

# Intelligent Traffic Management in Smart Cities Using Adaptive Routing, Emergency Prioritization, and Pollution-Aware Optimization

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## Abstract

Effective traffic management is essential for reducing congestion, lowering environmental impact, and improving overall commuting in smart cities. This work presents a set of integrated strategies addressing key challenges such as real-time vehicle rerouting, emergency vehicle prioritization, pollution mitigation, and proactive incident management using social media data. The first strategy focuses on dynamic vehicle rerouting based on real-time conditions, with particular emphasis on non-homogeneous road segment density. Unlike existing methods that treat density as uniform, this work recognizes that congestion affects road segments differently. By incorporating segment-specific density, the rerouting mechanism achieves more accurate traffic estimation and better route selection. Simulations show significant reductions in travel and waiting times compared to relevant existing approaches. Building on this foundation, the second strategy prioritizes emergency vehicles like ambulances and police cars, where timely response is critical. This approach integrates rerouting with traffic signal optimization through a bi-level framework that proactively manages changing traffic dynamics. The system minimizes delays for emergency vehicles while maintaining smooth flow for others. Experiments indicate superior performance over reactive methods that intervene only after congestion appears. Addressing environmental sustainability, the third strategy targets vehicular pollution near sensitive locations such as hospitals and schools. Since pollution is a major public health concern, the proposed solution introduces a pollution-aware routing model that combines meteorological and traffic data to accurately estimate emission levels. By detecting pollution hotspots, the system recommends alternative routes that keep pollutant levels within safe limits while avoiding major disruptions to travel time. The final strategy focuses on proactive incident detection using real-time social media input, especially from Twitter (now X). Instead of responding only after congestion forms, the system analyzes relevant tweets to identify potential incidents early. This enables timely traffic interventions and dynamic rerouting, preventing escalation and improving overall flow. In summary, these integrated strategies collectively enhance intelligent transportation by addressing congestion, emergency vehicle prioritization, pollution control, and proactive incident detection. Experimental findings validate their effectiveness in advancing smarter, safer, and more sustainable traffic management in smart cities.

## **Background**

The first approach optimizes vehicle routing by dynamically adjusting paths based on real-time traffic conditions, with a particular focus on road segment density. Existing work often considers density as a homogeneous factor; however, the impact of density on individual road segments varies significantly. By incorporating this nonhomogeneous density feature, the proposed solution ensures more accurate and efficient rerouting of vehicles. Extensive simulations demonstrate substantial reductions in both travel and waiting times compared to conventional methods. Building on this foundation, the second approach emphasizes the critical need for prioritization of emergency vehicles, such as ambulances and police cars, where timely response is essential for public safety. This strategy integrates vehicle rerouting with traffic signal optimization to create a coordinated system that minimizes delays for priority vehicles while maintaining smooth traffic flow for all road users. By combining these elements within a bi-level optimization framework, the system proactively manages traffic dynamics, demonstrating enhanced efficiency over reactive methods that respond only after congestion occurs. Recognizing the increasing importance of environmental sustainability, the third approach addresses vehicular pollution, particularly around sensitive areas like schools and hospitals. Pollution is a significant public health

concern, necessitating its incorporation into traffic management strategies. The proposed solution introduces a pollution-aware framework, utilizing an accurate pollution estimation model that factors in meteorological and traffic data. By identifying pollution hotspots, the system reroutes vehicles to maintain pollution levels within acceptable thresholds while minimizing disruptions to travel time, thus balancing environmental responsibilities with commuter needs.

Traffic congestion is a growing challenge in urban transportation systems around the world, significantly impacting quality of life, economic efficiency, and environmental sustainability. The U.S. Department of Transportation (DoT) reports that congestion stems largely from the sharp increase in vehicle load due to population growth and varying traffic demand. Special events, adverse weather, accidents, and other unexpected incidents add to the problem, while inefficient traffic signals exacerbate delays. Specifically, statistics show that road bottlenecks alone contribute 40% to congestion, with accidents responsible for 25%, poor weather for 15%, work zones for 10%, and inefficient signal timing adding to the challenge [5]. Congestion-related frustrations not only impact driver behaviour, often leading to more accidents but also carry a significant economic toll; in the U.S., these costs are projected to reach over \$2.8 trillion by 2030. In rapidly urbanizing countries like India, traffic congestion has become particularly severe, straining urban infrastructure and highlighting the need for innovative solutions.

Intelligent Transportation System (ITS) [6] and Vehicular Ad-hoc NETWORK (VANET) [7] provide advanced solutions for addressing urban mobility challenges. ITS leverages technologies like sensors, cameras, RFID systems, and data-gathering devices to monitor traffic conditions in real-time, helping to optimize traffic flow and reduce congestion. ITS strategies encompass both reactive and proactive measures: reactive systems respond after congestion has formed, typically through rerouting; however, this can sometimes shift congestion to new locations. Proactive systems, by contrast, aim to predict congestion before it occurs, allowing for preemptive action that prevents traffic from accumulating in the first place. By integrating real-time traffic data, ITS can dynamically adjust traffic signals or reroute vehicles to less congested routes [1, 2, 6]. VANET enhances ITS by enabling vehicles to communicate with each other Vehicle-to-Vehicle (V2V) and with roadside infrastructure Vehicle-to-Infrastructure (V2I), creating a connected network that supports adaptive traffic management. Through this communication network, vehicles can share real-time information on traffic conditions, road incidents, and weather, enhancing situational awareness and enabling quicker responses to emerging conditions. VANET-driven solutions can identify congestion hotspots, provide alternate routes, and streamline emergency responses. The integration of ITS and VANET enables a more responsive and adaptable urban transportation system. By reducing delays and minimizing congestion-related incidents, these technologies improve the overall travel experience while supporting economic efficiency and environmental goals.

### **Issues in Transportation Systems**

In this section, we address several critical issues that impact modern transportation systems. We analyze each issue to understand its underlying causes, impacts on the environment and society, and implications for future smart city development. A major issue in current transportation systems is traffic congestion, which disrupts efficient mobility, increases travel times and leads to higher fuel consumption and pollution. In urban networks, congestion can spread quickly from one road segment to another, creating widespread delays and amplifying the negative impacts on commuters and businesses alike. Though reactive approaches—such as real-time rerouting and traffic signal adjustments—are available, they often only provide temporary relief, addressing symptoms rather than underlying causes. Adaptive traffic congestion management is essential to tackle this challenge effectively. Unlike reactive methods, adaptive strategies continuously monitor and respond to dynamic traffic patterns, adjusting in real-time to shifts in vehicle density and flow. By implementing more adaptive and intelligent congestion management systems, transportation networks can improve overall efficiency, minimize delays, and better accommodate growing urban traffic demands.

Another important consideration in traffic management is the prioritization of different types of vehicles based on their function and importance. Traditional traffic management systems [8–11] often treat all vehicles equally, but in practice, certain types of vehicles—such as emergency vehicles, vehicles used for public transportation, and

private vehicles—are treated with different priority levels. For example, ambulances, fire trucks, and police cars are permitted to move quickly through traffic in emergencies, while prioritizing buses and other forms of public transportation can help to reduce overall congestion by encouraging more people to use public transit instead of driving private cars. These strategies not only improve traffic flow but also have significant environmental benefits, as fewer cars on the road generate reduced emissions. Traffic congestion also has serious environmental consequences, specifically in terms of air pollution. Vehicles, remaining idle in traffic, emit large amounts of harmful pollutants and become one of the major sources of poor air quality, especially near busy intersections and highly congested areas.

1. **Density-Based Rerouting:** In urban networks, congestion on a heavily trafficked road segment affects nearby segments more than those farther away. This ripple effect intensifies vehicle density on adjacent roads while distant segments remain less impacted. It introduces an edge-based road network model combined with a modified Dijkstra algorithm. This method will efficiently identify the shortest and most effective paths in the network, thereby enhancing the performance of vehicle rerouting. The objective is to ensure that priority vehicles can move swiftly through urban areas while maintaining efficient traffic flow for regular computers.
2. **Pollution-Aware Traffic Systems:** To develop a traffic management system that proactively identifies pollution hotspots within sensitive areas of a smart city. This chapter introduces an accurate model for estimating pollution concentrations, integrating both meteorological data and road network characteristics.
3. The study goes beyond real-time pollution detection by leveraging historical data to forecast future pollution hotspots. By identifying these hotspots in advance, the system can implement strategic vehicle rerouting to minimize environmental impact without causing significant delays. This approach ensures that traffic management decisions are not only focused on efficiency but also on reducing pollution in high-risk areas.
4. **Social Media-Guided Traffic Management:** Chapter 6 aims to enhance real-time traffic management by leveraging data from social media, particularly tweets, to detect incidents and disruptions on the road network.

## ROAD NETWORK (RN) AND BASIC TERMINOLOGIES

Road network (RN) that is the focus of this study. The network comprises two fundamental elements: road segments and intersection points, commonly referred to as crossroads. The crossroads within this network are categorized into two types: those equipped with Traffic Signals (TS) and those without. For the purpose of this analysis, it is assumed that the network is adequately covered by Road Side Units (RSUs), which are essential for collecting real-time traffic data and monitoring traffic conditions. The road network can be modelled as a directed graph, as depicted in Fig. 2.2. This graph, denoted by  $G = (V, E)$  consists of vertices  $V$  representing the crossroad points and edges  $E$  representing the road segments connecting these points. For clarity, let  $V_{TS}$  denote the subset of crossroads equipped with traffic signals. By definition,  $V_{TS} \subseteq V$ . The road network shown in Fig. 2.1 includes a total of ten crossroad points,  $V = \{a_0, a_1, a_2, a_3, a_4, a_5, a_5, a_7, a_8, a_9\}$  and twenty road segments,  $E$ . Among these crossroads,  $a_1, a_3, a_5,$  and  $a_7$  are equipped with traffic signals, which are highlighted in red in the figure. The remaining crossroads do not have traffic signals. Thus, the set  $V_{TS}$  is defined as  $V_{TS} = \{a_1, a_3, a_5, a_7\}$ . The directed edges in the graph indicate the permissible direction of traffic flow. For example, traffic is allowed to move from  $a_7$  to  $a_8$  but not in the reverse direction, whereas traffic is permitted in both directions between  $a_1$  and  $a_2$ .

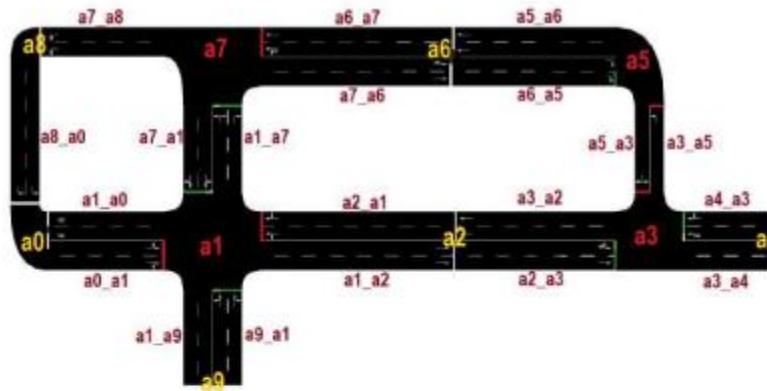


Figure 2.1: A Road Network

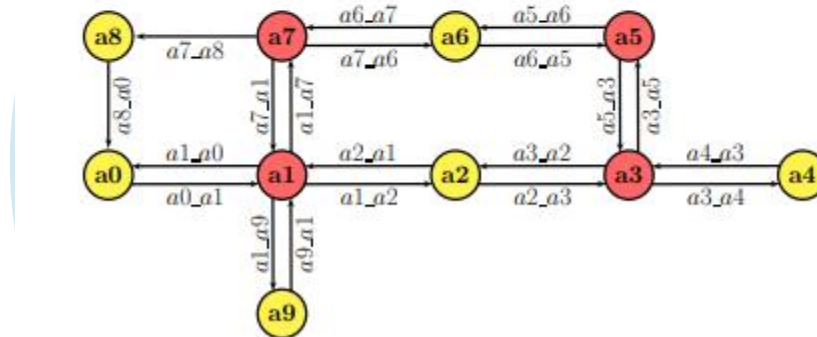


Figure 2.2: A directed graph representing the above road map

### Literature on Traffic Congestion:

Detection and Mitigation Traffic congestion detection methods can be broadly classified into two categories: infrastructure-based and infrastructure-less solutions. The infrastructure-based approach utilizes a centralised architecture, often employing client-server or Peer-to-Peer (P2P) models for data communication [25–28]. These methods rely on fixed infrastructure, requiring significant public investment from government agencies or relevant operators for development, maintenance, and management [25, 26]. Moreover, large-scale deployment of sensors is necessary to monitor traffic conditions effectively. However, the major drawback of this approach is the substantial network overload caused by the continuous transmission of traffic data [29]. Although installing preprocessing systems within individual vehicles could alleviate network overload, this would significantly increase the overall installation costs.

### Route Optimization Strategies

The development of Adaptive Traffic Signal Control (ATSC) systems marked a turning point in traffic signal optimization. ATSC systems dynamically adjust the timing of traffic lights based on real-time traffic data collected from sensors or connected vehicles. Early systems, such as Split Cycle Offset Optimization Technique (SCOOT) [61] and Sydney Coordinated Adaptive Traffic System (SCATS) [62], utilized data from inductive loop detectors and traffic cameras to adjust signal timings. These systems significantly improved traffic flow in urban areas by reducing stop-and-go traffic and minimizing waiting times at intersections.

This adaptive approach ensures a more efficient response to changing traffic situations, enhancing overall traffic flow.

1. Travel Time: Among the various parameters of Route Optimization, ‘travel time’ consistently remains a focal point. Techniques such as dynamic route guidance and signal timing optimization are designed to minimize delays and enhance traffic flow. Parmar et al. proposed a model that employs traffic routers and

dynamic signalling to optimize traffic flow, leading to a substantial reduction in overall travel time [64]. Furthermore, a dynamic route guidance system that incorporates signal timing optimization to significantly lower vehicle delays and improve travel efficiency during peak periods was developed in [19, 65, 80].

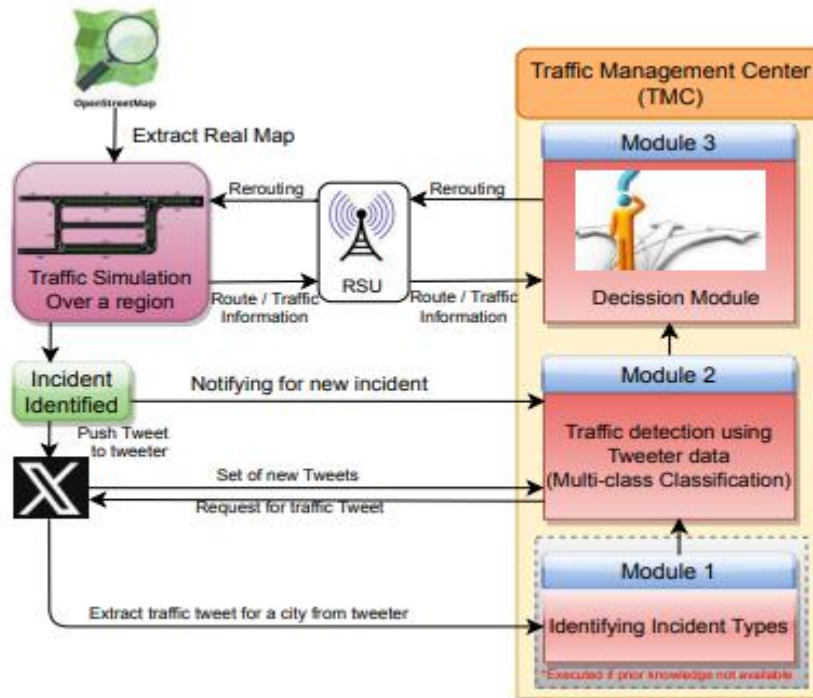
2. **Queue Length:** Effectively managing ‘queue lengths’ at intersections is crucial for alleviating congestion. Huang et al. introduced a dynamic evacuation route planning model that aims to reduce queue lengths during emergencies, highlighting the significance of effective traffic diversion strategies [69, 70]. Similarly, a real-time queue length perception system that monitors queue lengths at intersections and adjusts traffic signal timings to minimize waiting times was proposed in [71]. Another study utilized Queue growth equalization (QGE) to formulate an algorithm for oversaturated networks [68]. Additionally, Li et al. advanced this field with a lane-based real-time queue length prediction technique that assists in optimizing traffic signals [72]
3. **Vehicle Delay:** Minimizing vehicle delay enhances the overall traffic experience. Ren et al. introduced a congestion-aware routing algorithm that reduces delays in interconnected environments [75, 76], while Piccoli et al. applied a fluid dynamic model to optimize traffic behaviour and lessen delays at intersections [74].
4. **Congestion Levels:** Efficient traffic diversion strategies concerning traffic density (congestion level) are vital for ensuring smooth flow. A real-time group route diversion control method was suggested, optimizing traffic density by accounting for drivers’ dynamic responses [78]. Mei et al. created a coordinated route updating mechanism aimed at minimizing total travel time [79], and a real-time route diversion control strategy was developed within a model predictive control framework, addressing multiple objectives such as traffic efficiency and emission reduction [77].
5. **Fuel Efficiency:** While fuel efficiency is a crucial yet secondary consideration, research by Li et al. and Luo et al. has focused on eco-friendly route guidance methods to decrease fuel consumption [19, 77, 80]. Emission levels are similarly important, as reducing stop-start behaviour and idling helps to lower pollution levels.

**Research Contributions** The present study makes several significant contributions to the field of transportation optimization:

- ^ **Non-Homogeneous Vehicle Density Integration:** This research advances the conventional approach by considering vehicle density as a variable component in travel time calculations. Unlike traditional methods that assume uniform density, this study proposes a model that accounts for the variable impacts of congestion. This model aims to provide more accurate travel time estimations and optimize route planning in diverse traffic conditions.
- ^ **Introduction of Travel Satisfaction Index (TSI):** To complement the traditional focus on travel time, this study introduces a novel metric, the “Travel Satisfaction Index (TSI).” The TSI is designed to assess and enhance the satisfaction of individual vehicles by considering factors beyond mere travel time. This metric aims to offer a more holistic approach to route optimization, addressing the subjective experience of travellers and improving overall satisfaction.

Through these contributions, the research seeks to provide a more comprehensive framework for travel time optimization, addressing the limitations of existing methods and offering practical solutions for enhancing traffic management and traveller satisfaction.

This work aims to improve traffic management for smoother traffic flow, utilizing social media, particularly Twitter (now X), for insightful information. The proposed framework, depicted in Fig. 7.1, comprises three modules. Module 1, Module 2 and Module 3 are detailed in Sections 7.4 to 7.6, respectively. The Traffic Management Center (TMC) is responsible for overseeing the execution of these modules and ensuring that the traffic system operates efficiently.



The TMC has a central role in coordinating various components of the system. Its tasks include gathering new traffic-related tweets from Twitter (now X), collecting real-time route and traffic information from the road network via RSU, and transmitting updated vehicle routes back to vehicles through the RSUs. To gain a clearer understanding of how these processes work together, it's essential to first explore the dataset preprocessing techniques described in Section 7.3, as they form the foundation for effective data utilization.

## Conclusion

To consider vehicle density as a crucial component in computing travel time in a non-homogeneous manner and to optimize it for offering efficient route plans for individual vehicles. Unlike existing studies [77–79], which focus primarily on improving the overall traffic situation, this work emphasizes the importance of accounting for the dynamic behaviour of vehicle density on road segments. By incorporating the effects of these fluctuations in density, the solution aims to provide a more tailored approach that not only improves general traffic flow but also enhances the satisfaction of independent riders, a factor often overlooked in previous research. The proposed solution strives to strike a balance between optimizing the overall traffic efficiency and addressing the specific needs and satisfaction index of individual travellers, ensuring a more equitable and effective traffic management system. This dual focus—on overall traffic improvement and individual rider satisfaction—broadens the scope of traffic optimization beyond traditional approaches and integrates personalized route planning.