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Adaptive Traffic Signals: A Mitigative Approach to Solving Urban Intersection Congestion

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Traffic congestion is a pervasive issue that transcends geographical boundaries, affecting both developed and developing nations. While developed countries have been actively pursuing effective solutions, developing economies face distinct challenges owing to infrastructure constraints and improper road utilization. Inadequate infrastructure and inefficient traffic management not only exacerbate congestion but also result in unnecessary delays, wasted fuel, and lost productivity, ultimately impeding societal progress. This study recognizes the importance of addressing traffic congestion, particularly at critical junctions, through the implementation of intelligent traffic signalization systems leveraging artificial intelligence (AI) and optimized capacity utilization. By harnessing the power of AI and coding techniques, the proposed approach aims to mitigate congestion at intersections, thereby enhancing traffic flow, reducing travel times, and minimizing adverse socio-economic impacts. Moreover, the paper explores the role of traffic engineer in facilitating effective traffic management solutions. Ultimately, this research endeavors to contribute to the development of sustainable and efficient urban mobility systems, benefiting both commuters and society at large.
Keywords: Traffic Congestion, Urban Mobility, Intelligent Traffic Signals (ITS), artificial intelligence (AI) Traffic Management, Sustainable Transportation.

1. Introduction

Roads are essential for transporting people and freight globally. Roads drive economic development and provide significant social advantages. As urban areas continue to experience rapid growth in the number of vehicles on the roads and the demand for transportation, traffic congestion has emerged as a critical challenge that requires immediate attention from urban planners and policymakers [4]. India's transportation sector is vast and diverse, serving 1.3 billion people. India has the second largest road network in the world, covering over 63,31,791 km as of 31st March 2019 [5]. This includes national highways, expressways, state highways, district roads, rural roads, urban roads, and project roads. Effective problem-solving techniques are required by the urban transportation system to handle the current traffic conditions and satisfy the growing travel demand. It will take years and occasionally may not even be possible to make changes to the urban infrastructure. Therefore, one of the quickest and least expensive methods for reducing traffic at junctions and enhancing traffic flow in an urban network is traffic signal time (TST) optimization. The strategic timing and coordination of traffic signals is crucial in optimizing traffic flow and mitigating congestion at intersections, making it one of the most effective tools available for efficient traffic management [6].

2. Background of the study:

The substantial movement of people and goods within urban areas and across cities is predominantly facilitated through road transportation. This mode of conveyance is significantly preferred for short-distance travel due to its convenience and flexibility. In the Indian context, road transportation is the primary means of mobility for the majority of the population. The road infrastructure, which has evolved over an extended period, necessitates a comprehensive review and modification to align with contemporary requirements. This imperative arises from the rapid pace of population shift from rural to urban premises, resulting in increased density and consequent strain on existing transportation systems.

The burgeoning urban population and the concomitant rise in vehicular traffic have exacerbated the demand for efficient and sustainable road networks. Urbanization has led to the expansion of cities, often outpacing the development of transportation infrastructure, resulting in traffic congestion, Traffic congestion is defined as the mutual obstruction between vehicles due to the existing correlation between vehicle travel speed and flow volume in conditions of exhausting infrastructure capacity. In other words, congestion refers to the extent to which vehicles exceed the capacity of a given roadway leading to a reduction in vehicle speed or a complete ban on the free movement of vehicles [7][8]. Traffic congestion occurs when the demand for transportation exceeds the capacity of the existing infrastructure and services. The disparity between the number of cars trying to utilize the roads and the transportation network's ability to accommodate that volume causes gridlock and bottlenecks, resulting in substantial delays and disruptions to traffic flow.

3. The root cause of congestion:

Congestion in urban or central areas can occur for various reasons, such as excess requests, signals, incidents, and work areas, weather-related or special events so congestion can be of two types [9]. (1) Recurrent congestion and (2) Non-recurrent congestion.

In most metropolitan cities, travelers face daily traffic jams during daily rush hour. About half of traffic jams encountered by road users are recurrent [10]. Furthermore, the transition towards sustainable transportation solutions has become a global priority, driven by the need to mitigate the environmental impact of vehicular emissions and reduce dependence on non-renewable energy sources. The integration of electric vehicles, intelligent transportation systems, and the promotion of public transportation, along with the development of pedestrian-friendly and bicycle-friendly infrastructure, are crucial considerations for the future of urban mobility.

Table 1.1. Road Network in India [11]

Category of Road	Length in Km	% Share of Total Road
National Highways (NHs)	1,32,500	2.13
State Highway(SHs)	186528	3
District road	632154	10.17
Rural road	4535511	72.97
Urban road	544683	8.76
Projects road	354921	5.71
Total	6386297 Km	

The data presented in Table 1.1 reveals that a significant portion, approximately 21.93%, of the traffic entering urban areas originates from state highways, district roads, and urban road networks. This substantial influx of vehicular traffic from these critical transportation arteries is a primary contributing factor to the heightened levels of congestion witnessed within city limits. Consequently, it becomes imperative to develop and implement intelligent traffic signal systems that can effectively manage and regulate the intricate flow of vehicles converging from these various road networks into urban environments. By optimizing the timing and coordination of traffic signals, particularly at the intersections where these state, district, and urban roads converge with city streets, we can mitigate the adverse impacts of traffic congestion and facilitate smoother vehicular movement. Therefore, it is our responsibility as transportation researchers and engineers to design and deploy advanced traffic signal systems that can adapt to the dynamic traffic patterns arising from the convergence of these diverse road networks, thereby enhancing mobility and reducing the negative effects of urban traffic congestion.

Table 2.1:The trend in the category share of vehicle in the total registered vehicle(in Percentage)						
As on 31st March	Two wheeler	Car,Jeep &Tais	Buses*	Goods Vehicles	Other vehicles	Total
	(As % age of total vechicle population)					(Millions)
1951	8.80	52.00	11.10	26.80	1.30	0.30
1961	13.20	46.60	8.60	25.30	6.30	0.70
1971	30.90	36.60	5.00	18.40	9.10	1.90
1981	48.60	21.50	3.00	10.30	16.60	5.40
1991	66.40	13.80	1.50	6.30	11.90	21.40
2001	70.10	12.80	1.20	5.40	10.50	55.00
2002	70.60	12.90	1.10	5.00	10.40	58.90
2003	70.90	12.80	1.10	5.20	10.00	67.00
2004	71.40	13.00	1.10	5.20	9.40	72.70
2005	72.10	12.70	1.10	4.90	9.10	81.50
2006	72.20	12.90	1.10	4.90	8.80	89.60
2007	71.50	13.10	1.40	5.30	8.70	96.70
2008	71.50	13.20	1.40	5.30	8.60	105.30
2009	71.70	13.30	1.30	5.30	8.40	1 15.00
2010	71.70	13.50	1.20	5.00	8.60	127.70
2011	71.80	13.60	1.10	5.00	8.50	141.80
2012	72.40	13.50	1.00	4.80	8.30	159.50
2013	72.70	13.60	1.00	4.70	8.00	176.00
2014	73.10	13.60	1.00	4.60	7.70	190.70
2015	73.50	13.60	1.00	4.40	7.50	210.00
2016	73.50	13.10	0.80	4.60	8.10	230.00
2017	73.90	13.30	0.74	4.84	7.27	253.00
2018	74.40	13.37	0.71	4.69	6.85	272.60
2019	74.80	12.99	0.69	4.65	6.85	295.80

Source: Office of the State Transport Commissioner/UT Administrations.

Note: ’Other vehicles include tractors, trailers, three-wheelers (passenger vehicles/LMV and other miscellaneous vehicles) which are not classified separately. *Includes Omni buses since 2001.

The data presented in Table 2.1 [11] provides a compelling illustration of the rapid surge in vehicle registrations across India. This escalating trend in the number of registered vehicles on the nation's roads is an ominous indicator of the mounting pressure on urban transportation networks. As the vehicle population continues to swell, the resulting influx of additional cars and other modes of transport into city limits will inevitably exacerbate the already strained traffic conditions. This burgeoning vehicular presence will undoubtedly amplify congestion levels, particularly at critical junctions and intersections within urban areas, where converging traffic flows from multiple directions often converge. Consequently, these intersections will bear the brunt of intensified traffic volumes, leading to increased delays, longer queues, and heightened levels of gridlock. Therefore, proactive measures must be taken to address this impending crisis by implementing effective traffic management strategies and infrastructure enhancements to mitigate the adverse impacts of rising vehicle ownership on urban mobility.

4. Impacts of traffic congestion:

Traffic congestion can have a significant impact on various aspects of society and the environment. Here are some of the major impacts of traffic congestion:

4.1. Economic Impact: Congestion leads to delays and increased travel times, resulting in lost productivity and inefficiencies in the movement of goods and services. This can hurt businesses and the overall economy. According to estimates, traffic congestion in urban areas costs billions of dollars annually due to wasted fuel and lost productivity. [1]

4.2. Environmental Impact: Vehicles stuck in traffic consume more fuel and emit higher levels of greenhouse gases, such as carbon dioxide (CO_2), and other pollutants like nitrogen oxides (NO_x) and particulate matter (PM). These emissions contribute to air pollution, climate change, and potential health issues for people living in urban areas. [2]

4.3. Health Impact: Traffic congestion has a profound impact on the environment, leading to significant air and noise pollution that adversely affects the quality of life for commuters and residents alike. One of the primary environmental concerns is air pollution. When vehicles are forced to idle or crawl in stop-and-go traffic for extended periods, they continue to emit harmful gases such as Sulphur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), and nitrogen oxides (NO_x). While these emissions are lightweight compared to air, their harmful effects are significant. Prolonged exposure to these pollutants can lead to respiratory problems, cardiovascular diseases, and other health issues, particularly for vulnerable groups like children, the elderly, and those with pre-existing conditions.

4.4. Urban Sprawl: In some cases, traffic congestion can encourage people and businesses to relocate to suburban or exurban areas, leading to urban sprawl and increased commuting distances, further exacerbating the congestion problem. The relationship between urban sprawl and air pollution can be understood through two interconnected components: the impact of traffic congestion on emission rates per mile travelled, and the influence of low-density development patterns on vehicle miles travelled.

Traffic congestion, which is often exacerbated by urban sprawl, leads to an increase in emissions per mile traveled. [3] When vehicles are caught in heavily congested conditions, characterized by stop-and-go traffic and prolonged idling, their engines operate inefficiently, resulting in higher levels of pollutant emissions per mile traveled. These emissions include harmful substances such as carbon monoxide, nitrogen oxides, and particulate matter, which contribute to air pollution and associated health risks.

5. Methodology:

Consider a four-way intersection where traffic flows in from four different roads Fig.1, labeled A, B, C, and D. The traffic volume or distribution of vehicles approaching this intersection varies for each road. Specifically, the number of vehicles on Road A is 32, while on road B, the vehicular count is significantly higher at 74. In contrast, road C has a relatively low traffic volume of 6 vehicles, and road D falls somewhere in between with 38 vehicles.

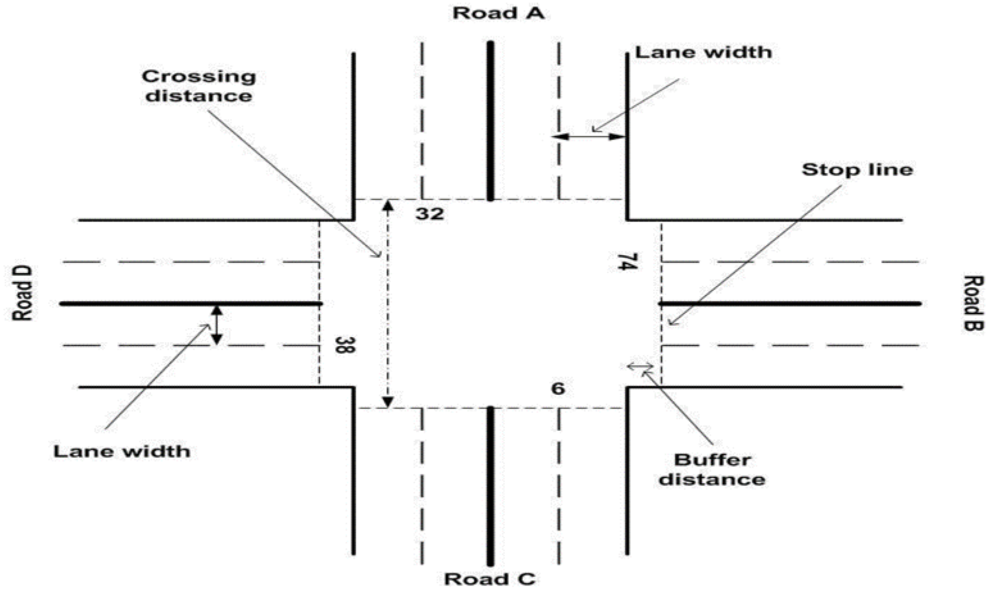

Fig.1. A four-way intersection where traffic flows in from four different roads.

This scenario presents a heterogeneous traffic situation, where the intersection needs to accommodate varying levels of vehicular flow from multiple directions. Optimizing the traffic signal timing and cycle lengths becomes crucial to ensure efficient traffic management and minimize delays or congestion at this intersection.

The given data points regarding the traffic distribution on each road serve as input parameters for developing models or algorithms to determine the ideal signal timing plans. These plans would need to allocate appropriate green light durations and coordinate the signal phases to facilitate smooth traffic flow while accounting for the disparities in traffic volumes across the four approaches.

The primary objective of optimizing signal timing based on the provided traffic distribution data is to maximize the throughput of vehicles traversing the intersection, thereby minimizing waiting times and enhancing the overall performance of the junction. Ultimately, such optimization strategies aim to improve the efficiency of the entire transportation network. However, it is noteworthy that most traffic signals installed on these critical arterial roads currently employ fixed-time control strategies, which have been widely recognized as highly inefficient [12]. To address this inefficiency and leverage the potential benefits of optimized signal timing, an automated traffic signal control system is proposed. The following code outlines an approach for implementing automatic traffic signalization, which can dynamically adapt to fluctuating traffic patterns and optimize signal timing accordingly.

```
#include <stdio.h>

#include <unistd.h> // For sleep() function
```

```
// Function declarations
void redLight(const char* junction);
void yellowLight(const char* junction);
void greenLight(const char* junction, int vehicles);
int main() {
    int vehicles[4];
    const char* junctions[] = {"A", "B", "C", "D"};
    int maxVehicles, maxIndex, cycleTime;
    while (1) {
        // Input number of vehicles for each junction
        printf("Enter the number of vehicles at junction A: ");
        scanf("%d", &vehicles[0]);
        printf("Enter the number of vehicles at junction B: ");
        scanf("%d", &vehicles[1]);
        printf("Enter the number of vehicles at junction C: ");
        scanf("%d", &vehicles[2]);
        printf("Enter the number of vehicles at junction D: ");
        scanf("%d", &vehicles[3]);
        for (int i = 0; i < 4; i++) {
            // Find the junction with the maximum number of vehicles
            maxVehicles = -1;
            for (int j = 0; j < 4; j++) {
                if (vehicles[j] > maxVehicles) {
                    maxVehicles = vehicles[j];
                    maxIndex = j;
                }
            }
            // Set cycle time for the green light
            cycleTime = maxVehicles * 2;
            if (cycleTime > 100) cycleTime = 100;
            // Display signals
```

```
            for (int j = 0; j < 4; j++) {
                if (j == maxIndex) {
                    greenLight(junctions[j], vehicles[j]);
                } else {
                    redLight(junctions[j]);
                }
            }
            // Wait for cycle time
            sleep(cycleTime);
            // Update the vehicle count for the junction with green light
            vehicles[maxIndex] = 0;
            // Display yellow light for all junctions
            for (int j = 0; j < 4; j++) {
                yellowLight(junctions[j]);
            }
            sleep(2); // Yellow light duration
        }
    }
    return 0;
}
// Function to simulate red light
void redLight(const char* junction) {
    printf("%s: RED light - STOP\n", junction);
}
// Function to simulate yellow light
void yellowLight(const char* junction) {
    printf("%s: YELLOW light - READY\n", junction);
}
// Function to simulate green light
void greenLight(const char* junction, int vehicles) {
    printf("%s: GREEN light - GO (%d vehicles)\n", junction, vehicles);
```

}

6. Results:

1. Inputs the number of vehicles at each of the four junctions.
2. Finds the junction with the maximum number of vehicles and sets its green light duration.
3. Limits the green light duration to 100 seconds.
4. Red light not to exceed 120 seconds.
5. Priority for green light display will be awarded to the maximum vehicles awaiting the lane and red lights for the others.
6. Waits for the duration of the green light.
7. Updates the vehicle count to zero for the junction that had the green light.
8. Displays yellow light for all junctions.
9. Repeats the cycle infinitely.

7. Conclusions:

This study underscores the critical importance of effective road traffic management in facilitating the efficient movement of goods and people. As urban populations and vehicle densities continue to rise exponentially, a multitude of factors contribute to the growing challenge of traffic congestion in cities. The research findings highlight that inadequate infrastructure is a significant contributor to traffic bottlenecks at various points within the transportation network. However, even in areas where the road infrastructure is ostensibly sufficient, improper utilization of these resources exacerbates congestion issues. Furthermore, the study identifies road geometry, particularly uneven road widths at junctions, commercial areas, and other critical points, as a compounding factor that further compounds the traffic situation. Ultimately, this research underscores the need for a comprehensive approach to traffic management, addressing both infrastructure deficiencies and optimizing the utilization of existing resources, while also considering the impact of road geometry on traffic flow.

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