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Optimization of Traffic Signal Timing to Minimize Queue Length at Tatarpur Intersection, Bhagalpur, Bihar

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Abstract - This study aims to determine the most effective traffic signal timing to reduce the number of idling vehicles at the Tatarpur Intersection during the rush hour 3 PM to 5 PM. The analysis considered all traffic movements, ensuring pedestrian safety by adhering to the U.S Federal Highway Administration's standard walking speed of four feet per second. To optimize signal duration, a linear programming approach was used, incorporating factors such as the average number of idling vehicles, existing pedestrian crossing times, and vehicular arrival rates at the intersection. Traffic flow data was collected for each movement to estimate the total number of vehicles waiting for a green signal. The findings indicate that the optimal green time for vehicles traveling from M.M College to the Railway Station was reduced by 16%. Similarly, the green time for vehicles traveling from Kotwali Chowk to M.M College also decreased by 16%. Additionally, the ideal green time for vehicles traveling from Station Road to either M.M College or Kotwali Chowk whether moving straight or making a right turn, was reduced by 12%. In conclusion, assigning longer green times to movements with higher vehicle arrivals does not always result in a proportional decrease in queuing. An extended green phase can lead to excessively long cycle times, which may cause longer queues in other directions. Thus, a balanced approach to traffic signal timing is crucial for optimizing overall intersection performance.

Key Words: Traffic Signal Timing, Idling Vehicles, Linear Programming, Intersection Performance, Pedestrian Safety

1.INTRODUCTION

Traffic signals at crossing points are essential for ensuring the safety of automobiles as well as pedestrians. Crossing points pose a safety risk to traffic because traffic follows in cross directions. Traffic signal durations must be manipulated to optimize the flow of traffic through the crossing points. Furthermore, improving traffic signals at crossing points and reducing vehicle idling can also contribute significantly to lowering fuel consumption and emissions, Mannering et al. (2020) & Stevanovic et al. (2009).

When designing traffic signals with a fixed timing pattern, the Webster formula is commonly used to calculate the ideal cycle length that minimizes delays, but this formula tends to result in a long cycle time in heavy, congested traffic conditions, Zakariya et al. (2016). Since traffic congestion at the intersection is mostly caused by the formation of long queues, this study chooses to employ an alternative approach by considering queue length as the primary measure to address traffic congestion, even though delay-based approaches are typically more common to determine the optimal signal plan Mannering et al. (2020). Using non-standardized traffic signal durations will improve vehicular and pedestrian traffic flow, X. Yang et al. (2004) at intersections, considering the rate of traffic flow and combined with different widths of crosswalks.

This study aims to optimize traffic signal durations at the Tatarpur Chowk intersection in Bhagalpur, Bihar, during the afternoon rush hour, which is from 3 PM to 5 PM. To achieve this objective, the study simplifies the traffic system at Tatarpur Chowk using Linear Programming(LP) to examine the existing condition, such as fluctuations in traffic demand.

2. Literature Review

The live feed is first processed before being transmitted to the servers, where a C++ based algorithm analyzes the data to produce results. A comparison between hard-coded and dynamically coded approaches revealed that the dynamic algorithm performed 35% better, Khushi et al.(2017).

An Arduino UNO-based system designed to ease traffic congestion and minimize waiting times. It captures images using a camera and processes them in MATLAB, where saturation and hues are removed to generate a threshold image for traffic density estimation. The Arduino communicates with MATLAB via USB and preinstalled simulation packages to adjust green light durations based on vehicle count and density. However, this approach has several limitations, including overlapping vehicles that make counting difficult, and nonvehicular objects such as billboards, poles, and trees that interfere with detection since they also appear in black and white, Vogel et al. (2018).

A fuzzy logic-based traffic light system has been developed to adapt to real-time traffic conditions. It utilizes two fuzzy controllers, each with three inputs and one output, to manage primary and secondary driveways. Simulations using VISSIM and MATLAB demonstrated improved traffic flow in low-density scenarios, Zaid et al. (2017).

An intelligent traffic light system integrating artificial neural networks (ANN) with a fuzzy controller. Cameras installed at intersections capture images, which are first converted to grayscale and normalized. A sliding window technique is then applied for segmentation, allowing vehicle counting irrespective of size. The ANN processes the segmented images, and its output is used by the fuzzy controller to determine the red and green light durations. The system achieved an average error rate of 2% with an execution time of 1.5 seconds, Renjith et al. (2018).

A support vector machine (SVM) algorithm combined with image processing techniques. It captures frames from live video feeds, processes them using Open CV, and converts them to grayscale before applying SVM. This system not only estimates traffic density but also detects red light violations, Kanungo et al. (2014).

A queueing model-based study was conducted to evaluate the performance of Continuous Flow Intersection (CFI) under multidimensional traffic conditions. The model incorporated key performance indicators such as average number of vehicles in the system and queue, average time spent in the system, average waiting time in the queue, and traffic intensity. Simulations were performed using MATLAB, considering heterogeneous traffic flow scenarios. The results showed that the CFI design significantly improved traffic efficiency compared to conventional intersection models, reducing delay and increasing throughput, Shinde et al. (2019).

Various methodologies for traffic light management systems, noting that they all follow a common framework: selecting input data, extracting traffic parameters, processing the data, determining traffic density, and updating the system parameters accordingly, Saili et al.(2016).

3. Signalized Intersection

Before drilling into the details of the study, a discussion on the nature of the Tatarpur Chowk signalized intersection shall be presented. At Tatarpur Chowk intersection, there are two lanes in each direction of the road. From M.M College Bhagalpur, a vehicle can either go straight to the railway station or take a left turn to go to Kotwali Chowk. And a vehicle can go to either M.M College Bhagalpur by taking a right turn or can go to the railway station road by taking a left turn at Kotwali Chowk.

A pre-timed 125-second cycle length is adopted for the intersection during the study period. Besides, all red times are assigned zero for all phases at the intersection in this study. In addition, the startup delay at the start of the green indication and the clearance delay are assumed to be zero and thus neglected in this model. Subsequently, the term "green time" comprises both green and yellow time. On the other hand, the term red time in this study accordingly means effective red time itself.

The signal control at the intersection consists of three phases, in which out of these three phases, two sides of the intersection simultaneously consolidate vehicles in their lanes. When the green time of any phase of the given movement ends, the vehicles on those lanes are signaled to stop, and vehicles on the next lane are signaled to proceed. The system runs in this manner until all three phases are activated, starting from the M.M College Bhagalpur right turn, the Railway Station left turn, and the Kotwali Chowk right turn, in that order, to complete the cycle.

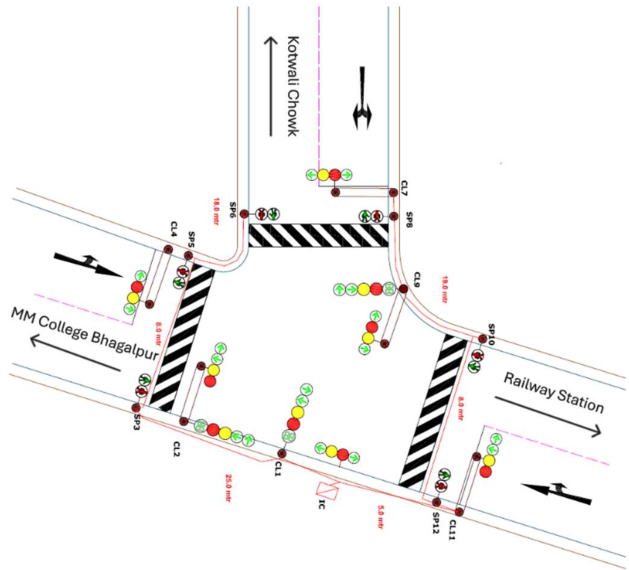

Fig -3.1: Tatarpur Intersection

Here, Fig. 3.1 illustrates the two-letter notation for vehicle arrival rate variables, which are explained as follows.

SR- Average vehicle arrival rate at the railway station road.

NR- Average vehicle arrival rate at the M.M College, Bhagalpur road.

TR- Average vehicle arrival rate at the Kotwali Chowk road.

Their effective green time are denoted by G_1, G_2 and G_3

G_1- Effective green time for TR phase.

G_2- Effective green time for SR phase.

G_3- Effective green time for NR phase

4. The Linear Programming Model

The goal is to minimize the number of automobiles idling at the intersection, considering the typical arrival rates of vehicles and the existing effective green duration for vehicles to turn right or left or make through movement. To approximate the number of vehicles, the study multiplied the arrival rate of automobiles travelling in each movement by the duration of the corresponding red time assigned to the affected traffic lanes. In other words, the queue length for each movement can be calculated by multiplying the rate of arrival by the corresponding idle time.

As an example, vehicles turning left from M.M College Bhagalpur to Kotwali Chowk and going through from M.M College Bhagalpur to Railway Station are in the lane NR, and the duration of the corresponding green signal is leveled as G_3. The duration of this cycle is $G_2+G_1+G_3$ in that order. Thus, the resultant queue length is $NR(G_2 + G_1)$.

Therefore, the objective function is,

$$\text{Min. } TR(G_2 + G_3) + SR(G_1 + G_3) + NR(G_2 + G_1). \quad (4.1)$$

5. Identification of Constraints

Effective green times should be maximized for those traffic lanes having relatively higher rates of traffic flow. However, pedestrian safety and vehicle flow rate, along with queue length, need to be considered as essential constraints for the traffic signal time at the intersection.

5.1. Pedestrian Constraint

According to the US Federal Highway Administration, the standard walking speed of pedestrians should be 4 feet per second for safe crosswalk countdown time at the intersection [10]. The width of the road at Tatarpur Chowk is 8 meters i.e, around 26 feet. This length is constant for all directions. To address safety concerns, the study uses the longest crosswalk on each street to establish a safe duration of the green time given to pedestrians. The minimum green time, corresponding to pedestrian safety, is determined by dividing the road width by the suggested pedestrian walking speed of 4 feet per second. So the Pedestrian constraints are,

$$G_2 > 6.5 \quad (5.1)$$
$$G_3 > 6.5 \quad (5.2)$$

5.2. Queue Length Constraints

To set the limit of the maximum number of vehicles waiting to make the turn for each movement, constraints related to queue length for all three considered turns are set in this study. To optimize vehicular flow through the intersection, a maximum of ten idling vehicles was used as a limiting factor. Thus, the maximum number of vehicles in each lane waiting for a green indication is 20 multiplied by the number of lanes available for the traffic to proceed in each movement. Hence, the following constraints are established to control queue lengths at the intersection. Here, each direction of the intersection contains two lanes. Thus,

$$NR(G_2 + G_1) \leq 40 \quad (5.3)$$
$$SR(G_1 + G_3) \leq 40 \quad (5.4)$$
$$TR(G_2 + G_3) \leq 40 \quad (5.5)$$

5.3. Constraints Related to Vehicle Flow

Constraints related to vehicle flow were established for all the vehicles making through, left, and right turns. For automobiles making through movement, the absolute distance for the final vehicle to proceed across the intersection was the width of the perpendicular road with an additional length of twenty vehicles. As the standard length has been taken of the vehicle from the Indo-HCM. Since we have data of the cars, bikes, buses, and autorickshaws. Thus, the average length of these vehicles is 15.50 feet. Besides the standard vehicle length ranges from 6.13 feet for bikes to 33.13 feet for buses Chandra et al.(2017). Thus, the vehicle length of 15 feet was estimated to calculate the constraints in this study. So this produced an estimated travel distance of 26 + (20 ∗ 15) feet = 326 feet for a vehicle proceeding through either the railway station or M.M College Bhagalpur, as shown in figure 5.1.

For example, the curve distance for a vehicle coming from Railway Station and making the right turn to go to Kotwali Chowk is approximated using a turning radius of 13 feet. Thus, the corresponding curve distance is estimated to be $1/2\,\pi * 13 = 20.42$ feet, shown in Figure 5.1.

In this study, the speed limit of vehicles has been taken 22 kmph i.e 20 fps, unless otherwise posted. However, a vehicle idling at an intersection starts from a speed of zero when the signal turns green. In addition, vehicles either going right or left end to travel slower than vehicles moving through. To provide a realistic speed of vehicles turning left or right through this intersection, a speed of 20 feet per second was applied. The minimum green time under the vehicle flow constraint for each straight movement is determined by dividing the total distance for the last car to travel across the intersection by 20 fps, the speed limit.

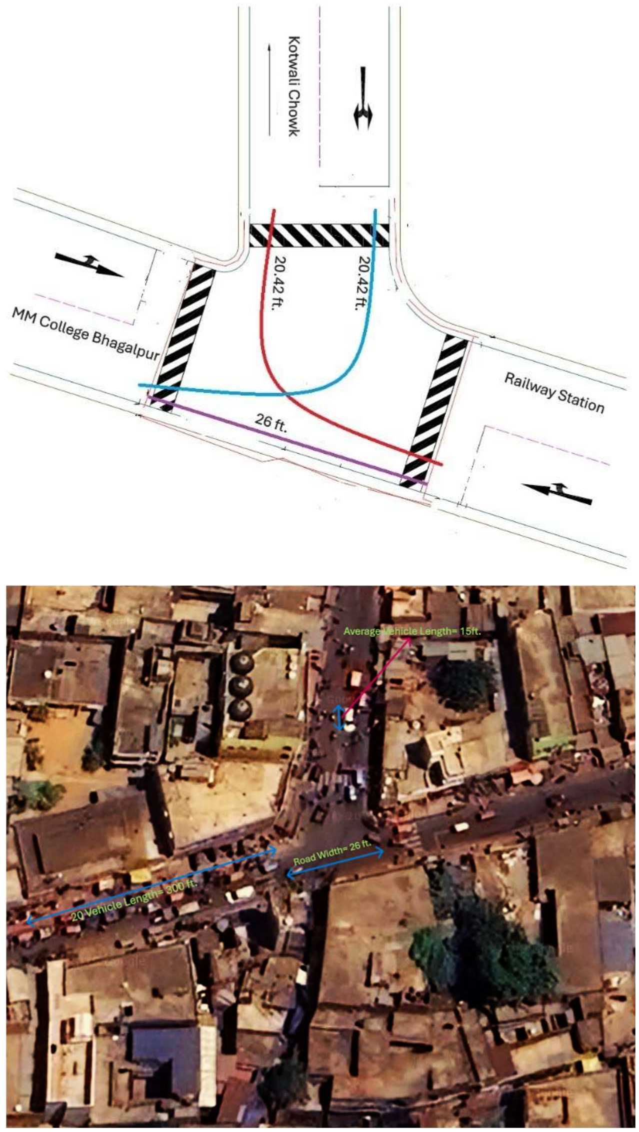

Fig -5.1: Intersection Lengths

Correspondingly, the vehicle flow constraints for each left or right turn estimate the minimum green time by adopting the 20 fps speed to divide the combination of 20 vehicle length plus the curve length. The longer duration for each movement, governed by the same green time, is proposed in the model. So, the vehicle flow constraints are established as follows:

$$G_1 \geq 17.3 \quad (5.6)$$
$$G_2 \geq 16.02 \quad (5.7)$$
$$G_3 \geq 16.02 \quad (5.8)$$
$$G_2 \geq 17.3 \quad (5.9)$$

6. Data Collection

We extend our sincere gratitude to the Smart City Management Bhagalpur authority for providing the raw data of the Tatarpur intersection, which has been valuable for the research. They collected data using video cameras. Given the existing traffic signal patterns at the intersection, the number of vehicles was assigned a designation specifying the lane in which they arrived at the intersection, their intended direction of travel, and the existing cycle of $G_2+G_1+G_3$. The vehicle arrival rate of each movement can be ascertained by dividing the total arrivals by the duration of data collection time. The statistical analysis shows that the vehicle arrival rates are: NR = 0.1413 veh/sec, SR = 0.0429 veh/sec, and TR = 0.1020 veh/sec.

7. Linear Programming Code

The study utilized linear programming and used Pyomo as a diagnostic tool. Here, we acknowledge that the stochastic simulation process would have been more accurate since the fluctuation of vehicle arrival rates is neglected when linear programming is adopted as the study tool. However, the study opts to scope merely on the two hour afternoon peak in which the vehicle arrivals rates at the intersection are perceived to be consistently high therefore the fluctuations were assumed to have less impact and negligible in this study since the short time interval of similar traffic demand was segmented Zhang et al. (2010). The full Pulp programming code used, which includes the objective function, constraints for vehicle flow rates, constraints for queue lengths, and crosswalk countdown time constraints, is presented given below.

```
from pulp import LpProblem, LpVariable, LpMinimize, LpStatus, PULP_CBC_CMD

# Define the problem
problem = LpProblem("Traffic_Optimization", LpMinimize)

# Epsilon for strict inequalities
epsilon = 5.001

# Decision variables
G1 = LpVariable("G1", lowBound=0)  # G1 >= 0
G2 = LpVariable("G2", lowBound=0)  # G2 >= 0
G3 = LpVariable("G3", lowBound=0)  # G3 >= 0

# Objective function
problem += (0.1020 * (G2 + G3) + 0.0429 * (G1 + G3) + 0.1413 * (G2 + G1)), "Total_Time"

# Constraints with strict inequalities
problem += 0.1413 * (G2 + G3) <= 40 - epsilon, "Queue_Length_1"
problem += 0.0429 * (G1 + G3) <= 40 - epsilon, "Queue_Length_2"
problem += 0.1020 * (G2 + G1) <= 40 - epsilon, "Queue_Length_3"

problem += G2 >= 6.5 + epsilon, "Pedestrian_G2"
problem += G3 >= 6.5 + epsilon, "Pedestrian_G3"

problem += G1 >= 17.3 + epsilon, "Vehicle_flow_G1"
problem += G2 >= 16.02 + epsilon, "Vehicle_flow_G2"
problem += G3 >= 16.02 + epsilon, "Vehicle_flow_G3"

# Solve the problem
problem.solve(PULP_CBC_CMD())

# Output the results
print("Status:", LpStatus[problem.status])
if problem.status == 1:  # 1 means Optimal
    print("G1:", G1.value())
    print("G2:", G2.value())
    print("G3:", G3.value())
else:
    print("Solution not found. Status:", LpStatus[problem.status])
```

Python script for traffic signal optimization using PuLP

8. Result

The study concludes that the optimal effective green time for through movement i.e., vehicles traveling straight from M.M College Bhagalpur to the railway station should be approximately 21 seconds. Similarly, the optimal green time for vehicles making a right turn toward Kotwali Chowk is around 22 seconds, while for those making a right turn toward M.M College Bhagalpur, it is about 21 seconds. These timings are ideal for minimizing vehicle idling at the intersection while also ensuring pedestrian safety and accommodating the volume of vehicles waiting to proceed.

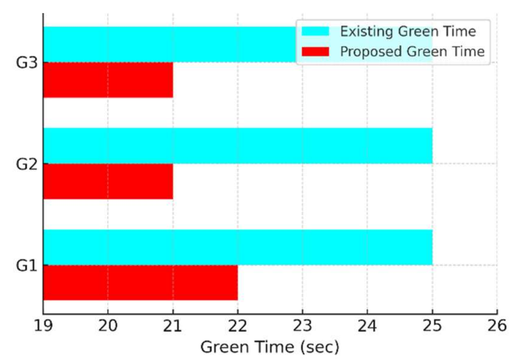

Fig -8.1: Comparison between Existing and Proposed Green Time

8. Conclusion

This study successfully demonstrates the application of a linear programming model to optimize traffic signal timings at the Tatarpur Intersection in Bhagalpur, with the aim of minimizing vehicle idling during peak hours. By incorporating constraints related to pedestrian safety, vehicle flow, and queue length, the proposed signal timings significantly reduced unnecessary delays and improved intersection performance. The optimized green time, approximately 21 to 22 seconds across different phases, reflects a balanced allocation that considers both vehicular demand and pedestrian requirements.

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