REAL-TIME PATH OPTIMIZATION AND ADAPTIVE GREEN CORRIDOR FOR EMERGENCY VEHICLE PRIORITIZATION

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ABSTRACT

To better prioritize emergency vehicles in urban traffic, this research examines the efficacy of adaptive green corridor systems and real-time route optimization. The study compared the pre- and post-system-enabled states of travel in terms of time, congestion, signal coordination, algorithm performance, and response SLA compliance using a quantitative experimental research approach. The study took place in a city traffic environment with changeable congestion, many signalized junctions, and a wide variety of emergency occurrence types, such as heart crises, road accidents, fire rescue, police escorts, and more. The suggested system's flexibility and robustness may be realistically assessed using such a diverse combination. Through the use of incident management records, traffic monitoring systems, and GPS-based tracking, data for the research was gathered from 125 emergency response trips. Results show that travel delays, route coordination, and on-time response rates were all much improved when adaptive traffic signal management and real-time path optimization were combined. Findings from this study may help urban planners, legislators, and traffic authorities better prepare for and respond to emergencies by shedding light on the role that intelligent transport systems can play in enhancing urban emergency management.

Keywords: Real-time Path Optimization, Adaptive Green Corridor, Emergency Vehicle Prioritization, Intelligent Transportation System, Traffic Signal Control.

I. INTRODUCTION

Problems with urban transportation systems are becoming worse as a result of factors including inadequate road infrastructure, increased vehicle density, and fast population expansion. Among these difficulties, the timely and secure delivery of emergency vehicles like fire trucks, ambulances, and police cars is of paramount importance. Deadly repercussions, worsened fire dangers, and impaired public safety are common outcomes of emergency response times that are too slow. The real-time needs of emergency vehicle mobility cannot be adequately met by conventional traffic signal systems. Therefore, a potential technological solution to the problem of prioritizing emergency vehicles in congested urban traffic is the combination of adaptive green corridors and real-time route optimization. To find the most effective routes for emergency vehicles using real-time traffic data, computational methods and intelligent routing systems are used in path optimization. Delays occur often when using traditional GPS-based navigation since it does not take unexpected traffic, blockages, or accidents into consideration. When it comes to navigating through ever-changing urban traffic, emergency vehicles may make the most of real-time route optimization by using cutting-edge technology like the Internet of Things (IoT), vehicle-to-infrastructure (V2I) connection, and artificial intelligence. These systems are always keeping an eye on things like traffic, road conditions, and any obstacles, so they may change routes instantly to make travel time as short as possible.

Simultaneously, intelligent transportation systems have elevated the notion of adaptable green corridors. An approach to managing traffic signals known as a "green corridor" involves synchronizing the green lights along a certain route so that priority cars may go through them without interruption. The development of priority lanes for emergency vehicles may be facilitated by the integration of adaptive green corridors with Internet of Things (IoT) sensors, GPS tracking, and cloud-based decision-making systems. To make sure an ambulance can pass through a junction without a hitch, the system can track its position and alter the traffic lights on the fly. Both emergency response times and general traffic flow are minimized as a result of this. One comprehensive approach to prioritizing emergency vehicles is to use adaptive green lanes in conjunction with real-time route optimization. By using path optimization, the green corridor system guarantees that the vehicle will choose the quickest and least crowded route possible, while still allowing for continuous travel along that route. When combined, they provide a multi-tiered strategy that improves dependability and efficiency. In order to prevent non-priority cars from abusing the system, it is possible to incorporate advanced image processing methods with vehicle identification systems to guarantee reliable detection of emergency vehicles.

In addition, smart cities aim to improve urban living standards via the implementation of these technologies, particularly intelligent transportation solutions. Cities may save lives and increase public faith in city government and technology by adding priority services for emergency vehicles to their current intelligent transportation networks. Policies may benefit from the storage and analysis of historical data on emergency responses made possible by cloud platforms and big data analytics, which allows for the creation of more efficient routes and the identification of high-risk zones. Significant environmental advantages are also associated with these systems. As a result of adaptive green corridors, fuel consumption and emissions are reduced due to less idle time and congestion near junctions. This not only makes them a life-saving option, but also a sustainable one. Additionally, by integrating across many cities and regions, standardized frameworks for emergency mobility may be created on a national level via the scalability of adaptive systems based on the internet of things.

Implementing adaptive green corridors and real-time route optimization isn't without its hurdles, but the potential benefits are worth the effort. Infrastructure development is expensive, there must be reliable wireless communication networks, there is a need to address cybersecurity concerns, and many parties, including government agencies, traffic departments, and emergency service providers, must cooperate together. Important factors to think about include safeguarding personal information and avoiding system abuse. The good news is that these problems are starting to go away thanks to developments like 5G connection, edge computing, and prediction models powered by artificial intelligence. One of the most important parts of managing traffic in cities is figuring out how to prioritize emergency vehicles. A revolutionary solution to this problem is real-time route optimization using adaptive green corridors. Smart routing algorithms, connectivity via the Internet of Things, and dynamic regulation of traffic signals may help cities improve public safety and drastically cut down on reaction times to emergencies. For cities to become smarter, more efficient, and less vulnerable to natural disasters, these technologies must be incorporated into smart transportation systems.

II. LITERATURE REVIEW

Hao, Zhengbo et al., (2024) In urban traffic networks, emergency vehicles (EMVs) are crucial for saving lives and reducing property damage. There is a higher chance of traffic accidents and bad effects on social vehicles (SVs) since EMVs can miss their rescue places because of traffic and inefficient priority management tactics along the rescue route. Impacts on urban environmental sustainability are inversely proportional to the severity of negative effects on SVs, such as longer wait times and longer queues. To fix this, you need a system to regulate priorities and choose rescue routes correctly. As a result, the research on EMV routing and priority control is thoroughly reviewed in this article. The process begins with a basic bibliometric analysis using VOSviewer. This research also divides the previous work on

EMV into three sections: EMV-TTP (travel time prediction), EMV-RO (routing optimization), and EMV-TPC (traffic priority control). Lastly, this study offers five areas for further research: first, by mining EMV data for real demand characteristics; second, by using EMV's unique features in EMV-RO models; third, by actively pursuing EMV-TPC strategies; fourth, by paying more attention to the negative effects on SVs; and fifth, by embracing new technology for the future of urban traffic.

Thakare, Dr et al., (2024) Using mobile networks and cameras, this study describes in detail how a traffic clearance system was developed. Congestion is a major obstacle for emergency vehicles to overcome in metropolitan environments, which may slow response times and put lives in risk. The article introduces a novel traffic management system that uses surveillance cameras to let emergency cars through ahead of regular traffic. To identify emergency vehicles' flashing lights and sirens, the suggested system employs a network of cameras positioned at junctions. When it senses an emergency vehicle, the system immediately changes the timing of the traffic signals to create a green corridor so that the vehicles may pass safely and quickly. In order to maximize efficiency, reduce congestion, and improve traffic flow, the system also uses machine learning algorithms. We demonstrate the potential of the proposed system to improve overall traffic management in urban contexts and to boost emergency response capabilities via simulation studies and real-world testing, which assess its efficacy and dependability.

Yadav, Shalini & Rishi, Rahul. (2022) An emergency vehicle may go faster in traffic with the help of a green corridor, which is a real-time, dynamic lane. The goal is to make emergency vehicles' trip times shorter. The submitted study investigates potential solutions to the problem of the longest possible travel times for both emergency vehicles and ordinary road users. Several traffic-guided and non-guided lights may be present on the roadways, and the study considers that all vehicles have variable acceleration and deceleration rates. With the goal of developing a long-term, scalable solution, additional considerations are given, including safety and speed. For the purpose of simulating real-world conditions, SUMO simulation libraries are used. The approach is also applicable in real-life scenarios since a deliberate trade-off was made between the number of variables and the degree to which they approximate the actual situation.

Zhong, Li & Chen, Yixiang. (2022) A primary focus of intelligent transportation system research is the development of solutions for the intelligent regulation of traffic signals as they pertain to emergency vehicles (EVs). In order to save lives and lessen property damages, its study will support the reduction of EV journey times. A new approach of controlling traffic lights in real time is suggested in this article. Following three indicators—the emergency response level (ERL), the congestion level of the road section (CLRS), and the time urgency level (TUL)—the first step is on-demand signal timing for reducing road saturation, which allows ordinary vehicles (OV) to make way for electric vehicles (EVs) and speeds up their travel. Step two is a hybrid of invasive and non-intrusive preemption techniques; it's termed innovative signal preemption. Electric vehicles are able go swiftly and without stopping at intersections thanks to this step, which delivers green signals. In the last stage, known as the recovery cycle approach, the road network is quickly returned to its regular state by using linear programming (LP) to determine the shortest green period in each phase after an EV's passage through the junction. Using the SUMO urban traffic simulator, this article does simulation tests. The testing findings demonstrate that our innovative approach may considerably lessen the traffic effect on the road network and cut travel times by giving EVs priority. Our solution outperforms the fixed-time control method (FTCM), Min's flexible signal preemption method (FSPM), and Qin's intrusive signal preemption method (ISPM) in terms of trip time optimization, with respective improvements of 62.83%, 50.83%, and 11.62%.

Moadi, Saeed et al., (2022) One way that contemporary cities are able to keep their traffic flows smoothly is via the use of adaptive traffic signal control, or ATSC. Several research have explored different methods for improving urban network performance (e.g., minimizing delay) by adjusting traffic signal designs in real-time in response to demand changes. Optimization of signal plans has recently seen encouraging results from learning-based approaches like reinforcement learning (RL). It is yet unclear, however, how to use these self-learning methods in traffic scenarios that will include CAVs in the future. To reduce overall stop delays, this research creates a real-time RL-based adaptive traffic signal management that optimizes a signal plan to minimize total queue length and lets CAVs alter their speed according to a defined timing approach. The integration of a speed guidance system with a traffic signal management system based on reinforcement learning is the main focus of this study. To reduce overall wait times and total halt delays, two distinct performance metrics are put into play. Under saturated and oversaturated situations, the results show that the suggested solution works better than a set timing plan and classic actuated control with optimum speed advisory in a CAV environment.

Humagain, Subash et al., (2019) Improving vital services like fire, police, and ambulance may be achieved by reducing the trip time of emergency vehicles (EVs). Efficient methods for reducing EV travel time include route planning and pre-emption. Methods for optimizing and pre-empting EV routes are reviewed in this paper's comprehensive literature review. In addition to a critical analysis and debate, a comprehensive categorization of current methodologies is provided. Several intriguing and crucial knowledge and implementation gaps need more exploration, as highlighted by the study, due to the absence of real-world implementations of the suggested pre-emption systems and the limits of current routing systems. There are a number of areas that need improvement in this area, such as optimizations using real-time dynamic traffic data, advanced algorithms, evaluating and reducing the impact of EV routing on other traffic, optimizing traffic networks with multiple EVs simultaneously, and addressing safety concerns.

Ranga, Virender & Sumi, Lucy. (2018) Tragic accidents, patients in critical care, medical equipment, and medications have all been unable to reach their destinations on time because of traffic congestion throughout the globe. The combination of the Internet of Things (IoT) and the Vehicular Ad Hoc Network (VANET) has emerged as a potential foundation for an Intelligent Traffic Management System (ITMS), which is crucial given the exponential increase in vehicle traffic worldwide. While several studies have attempted to address the problem of emergency vehicles, none of them have been able to guarantee that these cars would arrive at their destinations in the allotted time or even come up with a workaround for situations when traffic signals are compromised. Based on the ideas presented in this article, an intelligent traffic control system for a Smart City may be implemented using the Internet of Things (IoT) and VANET. The suggested approach involves scheduling emergency vehicles in a way that allows them to move through traffic more quickly and easily depending on the kind of occurrence. Not only does it help ambulances locate the fastest routes to their destinations, but it also offers a way to identify and counteract traffic signal tampering. We used the Cup Carbon simulator to create a virtual environment that mimics real roads and vehicle motions. This allowed us to prove that our suggested solution is better. In terms of congestion avoidance, transmission delay, trip duration, and response to hacking, comparative findings show that our proposed system outperforms the other ITS for emergency vehicles that have been developed previously.

RESEARCH METHODOLOGY

Research Design

This study used a quantitative experimental approach to assess how well adaptive green corridor systems and real-time route optimization improve emergency vehicle prioritizing. Time to destination, congestion, signal timing, algorithm efficiency, and response SLA adherence were the primary metrics measured in the design comparison between baseline and system-enabled scenarios.

Study Area and Context

Various forms of crises, including cardiac emergencies, road accidents, fire and rescue assistance, police escort operations, and other types of emergencies, were studied in an urban traffic environment with many signalized junctions and varied degrees of congestion. The diverse range of event types allowed for thorough testing of the system in many real-life circumstances.

Data Collection

A total of 125 emergency response trips were analyzed. The data were collected through a combination of:

- Traffic simulation models to replicate baseline and system-enabled conditions across different congestion levels.
- Incident logs categorizing emergency types and frequencies.
- GPS and route-tracking tools to record travel times, signal stops, and delays.
- Algorithm performance benchmarks comparing Dijkstra, A*, ALT, D* Lite, and Reinforcement Learning policies.

Variables

- Independent Variables: Congestion level, incident type, path-finding algorithm, and distance band.
- Dependent Variables: Travel time, intersection delay, green-wave success rate, number of stops, and SLA compliance.
- Control Variables: Road infrastructure, signal cycle times, and simulation parameters were standardized to ensure consistency across tests.

Data Analysis

- Descriptive Statistics: Frequency distributions of incident types, mean travel times, signal coordination success, and SLA compliance.
- Comparative Analysis: Percentage reduction in travel times under different congestion levels and performance gains across routing algorithms.
- Performance Metrics: Green-wave success rates, number of stops, and SLA compliance improvements were used as key indicators of system effectiveness.
- Validation: Cross-comparison of baseline versus system outcomes ensured reliability of findings.

III. DATA ANALYSIS AND INTERPRETATION

Table 1: Incident Mix and Priority Level

Incident Type	Count	Percent
Cardiac/Medical	38	30.4%
Road Trauma/Accident	29	23.2%
Fire/Rescue Support	24	19.2%
Police Escort	18	14.4%
Other Emergencies	16	12.8%
Total	**125**	**100%**

Table 1: Incident Mix and Priority Level shows the different sorts of incidents, which shows how varied the emergency situations are that need adaptive green corridors and real-time route optimization. Out of the 125 occurrences that were documented, 30.4% were related to cardiac and medical crises. This highlights the vital need for prompt action in these life-threatening situations, as every minute spared may greatly improve patient outcomes. Following closely behind with 23.2%, incidents involving road injuries and accidents indicate the increasing worry around urban traffic-related situations, which often need prompt transportation to trauma centers or hospitals. The significance of rapid response times for fire departments and associated rescue units in reducing fatalities and property damage is shown by the 19.2% of events involving fire and rescue assistance. The system's versatility is shown by the fact that it can handle a wide range of situations, including medical, fire, VIP, law enforcement, and sensitive security-related instances (14.4 percent). Last but not least, other crises account for 12.8% of all emergencies and include a wide variety of critical situations, from responding to disasters to occurrences involving dangerous materials. Intelligent traffic systems and green corridor strategies should be implemented to guarantee the timely and prioritized transportation of emergency vehicles in various scenarios, since a large number of these incidents are time-sensitive.

Table 2: Travel Time by Congestion Level (Baseline vs. System)

Congestion Level	n	Baseline Travel Time	With Optimization & Green Corridor	Mean Reduction
Low	22	9.8 ± 2.1	8.1 ± 1.9	17.3%
Moderate	41	14.7 ± 3.2	11.3 ± 2.7	23.1%
High	39	20.5 ± 4.4	14.8 ± 3.5	27.8%
Severe	23	28.6 ± 6.0	19.7 ± 4.8	31.1%
Overall	**125**	**18.5 ± 7.1**	**13.7 ± 5.6**	**26.0%**

Table 2 shows that under different degrees of traffic congestion, emergency vehicles may have their journey times reduced using adaptive green corridors and real-time route optimization. The baseline trip time was 9.8 minutes under low congestion circumstances; with the system, it dropped to 8.1 minutes, an improvement of 17.3%. Even in minor traffic, the effectiveness of signal synchronization is evident, however the decrease is small in comparison to more severe congestion. The technology was most effective in moderately congested areas, where it reduced average trip times by 23.1%, from 14.7 to 11.3 minutes. This shows that adaptive signal prioritizing is becoming more important in high-traffic areas. With a decrease in journey time from 20.5 to 14.8 minutes—a 27.8 percent improvement—the advantages become even more apparent under heavy congestion, demonstrating the crucial need of prioritizing emergency vehicles in crowded corridors. In areas with very heavy traffic, the benefits were most noticeable, cutting travel time by 31.1%, from 28.6 to 19.7 minutes. The solution significantly reduced the mean trip time from 18.5 to 13.7 minutes, a 26% decrease, across all congestion levels. This clearly shows that adaptive green corridors are great for improving emergency response efficiency, even in busy urban traffic.

Table 3: Signal Coordination Performance

Signals Coordinated per Trip	n	Avg. Green-Wave Success (%)	Avg. Stops per Trip
0–5	27	72.4%	1.2
6–10	46	78.9%	0.9
11–15	34	81.6%	0.7
>15	18	84.3%	0.6
Total/Mean	**125**	**79.8%**	**0.9**

The efficiency of signal coordination in facilitating the mobility of emergency vehicles across adaptive green lanes is seen in Table 3. An obvious pattern emerges from the data: the green-wave success rate and the average number of stops both go down as the number of synchronized signals per trip goes up. The green-wave success rate for journeys with synchronized 0-5 signals is 72.4%, and cars experience an average of 1.2 stops each trip. With 6-10 indications of coordination, success increases to 78.9% and stops decrease to 0.9, showing less delay and better flow. The success rate jumps to 81.6% in the 11–15 signal range, demonstrating the immediate advantages of improved synchronization, with just 0.7 pauses per trip. Trips with over 15 coordinated signals show the best performance, with 84.3% green-wave success and 0.6 stops per trip, indicating effective management of priorities. With an average of 0.9 stops per journey, the system had a 79.8 percent success rate throughout all 125 trips. In order to minimize disruptions and maximize operational efficiency, our findings show that broader signal synchronization leads to quicker and smoother emergency vehicle transportation.

Table 4: Path-Finding Algorithm A/B Comparison

Algorithm (Allocation)	n	Mean Travel Time (min)	Mean Delay per Intersection (s)	Mean Compute Time (ms)
Dijkstra (Baseline)	25	16.9	21.4	11.8
A* (Heuristic)	30	15.2	18.6	8.5
ALT (A* + Landmarks)	20	14.6	17.9	7.3
D* Lite (Dynamic)	25	14.1	16.8	9.1

RL Policy (Online)	25	13.7	15.2	12.6
Weighted Mean	**125**	**14.9**	**18.0**	**9.8**

For emergency vehicle routing, Table 4 evaluates the performance of several path-finding algorithms based on computing efficiency, junction delays, and journey time. Despite a reasonable compute time of 11.8 ms, the Dijkstra algorithm—used as a baseline—measured the longest mean trip time of 16.9 minutes and the largest delay per intersection of 21.4 seconds. These results demonstrate the algorithm's inadequacies under dynamic urban traffic situations. Reduced trip time to 15.2 minutes and lowered junction delays to 18.6 seconds with quicker compute time (8.5 ms) provide better outcomes from the A heuristic*, demonstrating its efficacy in actual navigation. Additional improvement was seen with ALT (A + Landmarks)**, which was computationally efficient for real-time applications, with a trip duration of 14.6 minutes and a delay of 17.9 seconds. The lowest compute time was 7.3 ms. Although its compute time (9.1 ms) was somewhat more than A*, the dynamically adjusted D Lite method achieved even better performance with a trip duration of 14.1 minutes and a delay of 16.8 seconds. The most successful policy was the Reinforcement Learning (RL) one, which had the longest computation time (12.6 ms) but the shortest journey time (13.7 minutes) and the lowest delay per intersection (15.2 seconds). Intelligent, adaptive algorithms such as RL and D* Lite are ideal for real-time emergency vehicle priority due to their superior performance compared to conventional techniques. The weighted mean across all methods was 14.9 minutes for trip time, 18.0 seconds for delay, and 9.8 ms for compute time.

Table 5: Response SLA Compliance by Distance Band

Distance Band	n	SLA Target (min)	% Within SLA (Baseline)	% Within SLA (With System)
0–5 km	33	8	72.7%	90.9%
5–10 km	44	12	61.4%	86.4%
10–15 km	31	15	51.6%	77.4%
>15 km	17	20	41.2%	70.6%
Overall	**125**	—	**57.6%**	**83.2%**

Table 5 shows how the real-time route optimization and adaptive green corridor system increase the ability to achieve the Service Level Agreement (SLA) standards for emergency response times across various distance bands. The method guarantees more regular on-time arrivals even for relatively short excursions, as compliance increased from 72.7% to 90.9% for short-distance trips (0-5 km). There were significant improvements in mid-range urban replies, where traffic congestion is more likely to create delays, as the system increased baseline compliance from 61.4% to 86.4% in the 5-10 km band. It is clear that signal prioritizing and route optimization are especially useful for longer-distance emergency trips, because SLA compliance increased from 51.6% to 77.4% for 10-15 km trips. The most difficult part is travels longer than 15 km. The baseline SLA compliance was just 41.2%, but the system managed to significantly improve performance to 70.6%, showing that it is quite successful at reducing delays over long distances, albeit it hasn't achieved perfect dependability just yet. Compliance improved dramatically, rising from 57.6% to 83.2% across all 125 instances, an improvement of more than 25%. In medium to long-distance crises, when prompt assistance is of the utmost importance, these data demonstrate that the system considerably promotes SLA adherence.

IV. CONCLUSION

The innovative use of adaptable green lanes and real-time route optimization provides a game-changing way to clear crowded metropolitan areas for emergency vehicles to go quickly and without interruption. These technologies greatly improve emergency response times by minimizing delays caused by traffic jams by integrating smart route planning with dynamic signal synchronization. Adaptive green corridors provide synchronized green signals to enable seamless travel without frequent halts, and path optimization guarantees that priority vehicles, such as ambulances, follow the most efficient paths. By working in tandem, they lessen the likelihood of dangers connected with delayed rescue or medical operations, which in turn saves lives. With these devices, not only can emergency response be enhanced, but general traffic management is improved, congestion at junctions is decreased, and idle emissions are reduced, which contributes to environmental sustainability. Their scalability makes them ideal for smart city frameworks, which may improve efficiency and security in the long run. Constant improvements in the Internet of Things (IoT), artificial intelligence (AI), and 5G connections are progressively removing obstacles including high implementation costs, cyber security concerns, and the need for multi-stakeholder collaboration. The use of adaptive green corridors and real-time optimization to prioritize emergency vehicles is a technical breakthrough that will ultimately benefit society. Smarter, more responsive, and safer cities may be shaped in large part by using such systems.

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