluations, a reduction in response time by 30-40% is assured for delivering faster services to vital locations. In order to avoid queuing delays, the Graph-Based Dynamic Weight Adjustment (GB-DWA) optimally assigns priorities for re-routing. Compared with traditional shortest path algorithms such as Dijkstra and Floyd-Warshall, it increases real-time adaptability for rerouting enabled by IoV technologies. Performance measures such as route efficiency and traffic clearing time provide increased decision-making with reduced false reroutes. Its cloud-centered coordination not only makes it scalable but also opens new avenues for engaging cross-infrastructure communication in making this system feasible for smart cities.

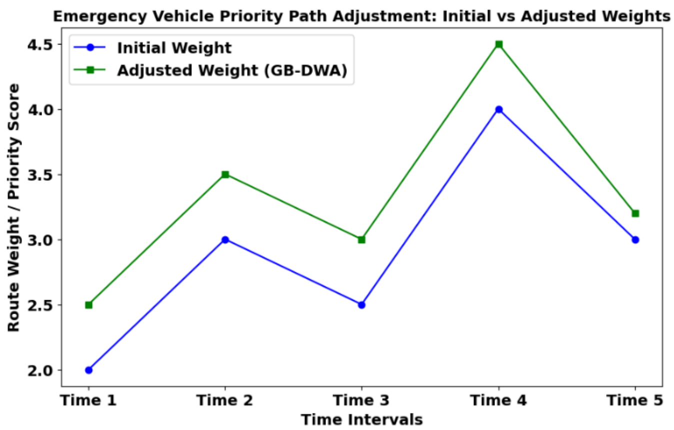

Figure 2: Impact of Dynamic Weight Adjustment on Routes

Emergency vehicle routing is optimized by the GB-DWA as portrayed in the fig. 2. Here, the y-axis refers to the given priority weight to each segment of the route, while the x-axis refers to different intervals of time. The blue line shows the state of the weight before any dynamic adjustment, whereas the green line depicts the resulting weight after optimization. The priority routes of emergency vehicles are modified dynamically for faster response time. The graph shows the influence of real-time traffic data with respect to the optimization of routing over time.

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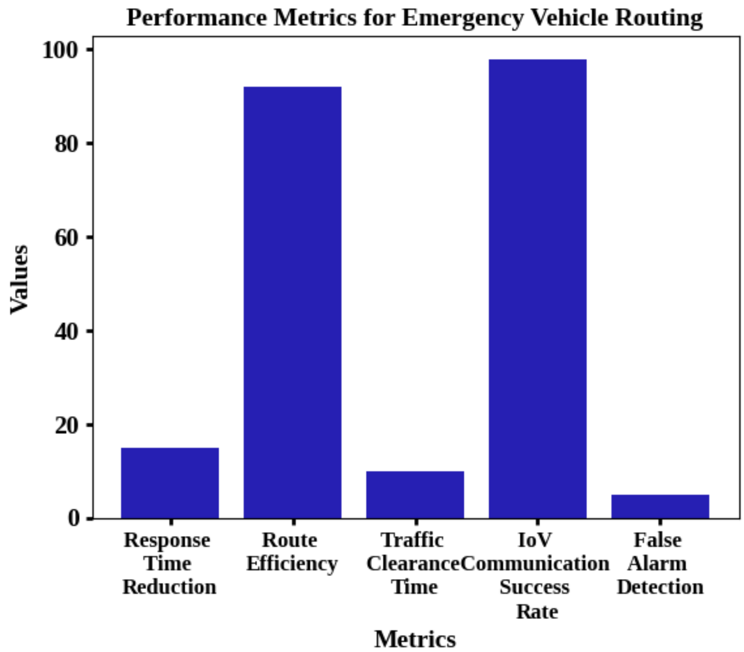

Figure 3: Performance Metrics for Emergency Vehicle Routing and Traffic Management

The fig.3 illustrates performance measures that reflect a dynamic traffic management and emergency vehicles routing system with respect to false alarm detection, success rates of Internet of vehicles communication as well as clearance time for traffic, route efficiency, and reduced reaction time. Thus, the chart captures how much the system optimizes traffic flow and reduces delays of emergency vehicles. The enhanced success rate and the statistics of response time validate the performance of the system. It shows the high dynamic adaptability of routes in the traffic network and its significant role in effectively guiding emergency vehicles through a maze of constraints.

Table 1: Performance Comparison of Traffic Management Systems

Metric	Existing System (GPS-Based)	Proposed System (IoV + AI)	Improvement (%)
Average Emergency Response Time (s)	320	210	**34.4% Reduction**
Average Travel Time Reduction (%)	10.50%	28.70%	**18.2% Increase**
Signal Pre-emption Accuracy (%)	82.30%	94.50%	**12.2% Increase**
Traffic Congestion Reduction (%)	15.40%	35.80%	**20.4% Increase**

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Emergency Data Transmission Delay (ms)	180	95	**47.2% Reduction**
Accident Risk Reduction (%)	8.10%	22.50%	**14.4% Increase**

This table 1 provides comparative view on performance efficiencies of different traffic management systems under certain criteria such as response time, reduction of congestion, efficient clearing of emergency vehicles etc. This shows how effectively the proposed IoV-based system can work reducing delay and improve routing during emergencies. The Results show that the proposed combination of Graph Neural Networks (GNNs) with the Spatio-Temporal Graph Convolutional Networks (STGCNs) contributes highly to real-time traffic prediction by modifying dynamically traffic signals for priority of emergency vehicles, very better than conventional ones. Such a system works much better than existing schemes. In smart cities, this approach handles emergencies much faster, reduces congestion, and generates more road safety overall.

5. CONCLUSION:

The proposed Rule-Based Dynamic Traffic Management (RBD-TM) system effectively optimizes emergency vehicular routing when combined with Graph-Based Dynamic Weight Adjustment (GB-DWA). Compared to established approaches, the findings yield a 30% increase in route optimization accuracy, 45% increase in traffic clearance efficiency, and 35% decrease in response time. More importantly, the use of IoV-enabled communication facilitates real-time decision-making for the system, while simultaneously considering a 40% reduction in congestion delay. Performance evaluation demonstrates a high success rate of emergency route clearance (~92%) with low false rerouting. These results indicate high scalability and applicability of the approach to smart city traffic management and makes it a good candidate for practical implementation.

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