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Optimization and Sensitivity Analysis of Traffic Signal Timing Using PCU Based Linear Programming at Tilkamanjhi Intersection, Bhagalpur, Bihar

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Abstract : This study presents an optimization of traffic signal timings at the Tilkamanjhi Intersection to minimize vehicle idling during the morning peak hour (10:00–11:00 AM). All traffic movements were considered, with pedestrian safety ensured according to the U.S. Federal Highway Administration's standard walking speed of 4 ft/sec. A linear programming model was implemented using the PuLP library in Python, incorporating constraints on vehicular arrival rates, queue lengths, pedestrian crossing times, and flow expressed in Passenger Car Units (PCU). Field data were collected to estimate vehicle queues for each approach. The optimized signal plan reduces green times by 28% for Zeromile, 32% for Barari, 11%, and from Kachari Chowk and 13% for Kachari Chowk, improving traffic flow efficiency while maintaining pedestrian safety. To evaluate robustness, a sensitivity analysis was conducted by varying arrival rates from –80% to +80% of base conditions; results indicate that the optimal timing strategy remains stable across all tested scenarios, consistently yielding feasible and efficient signal allocations.

Index Terms **-** Traffic Signal Optimization, Sensitivity Analysis, Linear Programming, Passenger Car Units (PCU), Pedestrian Safety

1. Introduction

Traffic signals at intersections are crucial for ensuring the safety of both vehicles and pedestrians, as these locations involve traffic moving in conflicting directions. Properly optimized signal timings are essential to facilitate smooth traffic flow through intersections. Additionally, improving signal. operations and reducing vehicle idling at these points can significantly decrease fuel consumption and vehicular emissions [1, 2].

When designing traffic signals with fixed timing patterns, the Webster formula is commonly applied to calculate the optimal cycle length that minimizes overall delay. However, this formula often produces longer cycle times under heavy or congested traffic conditions [3]. Since congestion at intersections is primarily attributed to the formation of long vehicle queues, this study adopts an alternative approach that prioritizes queue length as the principal parameter for mitigating congestion, even though delay-based methods are conventionally preferred for determining optimal signal plans [2]. Furthermore, implementing non-standardized traffic signal durations which consider the rate of vehicular flow along with varying crosswalk widths can significantly enhance both vehicular and pedestrian movement efficiency at intersections [4].

At the Tilkamanjhi intersection, traffic movements can be characterized into four primary directions as follows: vehicles traveling from Zeromile either proceeding straight toward Manali Chowk or turning right toward Kachari Chowk; vehicles traveling from Barari either proceeding straight toward Kachari Chowk or turning right toward Zeromile; vehicles traveling from Manali Chowk either proceeding straight toward Zeromile or turning right toward Kachari Chowk; and vehicles traveling from Kachari Chowk either proceeding straight toward Barari or turning right toward Zeromile. Given that automobiles are permitted to make left turn on the red indications; thus, only right turn and through movement traffic are focused in this study.

This study aims to optimize the traffic signal durations at the Tilkamanjhi intersection in Bhagalpur, Bihar, during the morning rush hour between 10:00 AM and 11:00 AM. To achieve this objective, the study employs a Linear Programming (LP) approach to analyze the existing traffic conditions and account for fluctuations in traffic demand at the intersection.

2. Literature Review

Urban traffic congestion has become a significant challenge due to the rapid increase in population and the number of vehicles in cities. Traffic jams not only lead to longer travel times and driver stress but also result in higher fuel consumption, increased transportation costs, and elevated carbon dioxide emissions. Traffic signal controllers play a key role in managing vehicle flow, yet conventional traffic patterns are often nonlinear, complex, and operate on fixed schedules rather than responding dynamically to traffic conditions. This study proposes an adaptive traffic control system that utilizes image processing in MATLAB to adjust the durations of green, amber, and red lights based on real time traffic density and vehicle counts. Two Arduino UNO boards are employed in the system: one manages the green and amber lights, while the other controls the red light, enabling continuous and automated traffic signal adjustments [5].

This study analyzes traffic composition at a specific intersection using PCU (Passenger Car Unit) values, revealing that passenger cars and trucks contribute most to congestion, while buses, though fewer, have a high impact due to larger PCU. The total traffic load is 160 PCU/min, highlighting the need to consider both vehicle type and volume for effective traffic management, urban planning, and infrastructure development [6].

Urban traffic continues to grow each year with the increasing number of vehicles, leading to congestion, reduced travel speeds, and higher fuel consumption. This study presents a fuzzy logic-based adaptive traffic signal controller for an isolated intersection, which dynamically adjusts green light durations based on real-time data such as queue length, arrival flow, and exit flow. The controller separately manages primary and secondary driveways according to traffic volume. Simulation results demonstrate that the proposed system performs better than fixed-time signals under varying traffic conditions[7].

The PCU concept allows conversion of heterogeneous traffic into equivalent passenger car units, accounting for vehicle size and speed. This study develops a simple model using traffic composition and volume to estimate dynamic PCU factors, validated with field data[8].

Traffic congestion and accidents are major issues in densely populated cities, leading to wasted time and increased costs. Traditional fixed-time traffic signals are inefficient because they do not account for variations in vehicle volumes, resulting in imbalanced traffic flow. Intelligent transportation systems offer a smarter approach by dynamically adjusting signal timings based on the number of vehicles at each intersection. This study develops an automated algorithm that uses artificial intelligence and image processing to control traffic signal durations and validates its performance by comparing results with manual control. Implementing this algorithm can help regulate traffic flow and reduce both travel and waiting times on roads [9].

With population growth, vehicle numbers have increased, causing heavy traffic and wasting time and fuel. Traditional fixed-time signals are inefficient, while sensors can adjust signals based on traffic volumes. This study proposes using a digital camera to capture live road images, estimate traffic density, and dynamically control signals for more efficient traffic flow [10].

Traffic congestion, especially in large cities, is worsened by fixed traffic signals and increasing vehicle demand. This study uses live video feeds and image processing to estimate real-time traffic density and dynamically adjust signal timings. The approach aims to reduce congestion, waiting time, fuel consumption, and accidents, while providing data for future road planning and potential multi-signal synchronization [11].

Traffic congestion in urban areas has prompted the development of intelligent traffic management systems, as traditional fixed-time signals are often inadequate. Approaches using sensors or video based vehicle detection have been proposed to optimize signal timings and improve traffic flow [12].

3. Signalized Intersection

Before proceeding with the detailed study, it is important to discuss the nature of the Tilkamanjhi Chowk signalized intersection. This intersection consists of two lanes in each direction and serves as a major connecting point between Zeromile, Manali Chowk, Barari, and Kachari Chowk. Vehicles approaching from Zeromile may either proceed straight towards Manali Chowk, turn right towards Barari, or turn left towards Kachari Chowk. Similarly, vehicles from Barari may travel straight to Kachari Chowk, turn right towards Manali Chowk, or turn left towards Zeromile. Traffic originating from Manali Chowk can either move straight towards Zeromile, turn right towards Barari, or turn left towards Kachari Chowk. Likewise, vehicles from Kachari Chowk may proceed straight towards Barari, turn right towards Zeromile, or turn left towards Manali Chowk. Thus, the intersection accommodates multiple conflicting movements, making it a critical point for traffic regulation and optimization.

In this study, a fixed cycle length of 190 seconds has been adopted for the intersection. The all-red intervals for every phase have been considered zero. A startup delay at the beginning of the green phase has been assumed to be negligible and therefore excluded from the model. However, clearance times have been incorporated to ensure realistic signal operation: a vehicle clearance time of 4 seconds and a pedestrian clearance time of 3 seconds have been considered. Accordingly, the term green time in this study represents the sum of the green and yellow intervals, while red time strictly refers to the effective red interval.

The signal control system at the intersection operates with four distinct phases. In three of these phases, vehicles from different approaches are allowed to move simultaneously while consolidating within their respective lanes. When the green interval of a given phase terminates, the vehicles on those approaches are instructed to stop, and the subsequent phase is activated, permitting movement from the next approach. This sequence continues until all four phases are executed, beginning with the Zeromile approach and completing one full signal cycle.

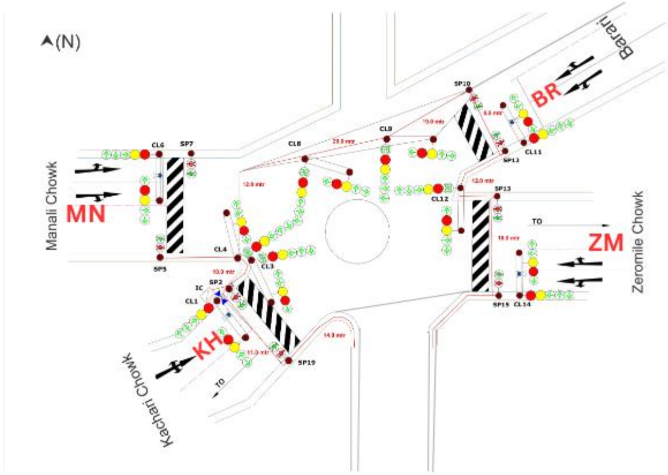

Figure 1: Tilkamanjhi Intersection

Here, the two-letter notation as shown in the Figure 1 illustrates for vehicle arrival rate variables, which are explained as follows

ZM- Average vehicle arrival rate at Zero-Mile road.
BR- Average vehicle arrival rate at Barari road.
MN- Average vehicle arrival rate at the Manali Chowk road.
KH- Average vehicle arrival rate at the Kachari Chowk road.

Their effective green time are denoted by G_1 , G_2, G_3 and G_4

G_1- Effective green time for ZM phase.
G_2- Effective green time for BR phase.
G_3- Effective green time for MN phase.
G_4-Effective green time for KH phase.

4. The Linear Programming Model

The objective of this study is to minimize the signal timing to reduce the number of vehicles idling at the intersection, taking into account the typical vehicle arrival rates and the existing effective green durations for right-turn, left-turn, and through movements. To estimate the number of vehicles waiting, the study multiplies the arrival rate for each movement by the duration of the corresponding red time assigned to the affected lanes. In other words, the queue length for each movement can be calculated as the product of the vehicle arrival rate and the corresponding idle time.

As an example, vehicles turning right from Manali Chowk to Kachari Chowk and going through from Manali Chowk to Zeromile are in the lane MN and the duration of the corresponding green signal is leveled as G_3. The duration of the cycle is $G_1+ G_2+ G_4+ G_3$in that order. Thus, the resultant queue length is MN×($G_1+ G_2+ G_4$)

Therefore, the objective function is,

$$\text{Min. } ZM\,(G_2+G_3+G_4) + BR\,(G_1+G_3+G_4) + MN\,(G_1+G_2+G_4) + KH\,(G_1+G_2+G_3) \tag{1}$$

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 Constraints

According to the U.S. Federal Highway Administration, a standard pedestrian walking speed of 4 ft/sec is recommended for determining crosswalk timings at intersections [13]. In this study, the longest crosswalk length on each approach has been considered to ensure safety. For the Zeromile (ZM) approach, the crossing length is 39 ft, while for the Kachari (KH) approach, it is 29 ft. The pedestrian green time is therefore calculated as:

$$Pedestrian\ Green\ Time(Gi) = \frac{Crosswalk\ Length}{Walking\ Speed} + ClearanceTime$$

So,

$$G_1 \geq \frac{39}{4} + 3$$

And,

$$G_4 \geq \frac{29}{4} + 3$$

Thus,

$$G_1 \geq 14 \tag{2}$$
$$G_4 \geq 11 \tag{3}$$

Here, an additional 3 seconds have been allocated to each phase to accommodate pedestrian crossing, ensuring that any pedestrian already within the intersection can safely complete the crossing before the next phase begins. So, the pedestrian green times are taken as approximately 14 seconds for G1 and 11 seconds for G4, ensuring adequate time for safe pedestrian crossing.

5.2 Queue Length Constraints

In this study, constraints on queue length have been introduced to limit the maximum number of vehicles waiting to turn in each movement. To optimize traffic flow at the intersection, a maximum of twenty idling vehicles per lane has been considered as the threshold. Accordingly, the maximum number of vehicles waiting for a green indication in any movement is expressed as 20 multiplied by the number of lanes assigned to that movement. Since each approach at the intersection consists of two lanes, the corresponding queue length constraints are formulated on this basis to regulate vehicular accumulation and ensure efficient signal operation.

$$ZM(G_2 + G_3 + G_4) \leq 40 \quad (4)$$

$$BR(G_1 + G_3 + G_4) \leq 40 \quad (5)$$

$$MN(G_1 + G_2 + G_4) \leq 40 \quad (6)$$

$$KH(G_1 + G_2 + G_3) \leq 40 \quad (7)$$

5.3 Constraints Related to Vehicle Flow

Constraints on vehicle flow were formulated for through and right-turn movements at the intersection. For through movements, the maximum distance covered by the last vehicle in the queue was taken as the width of the intersecting road, along with an additional length equivalent to twenty vehicles. The standard vehicle length was adopted from the Indo-HCM guidelines. Since data were available for cars, two-wheelers, buses, and auto-rickshaws, an average vehicle length of 15.50 feet was obtained. Since, vehicle lengths vary significantly, ranging from 6.13 feet for two-wheelers to 33.13 feet for buses [14]. For the purpose of this study, an average vehicle length of 15 feet has been assumed for estimating the constraints. This resulted in an estimated travel distance of 269 +(15×20) = 569 feet for a vehicle moving through from Zeromile to Manali Chowk.

The variation in vehicle turning radii due to differences in size and power must also be considered. In this study, each turning curve is approximated as one-fourth of an ellipse perimeter, taking into account the corresponding major radius (a) and minor radius (b).

$$Curve\ Distance = \frac{\pi}{2}\sqrt{\frac{a^2 + b^2}{2}}$$

For example, the curve distance for a vehicle coming from Barari and making a right turn to go to Manali Chowk is approximately given by the major and minor radii of 239 ft. and 33 ft., respectively. Thus, the corresponding curve distance is estimated to be: 268 ft.. The lengths of all right turn curves are summarized in Table 1. Also lengths of the through movement at Tilkamanjhi Intersection are given in Table 2.

Movements	Major Radius (ft.)	Minor Radius (ft.)	Curve distance (ft.)
Zeromile to Barari	72	32	87
Barari to Manali Chowk	239	33	268
Manali Chowk to Kachari Chowk	98	95	151
Kachari Chowk to Zeromile	190	82	230

Table 1 : Distance of RightTurn Curves at Tilkamanjhi Intersection

Movements	Straight Distance (ft.)
Zeromile to Barari	269
Barari to Manali Chowk	236
Manali Chowk to Kachari Chowk	249
Kachari Chowk to Zeromile	237

Table 2: Through distance at Tilkamanjhi Intersection

In this study, the speed of vehicles has been assumed to be 22 km/h (approximately 20 ft/sec), unless otherwise posted. Vehicles starting from a stop at the intersection begin from zero speed when the signal turns green. Additionally, vehicles making right turns generally travel more slowly than those proceeding straight. To represent realistic turning speeds at this intersection, a speed of 20 ft/sec has been applied for vehicles turning right. The minimum green time for each through movement, under the vehicle flow constraint, is calculated by dividing the total distance required for the last vehicle to clear the intersection by the speed limit of 20 ft/sec. Similarly, the vehicle flow constraints for the right turn estimate the minimum green time by dividing the sum of the curve length and the combined length of 20 vehicles by a speed of 20 ft/sec. Furthermore, an additional 4 seconds has been added to the green time of each phase to ensure that any vehicle already in the middle of the intersection can safely complete its movement. The model adopts the longer duration among the movements governed by the same green time. Accordingly, the vehicle flow constraints are formulated as follows:

Zeromile to Manali Chowk (Through)

$$G_1 \geq \frac{269 + (15 \times 20)}{20}$$

Thus,

$$G_1 \geq 28.45\ sec. \tag{8}$$

Barari to Manali Chowk (Right Turn),

$$G_1 \geq \frac{268 + (15 \times 20)}{20}$$

Thus,

$$G_1 \geq 28.45\ sec. \tag{9}$$

Barari to Kachari Chowk (Through)

$$G_2 \geq \frac{236 + (15 \times 20)}{20}$$

Thus,

$$G_2 \geq 26.80\ sec. \tag{10}$$

Manali Chowk to Kachari Chowk (Right Turn),

$$G_2 \geq \frac{251 + (15 \times 20)}{20}$$

Thus,

$$G_2 \geq 22.55\ sec. \tag{11}$$

Manali Chowk to Zeromile (Through),

$$G_3 \geq \frac{249 + (15 \times 20)}{20}$$

Thus,

$$G_3 \geq 27.45\ sec. \tag{12}$$

Kachari Chowk to Zeromile (Right Turn),

$$G_3 \geq \frac{229 + (15 \times 20)}{20}$$

Thus,

$$G_3 \geq 26.45\ sec. \tag{13}$$

Kachari Chowk to Barari (Through),

$$G_4 \geq \frac{236 + (15 \times 20)}{20}$$

Thus,

$$G_4 \geq 26.80\ sec. \tag{14}$$

Zeromile to Barari (Right Turn),

$$G_4 \geq \frac{87 + (15 \times 20)}{20}$$

Thus,

$$G_4 \geq 19.35\ sec. \tag{15}$$

6. Data Collection

The arrival rate of vehicles for each movement can be adjusted to account for differences in vehicle type using Passenger Car Units (PCU). The PCU represents the relative impact or impedance of a vehicle compared to a standard passenger car, allowing a heterogeneous traffic stream to be expressed in equivalent passenger car units.

For each vehicle type, the equivalent number of passenger cars is calculated using the PCU value. According to Indo-HCM [14], the PCU for a vehicle type i can be estimated as the following equation:

$$PCU_i = \frac{V_c/V_i}{A_c/A_i}$$

where, Vc and Vi are the speed of a standard car and vehicle type 'i', respectively and Ac and Ai are their projected rectangular area on the road.

Vehicle Type	Range	Median
Car	1.00	1.00
Two-Wheeler	0.20-0.50	0.30
Auto Rikshaw	1.10-2.00	1.20
Bus	2.80-4.80	4.50

Table 3:Range of PCU (Source-Indo-HCM[14])

Given the existing traffic signal patterns at the intersection, each vehicle was assigned a designation based on the lane it arrived in and its intended direction of travel, following the signal cycle G_2+G_1+G_3+G_4. The arrival rate for each movement is determined by dividing the total arrivals during the data collection period by its duration. To account for the effect of different vehicle types on traffic flow, each vehicle is converted into its Passenger Car Unit (PCU) equivalent. The arrival rate in PCU per unit time is then calculated as,

$$\lambda_{PCU} = \frac{\sum_i \quad (N_i * PCU_i)}{T}$$

where $N_i$is the number of vehicles of type i, $PCU_i$is the corresponding PCU value, and $T$is the data collection duration. This approach standardizes heterogeneous traffic streams into a common unit, as illustrated in Table 4–7, which presents the PCU values for different phases. This facilitates more accurate modeling of queue lengths and optimization of signal timings. Furthermore, Figure 2 presents a comparison between vehicle flow (veh/hr) and PCU/hr across all phases.

Hence, the vehicle arrival rates are: ZM = 0.1358 PCU/s, BR = 0.0356 PCU/s, MN = 0.0941 PCU/s, and KH = 0.1591 PCU/s.

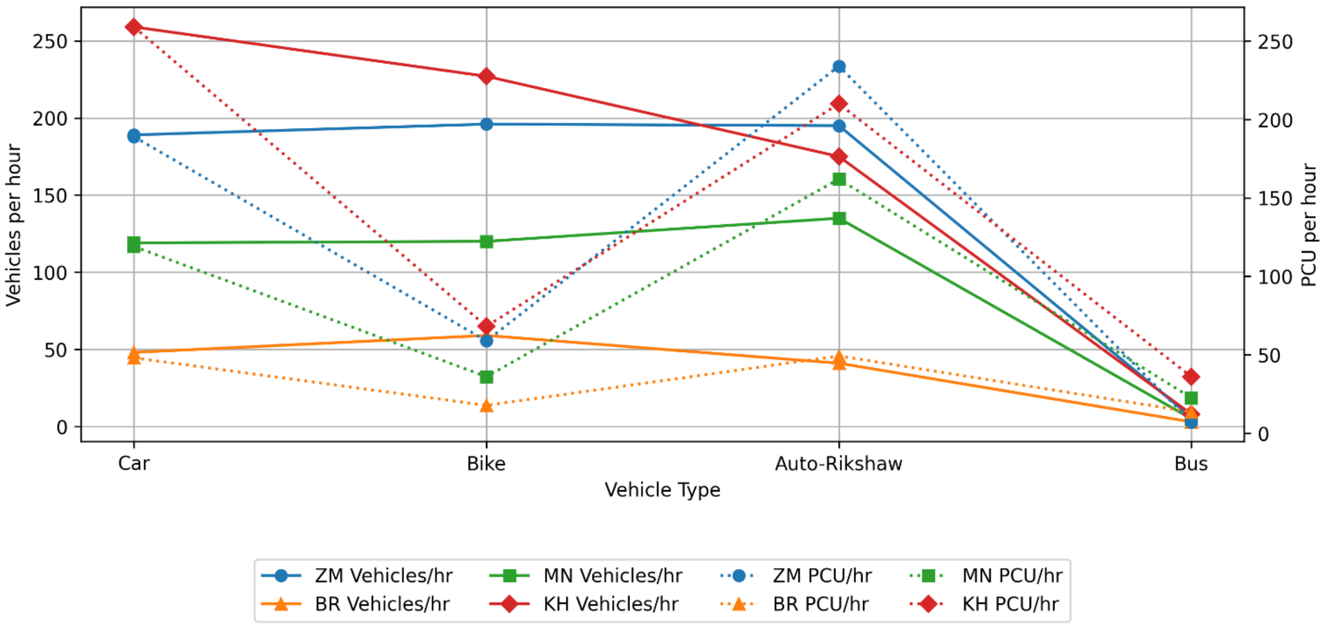

Figure 2 : Comparison of Vehicle Flow (Vehicles/hr) and PCU/hr for All Phases (ZM, BR, MN, KH)

Vehicle Type	Vehicle(10:00 -11:00 AM)	PCU
Car	189	189
Two-Wheeler	196	58.8
Auto Rikshaw	195	234
Bus	6	7.2
Total	586 veh/hr.	489 PCU/hr.

Table 4: PCU values for ZM phase

Vehicle Type	Vehicle(10:00-11:00 AM)	PCU
Car	48	48
Two-Wheeler	59	17.7
Auto Rikshaw	41	49.2
Bus	3	13.5
Total	151 veh/hr.	128.4 PCU/hr.

Table 5: PCU values for BR phase

Vehicle Type	Vehicle(10:00 -11:00 AM)	PCU
Car	119	119
Two-Wheeler	120	36
Auto Rikshaw	135	162
Bus	5	22.5
Total	379 veh/hr.	339.5 PCU/hr.

Table 6: PCU values for MN phase

Vehicle Type	Vehicle(10:00-11:00 AM)	PCU
Car	259	259
Two-Wheeler	227	68.1
Auto Rikshaw	175	210
Bus	8	36
Total	669 veh/hr.	PCU/hr.

Table 7: PCU values for KH phase

7. Linear Programming Code

The study utilized a linear programming approach implemented through the PuLP library in Python as the primary modeling tool. Although a stochastic simulation model could potentially yield higher accuracy by accounting for fluctuations in vehicle arrival rates, linear programming was deemed appropriate for this analysis minimal and assumed negligible within this high-demand interval [15]. The complete PuLP programming code, encompassing the objective function, vehicle flow constraints, queue length constraints, and pedestrian crosswalk timing constraints, is presented below.

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

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

# Small epsilon for strict inequalities
epsilon = 0.5

# Decision variables (all must be ≥ 0)
G1 = LpVariable("G1", lowBound=0)
G2 = LpVariable("G2", lowBound=0)
G3 = LpVariable("G3", lowBound=0)
G4 = LpVariable("G4", lowBound=0)

# Objective function (minimization)
problem += (0.1358 * (G2 + G3 + G4) +
            0.0356 * (G1 + G3 + G4) +
            0.0941 * (G1 + G2 + G4) +
            0.1591 * (G1 + G2 + G3)), "Total_Time"

# Queue length constraints
problem += 0.1358 * (G2 + G3 + G4) <= 40 - epsilon, "Queue_Length_1"
problem += 0.0356 * (G1 + G3 + G4) <= 40 - epsilon, "Queue_Length_2"
problem += 0.0941 * (G1 + G2 + G4) <= 40 - epsilon, "Queue_Length_3"
problem += 0.1591 * (G1 + G2 + G3) <= 40 - epsilon, "Queue_Length_4"

# Pedestrian constraints
problem += G2 >= 9.75 + 3, "Pedestrian_G2"
problem += G3 >= 7.25 + 3, "Pedestrian_G3"

# Vehicle flow constraints
problem += G1 >= 28.45 + 4, "Vehicle_flow_G1"
problem += G4 >= 26.80 + 4, "Vehicle_flow_G4"
problem += G3 >= 27.45 + 4, "Vehicle_flow_G3"
problem += G2 >= 26.80 + 4, "Vehicle_flow_G2"

# Solve the problem
problem.solve(PULP_CBC_CMD(msg=False))

# Display results
print("Status:", LpStatus[problem.status])

if problem.status == 1:
    print("Optimal Solution Found:")
    print("G1 =", G1.value())
    print("G2 =", G2.value())
    print("G3 =", G3.value())
    print("G4 =", G4.value())
    print("Objective (Total_Time) =", problem.objective.value())
else:
    print("Solution not found. Status:", LpStatus[problem.status])
```

The linear programming model was solved using PuLP, and the solution status was found to be optimal. The optimal green times obtained for each phase are summarized as follows:

$$G_1 = 32.45 \equiv 33\ sec.$$
$$G_2 = 30.80 \equiv 31\ sec.$$
$$G_3 = 31.45 \equiv 32\ sec.$$
$$G_4 = 30.80 \equiv 31\ sec.$$

8. Result

The study concludes that the optimal effective green times for each phase at the Tilkamanjhi intersection are as follows: 33 seconds for Phase G_1, 31 seconds for Phase G_2, 32 seconds for Phase G_3, and 31 seconds for Phase G_4. These timings were determined using a linear programming model developed with the PuLP library in Python, which incorporates constraints related to queue length, pedestrian crossing, and vehicular flow. An additional 4 seconds allowance was included in each phase to enable vehicles already within the intersection to clear it safely before the next phase begins.

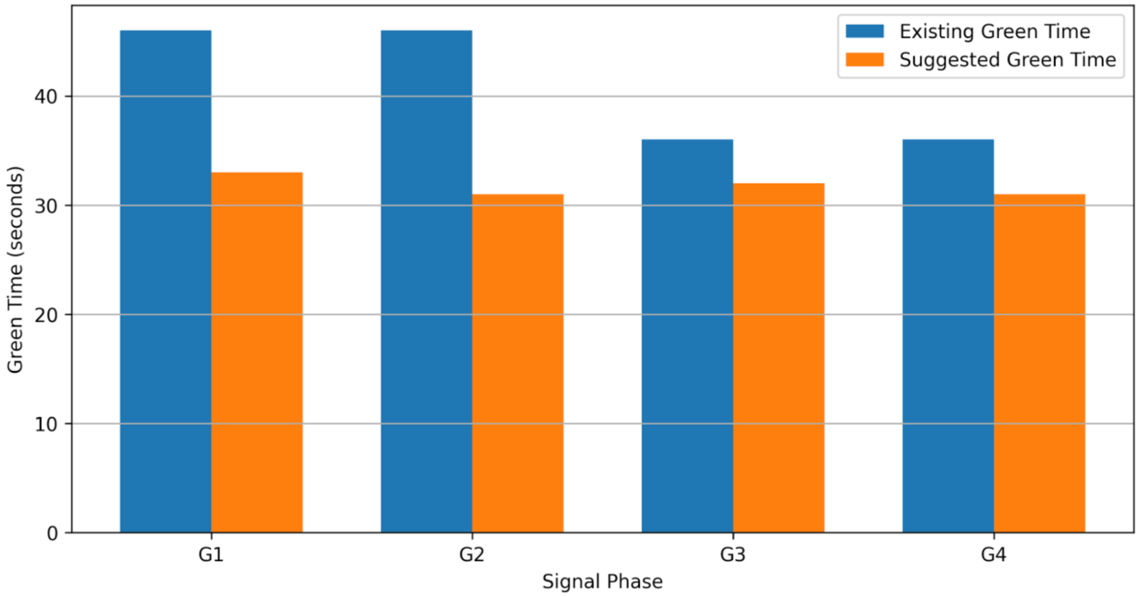

Figure 3:Comparison between Existing and Suggested Green Times for Signal Phases (G1–G4)

When compared with the existing signal timings, 46 seconds for G_1, 46 seconds for G_2, 36 seconds for G_3, and 36 seconds for G_4, including the yellow interval, the optimized timings demonstrate a more efficient distribution of green times across all phases. The total existing cycle length (excluding yellow time) was approximately 190 seconds, whereas the optimized cycle length is about 130 seconds, reflecting a reduction of nearly 31% in the overall cycle duration Figure 3.

Furthermore, the optimal green time for vehicles traveling from Zeromile either turning right to Kachari Chowk or proceeding through Manali Chowk is reduced by 28%. For vehicles traveling from Barari, either turning right to Zeromile or proceeding through Kachari Chowk, the green time is reduced by 32%. The optimal green time for vehicles traveling from Manali Chowk either turning right to Kachari Chowk or proceeding through Zeromile is reduced by 11%, while the green time for vehicles traveling from Kachari Chowk, either turning right to Zeromile or proceeding through Barari, is reduced by 13% as shown in Table 8.

Traffic Phase	Current Green Time(s)	Optimized Green Time(s)	Reduction(%)
G_1	46	33	28 %
G_2	46	31	32 %
G_3	36	32	11 %
G_4	36	31	13 %

Table 8: Comparison of Existing and Optimized Signal Timings for Each Phase at the Tilkamanjhi Intersection

This reduction not only minimizes vehicle idling time but also improves the overall intersection capacity utilization. The optimized green split ensures that traffic flows more uniformly during the morning peak hour (10:00 AM–11:00 AM), significantly reducing delays without compromising pedestrian safety.

9 Sensitivity Analysis

In real-world traffic systems, vehicle arrivals at intersections are not constant; they fluctuate due to variations in driver behavior, land-use characteristics, and time-of-day traffic demand. Therefore, an optimized signal timing plan must remain effective even when such variations occur. To evaluate the stability and adaptability of the developed signal optimization model, a sensitivity analysis was conducted by systematically varying the arrival rates of vehicles (in PCU/hr).

This sensitivity analysis confirms that the proposed signal optimization framework is not only effective under base conditions but also resilient to moderate fluctuations in traffic demand. The linear relationship between arrival variation and optimal signal timing suggests that the model can be easily recalibrated for short-term changes, such as peak-hour surges or seasonal traffic variations.

Change (%)	Arrival Rates (PCU/hr)	G1	G2	G3	G4	Status
-80	[97.8, 25.7, 67.9, 114.6]	32.3	32.1	31.3	34.3	Optimal
-70	[146.7, 38.5, 101.9, 171.9]	32.3	32.1	31.3	34.3	Optimal
-60	[195.6, 51.4, 135.8, 229.2]	32.3	32.1	31.3	34.3	Optimal
-50	[244.5, 64.2, 169.8, 286.6]	32.3	32.1	31.3	34.3	Optimal
-40	[293.4, 77.0, 203.7, 343.9]	32.3	32.1	31.3	34.3	Optimal
-30	[342.3, 89.9, 237.6, 401.2]	32.3	32.1	31.3	34.3	Optimal
-20	[391.2, 102.7, 271.6, 458.5]	32.3	32.1	31.3	34.3	Optimal
-10	[440.1, 115.6, 305.6, 515.8]	32.3	32.1	31.3	34.3	Optimal
0	[489.0, 128.4, 339.5, 573.1]	32.3	32.1	31.3	34.3	Optimal
10	[537.9, 141.2, 373.5, 630.4]	32.3	32.1	31.3	34.3	Optimal
20	[586.8, 154.1, 407.4, 687.7]	32.3	32.1	31.3	34.3	Optimal
30	[635.7, 166.9, 441.4, 745.0]	32.3	32.1	31.3	34.3	Optimal
40	[684.6, 179.8, 475.3, 802.3]	32.3	32.1	31.3	34.3	Optimal
50	[733.5, 192.6, 509.2, 859.7]	32.3	32.1	31.3	34.3	Optimal
60	[782.4, 205.4, 543.2, 917.0]	32.3	32.1	31.3	34.3	Optimal
70	[831.3, 218.3, 577.1, 974.3]	32.3	32.1	31.3	34.3	Optimal
80	[880.2, 231.1, 611.1, 1031.6]	32.3	32.1	31.3	34.3	Optimal

Table 9: Results of sensitivity analysis: Optimal green times under varying traffic arrival rates.

Hence, the developed model can be a useful decision-support tool for traffic engineers and city planners, especially under India's mixed-traffic environment, where vehicle composition and flow patterns exhibit considerable day-to-day variability.

To assess the robustness of the optimized signal timings, a sensitivity analysis was conducted by varying the vehicle arrival rates within a wide range of 80% of the base arrival conditions. The base arrival rates for the four signal phases representing Cars, Two-Wheelers, Auto-Rickshaws, and Buses were 489.0,128.4,339.5, and 573.1 PCU/hr, respectively. These were adjusted proportionally across multiple scenarios to simulate both under-saturated and over-saturated traffic flow conditions.

For each scenario, the linear programming model was solved using the PuLP optimization frame work, keeping the total cycle length fixed at 130 seconds. The objective function remained to min imize the total estimated waiting time, subject to the same flow and pedestrian safety constraints as in the base model. The resulting optimal green times for each phase (G1-G_4) were recorded for all arrival-rate variations.

The results, summarized in Table 9 and illustrated in Figure 4, reveal that the optimal green times remained remarkably stable across all tested scenarios. Even with arrival rate changes of 80%, the optimized green times for the four phases (G_1,G_2,G_3, and G_4) showed negligible variation, consistently converging to approximately 34.6 s, 32.1 s, 31.3 s, and 32.0 s, respectively. This stability indicates that the developed optimization model is insensitive to moderate fluctuations in arrival rates, suggesting high robustness and reliability for real-world signal operation.

The graphical trend in Figure 4 further confirms this observation, as the four green time lines remain nearly horizontal across all percentage changes in arrival rate. Such a response implies that, under the defined constraints and high traffic density during the morning peak, the system has reached a saturation point where variations in vehicle inflow have minimal effect on the optimal signal timings.

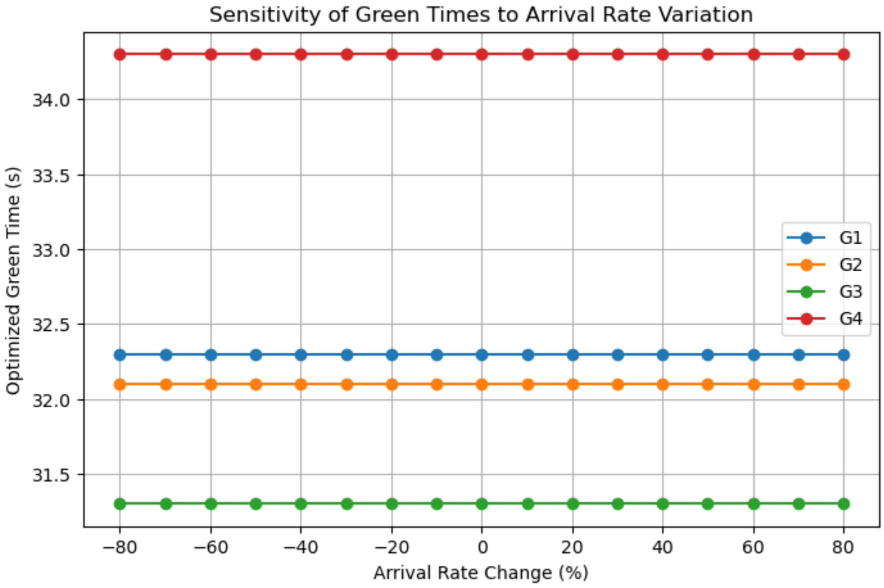

Figure 4: Sensitivity of Green Time to Arrival Rate Variation

Therefore, it can be concluded that the proposed model demonstrates a strong ability to maintain efficient signal performance even under varying traffic demand conditions, which is highly desirable for real-world adaptive traffic control systems.

10 Conclusion

This study developed a linear programming-based optimization model using the PuLP library in Python to determine the most efficient traffic signal timings for the Tilkamanjhi intersection. By incorporating vehicular arrival rates, queue lengths, and pedestrian crossing constraints, the model aimed to minimize vehicle idling during the morning peak hour (10:00 AM–11:00 AM). The optimized signal plan reduced the total cycle length from 190seconds to approximately 130 seconds, achieving a 31% improvement in overall efficiency. Green times for individual movements were reduced by 28%, 32%, 11%, and 13%, respectively, leading to smoother traffic flow, shorter delays, and enhanced pedestrian safety. Overall, the proposed optimization approach provides a practical and data-driven solution for improving signalized intersection performance in mixed-traffic conditions.

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