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Article

Variable Duration Traffic Light Scheduling Algorithm based on Real Time Vehicle Density and Waiting Time

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Abstract: Rapid population growth and the corresponding rise in vehicle ownership have led to severe traffic congestion, especially at urban junctions where multiple flows intersect. Efficient traffic management at these cross-road junctions is therefore critical for reducing travel delays, fuel consumption, and vehicular emissions. Conventional fixed-time traffic signal systems fail to adapt to dynamic traffic conditions, often resulting in inefficient green-time allocation and prolonged waiting periods. To address these challenges, this study proposes a dynamic traffic light control algorithm that adjusts signal durations in real time based on vehicle density and cumulative waiting time at each approach. The algorithm continuously analyzes incoming traffic data to determine the optimal green phase duration, ensuring balanced queue clearance and improved intersection throughput. Simulation results demonstrate significant performance improvements compared to conventional fixed-time control. The proposed system reduces average trip duration by 4–28%, fuel consumption by 6–25%, and CO_2 emissions by 4–28%, indicating substantial gains in both mobility and environmental sustainability. These findings highlight the potential of adaptive, data-driven signal control as a practical solution for modern urban traffic management systems.
Keywords: Variable traffic light duration, Fuel Consumption, CO2 Emission, SUMO Simulator

1. INTRODUCTION

With expanding metropolitan size and the quantity of vehicles and excursions, traffic congestion has become the critical obstacle in progress of urbanization. Although the reproduction and expansion activities of road network organization could tackle a portion of the help issues, the limitation of the road network actually can't meet the prerequisite coming from the exponential growth of private vehicles and number of journeys. Therefore appropriate transportation planning is required in order to meet current and future road network issues and to improve metropolitan transportation [23]. Traffic lights have been used since 1868 [26] to control and regulate traffic at each cross road intersection. Traffic lights smoothes the flow of vehicle traffic. However traffic lights are inefficient when vehicle density distribution in each direction has vast difference and that motivates to update existing traffic light algorithm that consider real time parameters like vehicle density.

Number of personal vehicles, commercial vehicles and vehicle fuel prices are increasing day by day. In July 2021, Petrol prices increased by 60% and diesel prices increased by 64% compared to July, 2016 [21]. Overall transportations are dependent on fuels like petrol and diesel and hence if these fuel prices are increased then personal journeys and commercial transportations cost increase. If we aim to reduce fuel consumption without changing travel distance then intelligent traffic algorithm may one of the possible solutions.

Vehicle emissions are one of the sources of air pollution. In order to reduce air pollution effects from vehicles, the government is providing subsidies to purchase hybrid and electric vehicles [22]. Compared to Petrol and Diesel, CNG fuel has lower pollution and is economically affordable however CNG cannot be used in heavy transport vehicles like trucks. Indian State governments also use CNG as a fuel in public transport vehicles like as of now Delhi Transport corporation is the world's largest operator of CNG bus fleet [18]. In June 2020, the supreme court of India ordered the government to improve emissions from vehicles; all BS4 vehicles must be upgraded to BS6 standards [20]. However Indian roads still consist of a significant amount of vehicles that use petrol or diesel as fuel.

From the above discussion it has been observed that in order to reduce traffic congestion, fuel consumptions and environmental pollution, expanding the road network only is not sufficient in the city area. One of the possible solutions can be introducing an intelligent traffic light algorithm that evaluates real time vehicle density from cross road sections and decides traffic light duration. Apart from this, algorithm should be capable of adjusting traffic light duration based on changing density of the vehicles from time to time. However, before implementing such an algorithm in the real cross road section, systematic performance evaluation must be required that claims improvement in reducing traffic congestion, fuel consumptions and environmental pollution.

The reminder of this paper is organized as follows: in section II, we discuss the basics of traffic light intersection. We studied and reviewed different smart traffic algorithms proposed in the transportation field till date discussed in section III. Proposed Variable traffic light duration algorithm discussed in section IV, Simulation parameters and setup discussed in section V and algorithm validation and performance measurement has been done in section VI. Finally, section VII discusses conclusion and future work.

2. ISOLATED TRAFFIC LIGHT INTERSECTION

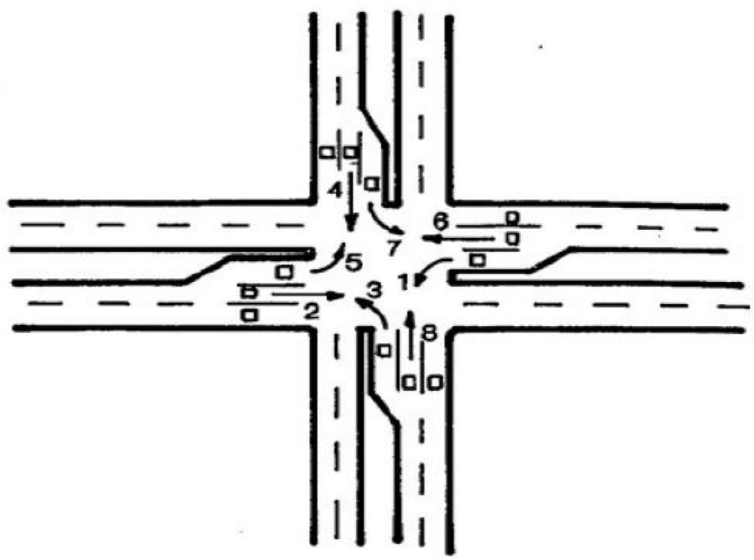


Figure 1: Intersection with traffic light

Before discussing our algorithm, it is necessary to understand traffic light intersections and how it works in a normal scenario. Figure 1 shows a cross road junction. Here in each direction two flows are possible and hence total 8 flows represented in the figure. In our study we have considered isolated traffic light intersections. Isolated traffic light intersection is an intersection where traffic lights are working without considering neighbour traffic light characteristics and operations.

It is important to mention some of the assumptions that vehicles are driven on the left hand side of the road and left turn is excluded from control of the traffic light function hence left turns are always possible even if the traffic signal is red. All intersections used in the experiment are isolated 4-leg intersections. Different types of vehicles included in the experiment are car, bike, bus, truck and bicycles and no vehicles are given high priority in the experiment. Car, bike and rickshaw are using petrol as fuel and bus, trucks are using diesel as fuel.

Table 1: Traffic Light Timing Variable Definitions

Variable	Definition
Cycle Length	The total duration of one complete sequence of signal indications at a junction, including all green, yellow, and red intervals for every phase.

Phase	A distinct set of traffic movements that receive the right-of-way simultaneously under a given signal indication (e.g., North–South straight, East–West left turn).
Interval	A portion of a phase during which a specific signal color (green, yellow, or red) is displayed. Each phase typically consists of multiple intervals.
Green Interval	The time period within a phase during which traffic movement is permitted to proceed. This interval may be fixed or dynamically adjusted based on real-time traffic conditions.

3. LITERATURE SURVEY

Indian metro cities roads are congested with the huge increase in traffic density. In India at many places it is very difficult to widen roads or improve existing transportation infrastructure. The load of traffic is very high on some roads and highways that the average speed of a bus and truck is 30- 40 kmph [27]. The traffic congestion at crossroads is common and it leads to pollution, delay in journey, higher fuel consumption and health related problems. The traffic scheduling at crossroads is very important. The economic impact of traffic congestion with considering delays at intersections is studied in [2]. The proper scheduling of traffic at crossroads can improve the situation many fold.

Conventional traffic signals use static approaches to guide traffic at intersections. This static approach leads to traffic jams, delay and low throughput. The traffic flow modelling at signal towards solving the problem is attempted in [4] [5]. The traffic flow guidance is analogous to the problem of routing in computer networks. The traffic scheduling decision is the key for improving throughput, reducing delay and congestion at intersections. Number of authors have tried to introduce different methods to solve traffic problem in cross road junction. Fig shows traffic signal controlling methods classification.

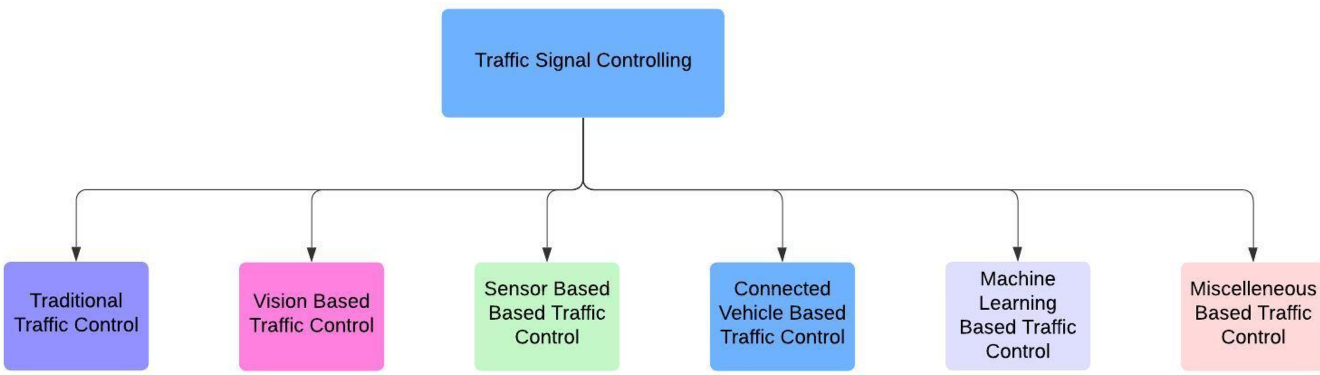


Fig : Different categories for traffic signal control technologies

Various efforts [28] [29] have been done for path optimization for improving traffic situations dynamically. Adaptive traffic signal control implemented in [6] [13]. Machine learning [7] and other probabilistic approaches [8] [9] are applied to optimize traffic flow. Traffic scheduling algorithms like [10] [11] use VANET (Vehicular Ad-hoc Networks technology) to improve the existing scenario. In VANETs exchange of information about traffic density destination, delay, speed characterize traffic flow and enable better scheduling decisions. We have also observed development of adaptive intelligent traffic light algorithms like ITLC [11], ATL [12]. ITLC schedules the largest density flow at each traffic control light. The ITLC exhibits less delay and improved throughput over OAF [13]. With ITLC 30% increase in throughput can be achieved than OAF demonstrated in [11].

ATL [12] is an improved version of ITLC which schedules traffic by giving preference to arterial flow. ATL considers adjacent traffic lights and real-time traffic characteristics to make scheduling decision at any point. The benefit of moving arterial traffic flows without being stuck at any intersection improves overall throughput and reduce average delay. The traffic light scheduling algorithm using VANET is mainly devised for isolated traffic intersection and arterial traffic flow. The main problem in implementing this is the upgradation cost and effort required to be equipped with a VANET device in each vehicle. Considering the scenario of Indian roads and driver behaviours, it is very difficult to equip every vehicle using a VANET enabled device.

Smart traffic light scheduling algorithm and its variant algorithm proposed in [31]. STLSD algorithm considers vehicle density to decide traffic light durations. Another variant algorithm STLSDT takes traffic density and waiting time of the vehicle in each direction of the cross road to decide traffic light durations. However all the algorithms are implemented in their own isolated intersection simulator (IIS) that uses the Java platform. Car following and overtaking models are an important part of the traffic simulator and correct models only able to replicate actual traffic scenario into simulator. No information is provided about which car following and overtaking models are used in isolated intersection simulator (IIS).

Advancement in Artificial Intelligence (AI) has similarly led to the improvement in traffic control algorithms. Traffic control algorithms employ AI, machine learning to automatically predict the best suitable duration of each traffic light based on traffic conditions. We have witnessed fuzzy logic traffic light controllers [29] and neural network based traffic signal controllers [30]. AI based systems provide substantial benefits for traffic management but it requires processing infrastructure. Authors in [32] proposed local parameters of traffic junction combining with junction communication based traffic optimization has been proposed.

In order to perform an experiment with real data in a simulator, key factor is that the simulator must be capable of closely representing real world scenario then only results obtained from study are useful. Many vehicle traffic simulators are available however most of the simulators are developed in countries where vehicles are driven on the right hand side of the road whereas in India vehicles are driven on the left hand side of the road. Apart from this lane disciplines are not strictly followed on Indian roads and hence default car following and overtaking models in the vehicle simulators that consider lane behaviour are not useful for Indian traffic scenario representation. Transportation Group in IIT Bombay [16] adopted SUMO simulator and made changes in car following and overtaking model, lane disciplines converted into strips and made SiMTram simulator specially to represent Indian traffic scenario. Viral patel et. all [15] made comparison of SUMO and SiMTram simulator and concluded that SiMTram closely represents Indian traffic scenario. Later in the newer version of the SUMO simulator, strips based model [17] was adopted for developing countries like India where lane disciplines are not strictly followed. In our study, simulations are done in SUMO simulator version 0.31 and SUMO simulator configured for strip based model in order to closely represent Indian traffic scenario.

4. PROPOSED METHOD

In this algorithm, we introduce a variable duration traffic light scheduling algorithm that considers real time vehicle traffic density from each direction of cross intersection and allocated traffic light timing duration based on real time density of the vehicles on road. In our study, we consider cross road intersections with traffic lights in each direction as illustrated in figure 1 and flowchart of the algorithm is illustrated in figure 2.

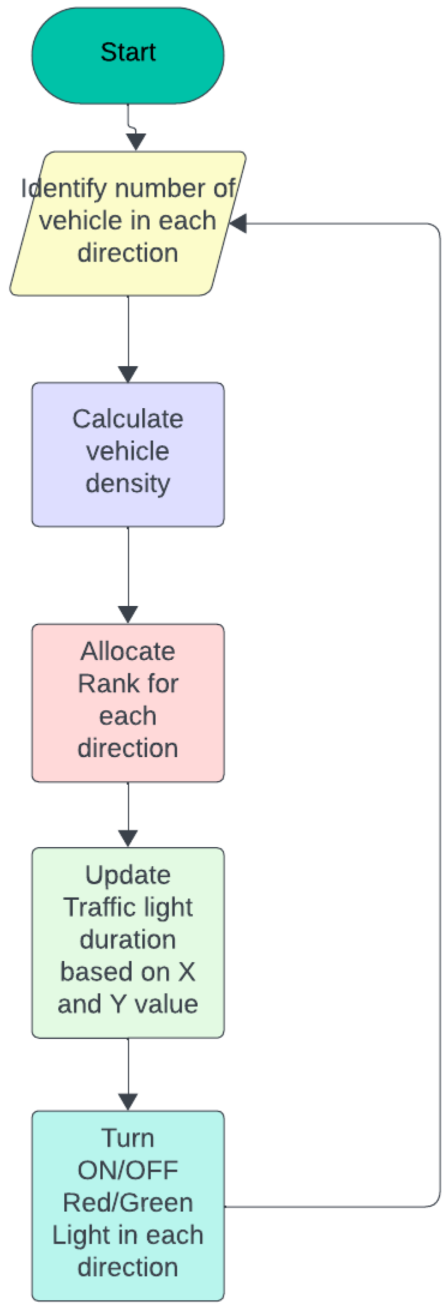


Fig: Flowchart of the proposed algorithm

Algorithm 1: Intelligent Traffic Light Scheduling Algorithm

1. Initialize:

Default_TL = 60 s

X = 30 s, Y = 20 s

α = weight for vehicle density (0–1)

β = weight for waiting time (0–1), where α + β = 1

2. Loop continuously:

2.1 Measure VD_i for each approach i

2.2 Measure WT_i for each approach i

2.3 Normalize VD_i and WT_i to [0, 1] across all approaches

2.4 Compute priority score:

$Score_i = \alpha \times VD_i + \beta \times WT_i$

2.5 Rank all approaches based on $Score_i$

Highest score → Rank R1

Next highest → R2

Next → R3

Lowest → R4

2.6 Check priority spread:

If (Score(R1) – Score(R4)) / Score(R1) > 20% then

Assign green times:

TL(R1) = Default_TL + X

TL(R2) = Default_TL + Y

TL(R3) = Default_TL – Y

TL(R4) = Default_TL – X

Else

Assign:

TL(i) = Default_TL (no major imbalance)

2.7 Enforce green-time limits:

TL(i) = max(TL(i), Minimum_Green)

TL(i) = min(TL(i), Maximum_Green)

2.8 Sequentially activate green phase:

For each approach i in signal order:

Provide green for TL(i) seconds

3. End Loop

The proposed dynamic traffic signal control algorithm adjusts green-time durations in real time by jointly considering vehicle density and average waiting time for each approach of the junction. At every decision cycle, the system measures the number of vehicles present on each approach (vehicle density, VD_i) and the accumulated waiting time (WT_i). Both quantities are normalized and combined into a single priority score, computed as a weighted sum of density and waiting time ($Score_i = \alpha \cdot VD_i + \beta \cdot WT_i$). This score reflects both the magnitude of congestion and the fairness requirement of preventing excessive delays. Based on these scores, all approaches are ranked from highest to lowest priority. When the difference between the highest and lowest priority exceeds a 20% threshold, the algorithm dynamically reallocates green times using predefined offsets: the highest-ranked approach receives an extended green interval (+X seconds), the second receives a moderate extension (+Y seconds), and the lower-ranked approaches receive proportionally reduced durations (–Y and –X seconds). If traffic imbalance is small, the controller maintains the default green time to ensure stable operation. Minimum and maximum green limits are applied to prevent unsafe or overly long signal phases. Finally, the traffic signal cycles through the approaches using the updated green times.

This integrated density–waiting-time mechanism allows the controller to respond adaptively to varying traffic demand while maintaining fairness and improving overall intersection performance.

Algorithm 1 describes Intelligent Traffic Light Scheduling Algorithm in which default traffic light time duration assumes 60s for each direction. This algorithm includes 3 phases, vehicle density computation with rank allocation, traffic light duration updation and vehicle passing at cross junction. In Phase 1 algorithm calculates real time vehicle density using equation 1 for each traffic flow direction and then allocates rank R to each traffic flow. Phase 2 analyses traffic flow having lowest rank which has lowest traffic density and then reducing X amount of time from that traffic light direction and same X amount of traffic light duration allocated to highest rank traffic flow. Similar calculation is done for Rank 2 and 3 traffic flow using traffic duration Y.

This algorithm makes sure that variable traffic light duration will only be allocated if vehicle density difference between highest rank and lowest rank is more than 20%. This type of condition is required in the algorithm in order to prevent getting a high amount of duration for approximately equally dense roads. When all traffic flow at an intersection has approximately equal vehicle density, all traffic flow lights should get equal time duration and it does not make any sense to update time duration for any direction.

5. DATA, METHODS AND SIMULATION SETUP

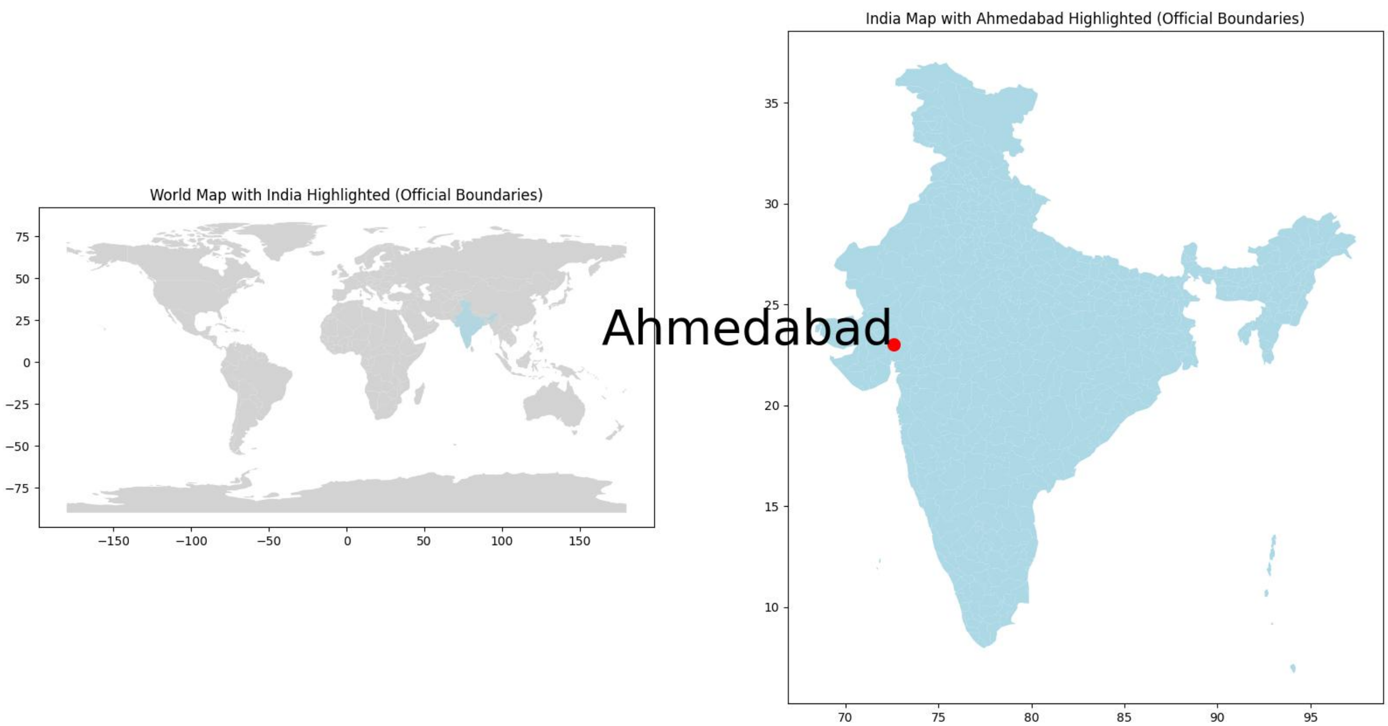


Fig : Map of Ahmedabad city on world map scale

Proposed algorithm uses vehicle density to calculate time duration needs to be allocated to traffic signal in each direction for 1 phase. In order to calculate vehicle density on any road, we are using equation of PCU (Passenger car unit) for every vehicle is calculated as described in [24]:

$$\mathrm{PCU}_i = \frac{\mathrm{Vc/Vi}}{\mathrm{Ac}/A_i} \quad ..(1)$$

where,

PCU_i = PCU value of the i^{th} vehicle
V_C = Average car speed
V_i = Average speed of the i^{th} vehicle
A_C = Area (rectangular) occupied by the car

A_i = Area (rectangular) occupied by the i^{th} vehicle

Proposed algorithm has been carried out in a SUMO simulator with strip-based configuration to represent lane less discipline. Table 1 shows vehicle distribution and vehicle dimension for each vehicle category used in simulations. The vehicle distribution and traffic flow information were retrieved from Greater Ahmedabad Mobility Report (2012) and the approximate dimensions for each vehicle category was accessed from website of various vehicle manufacturers. One scenario Nirma University to Pakvan Cross Road has been considered for the experiment, represented in table-2. In this scenarios, vehicle insertion rate varies from 500 veh/hr to 5000 veh/hr and hence 10 different sub-scenario have been considered for each case. Simulation carried out for 3 hrs and no data has been considered for the first half hour assuming cooling period. SUMO simulator generates an output file in xml format which is extracted using python 3.8 language script. Various simulation parameters have been shown in table-3.

Table 1 summarizes the heterogeneous vehicle composition used in the simulation, including bikes, rickshaws, cars, trucks, and buses. Each vehicle type is assigned a distribution proportion reflecting its presence in typical mixed urban traffic. The table also lists the physical dimensions of each vehicle class, which are used to model space occupancy, queue formation, and flow behavior at the intersection.

Table 2 describes the simulation scenario used for evaluating the proposed traffic control algorithm. The experiment is performed on a 12 km stretch of the S.G. Highway corridor between Nirma University and Pakvan Cross Road, with vehicle insertion rates ranging from 500 to 5000 vehicles per hour. Each simulation runs for a duration of 3 hours, allowing analysis under varying traffic demand levels.

Table 3 summarizes the simulation parameters used in this study. The experiments were conducted in SUMO on an isolated 4-leg intersection located along the S.G. Highway corridor. A total of 10 sub-scenarios were simulated over a 3-hour duration, with vehicle volumes ranging from 500 to 5000 to represent varying traffic demand levels.

Table 1: Vehicle Distribution

Vehicle Type	Distribution	Dimension (length x width) m^2
Bike	0.39	2 x 1
Rickshaw	0.17	3 x 2
Car	0.38	4 x 2
Truck	0.05	10 x 3
Bus	0.01	10 x 3

Table 2: Simulation Scenario

No	Scenario Name	Description	Vehicle Insertion Rate	Simulation Duration
1	Nirma University to Pakvan Cross Road	a 12 km road stretch on S. G. highway in between Ghandhinagar to Sarkhej	500 veh/hr to 5000 veh/hr	3hr

Table 3: Simulation Parameters

Parameter	Value
Simulator	SUMO Simulator
Number of Traffic Light	1
Traffic Light Type	Isolated
Simulation Map	4-leg Traffic Intersection
Simulation Duration	3 Hrs

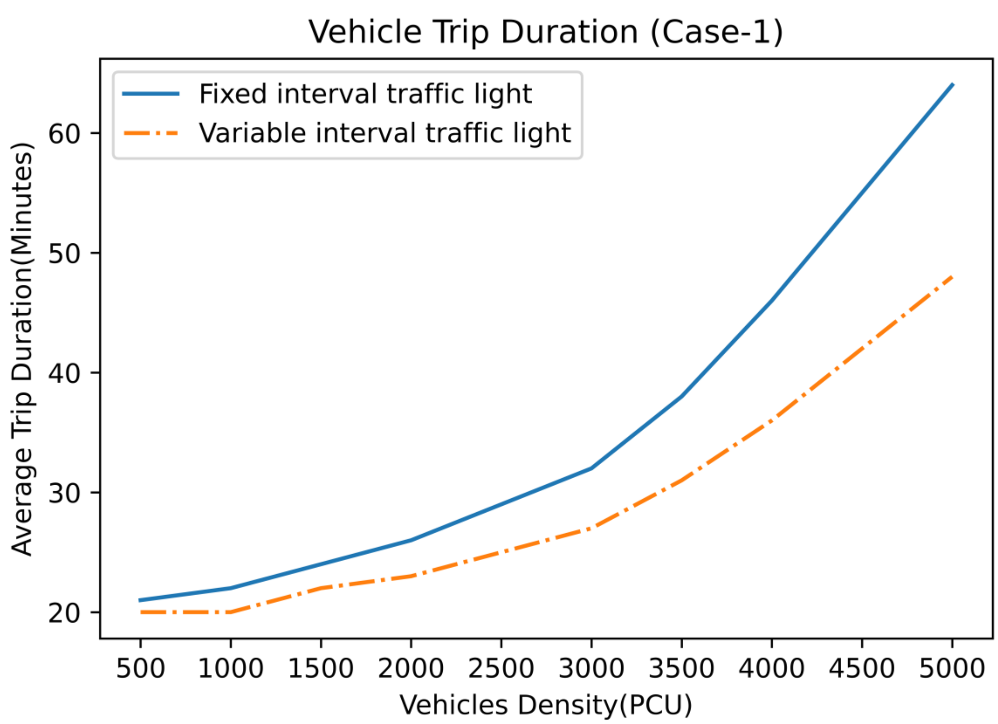
Number of Sub-Scenarios	10
Number of Vehicles	500 to 5000 vehicle
Simulation Area	S. G. Highway

6. ANALYSIS OF SIMULATION RESULTS

Variable traffic light duration algorithm discussed in the previous section was analyzed with different parameters like vehicle trip durations, fuel consumption and CO2 emission observed in SUMO simulator against the real parameter values retrieved from Greater Ahmedabad Mobility Report (2012). Two different cases are considered for experimenting with the algorithm. Case -1 consider X=30 and Y=20 that means highest density rank direction road traffic light duration increase by 30 second and 2nd highest density rank direction road traffic light increase by 20 second whereas 3rd and 4th density rank direction road traffic light decrease by 20 and 30 second respectively. Similarly case 2 considers X=30 and Y=30. All the parameters are measured for both different cases. The following subsections describe the major findings from analysis of simulation results.

A. Vehicles Trip Durations

Figure 2 shows average trip duration for fixed interval traffic light and variable interval traffic light duration for different vehicle density ranging from 500 to 5000 vehicles. In each vehicle density scenario, for each vehicle we have count time duration required to reach a destination using vehicle start and end time and then make a total of all vehicles. From the above graph it has been observed that when we have less vehicles (500 to 2500 veh/hr) the average trip duration for fixed interval traffic light and variable interval traffic light is almost similar. As the vehicle density increase further (2501-5000 veh/hr) roads gets congested in fixed interval traffic light scenario and increase in average time duration observed whereas in variable traffic light scenario it permits lower average trip duration using more realistic vehicle density value. The reason behind that is, variable traffic light duration algorithm allows more number of vehicles to be passed from cross section by taking some extra time duration from less dense road and thus more number of vehicles reach destination early. The reduction of 5 to 28% in average trip duration observed in variable traffic light duration scenarios.



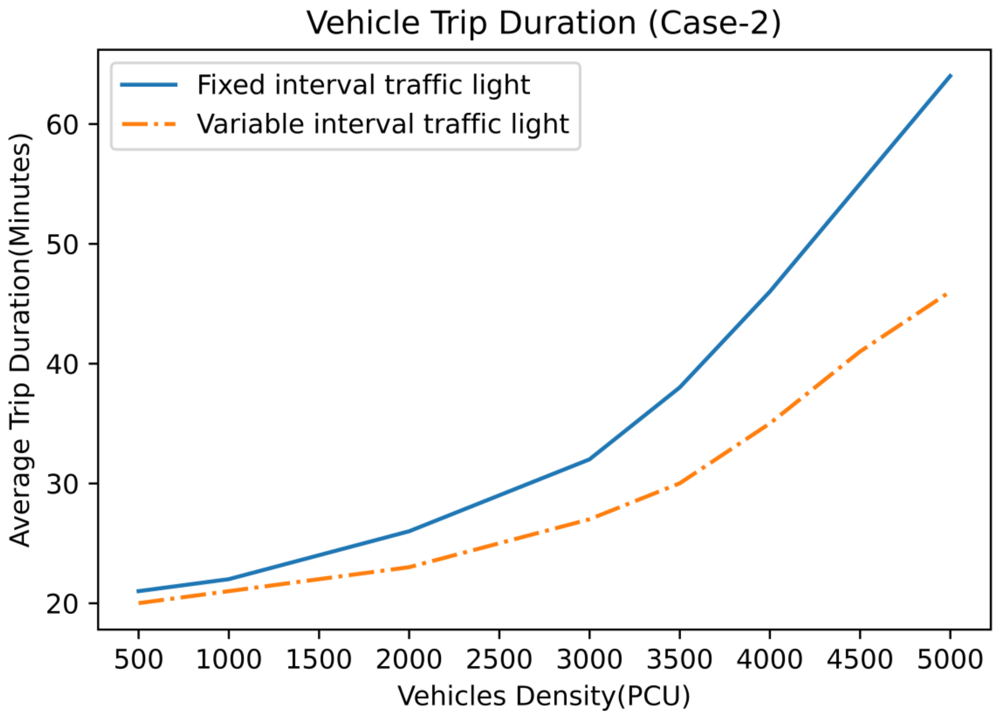


Figure 2: Average Trip duration versus Vehicle Density

B. Fuel Consumption

Figure 3 shows average fuel consumption for fixed interval traffic light and variable interval traffic light duration for different vehicle density ranging from 500 to 5000 vehicles. In each vehicle density scenario, for each vehicle we have count fuel required to reach source to destination. From the above graph it has been observed that when we have less vehicles (500 to 2500 veh/hr) the total fuel consumption for fixed interval traffic light and variable interval traffic light is almost similar. As the vehicle density increase further (2501 – 5000 veh/hr) road gets congested in fixed interval traffic light scenario and increase in fuel consumption is observed whereas in variable traffic light scenario it permits lower fuel consumption using a more realistic vehicle density value. The reason behind that is, variable traffic light duration algorithm allows more number of vehicles to be passed from cross section by taking some extra time duration from less dense road and reduce average waiting time of each vehicle at cross section thus reducing fuel consumption. The reduction of 4 to 25% in average fuel consumption observed in variable traffic light duration scenario.

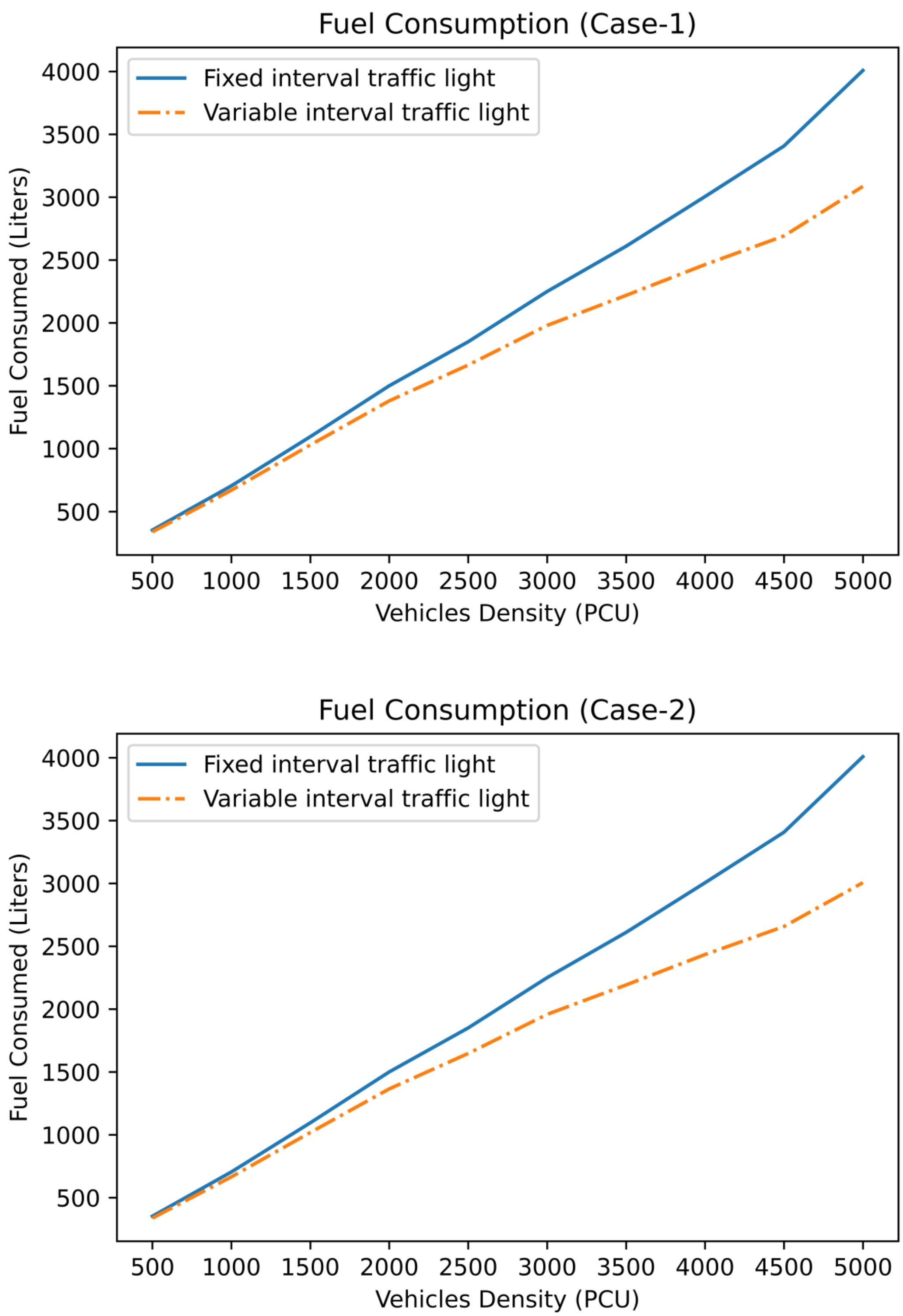


Figure 3: Fuel Consumption versus Vehicle Density

C. CO2 gases emission

Emission of different types of gases can be measured based on number of vehicles for each types and distance travel by vehicles, which is expressed by equation [19],

$$E_i = \sum(Veh_j \times D_j) \times E_{ijkm}$$

Where,

E_i = Emission of the gas i

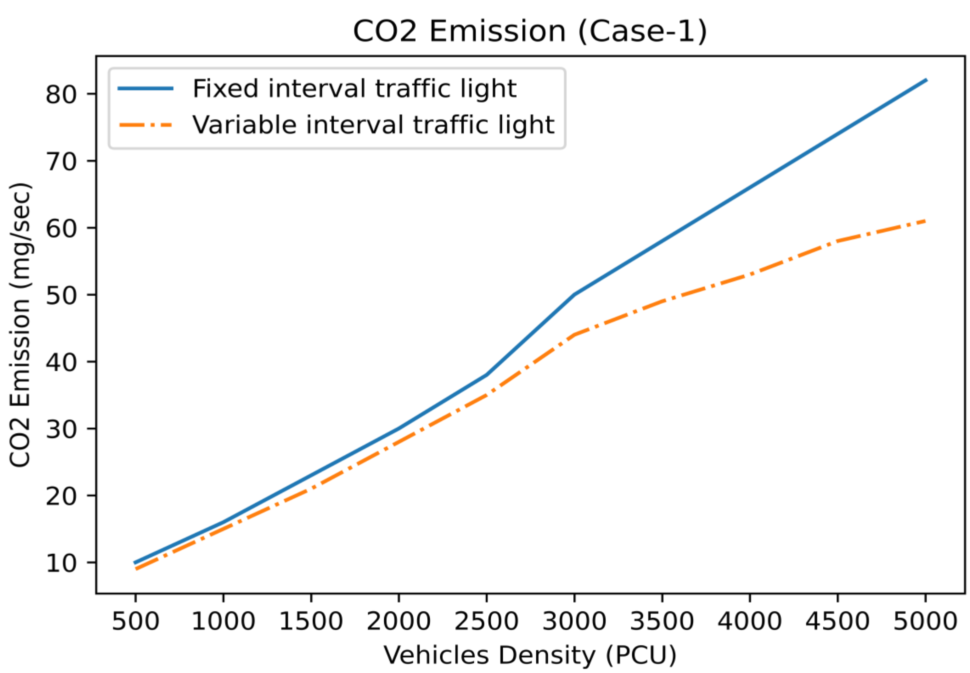
Veh_j = Number of vehicles per category (j)

D_j = Distance travelled by vehicle

E_{ijkm} = emission of gas (i) from vehicle category (j) per driven kilometre

However, to calculate the emission of the vehicle using the above equation, do not consider the waiting period of the vehicle if the vehicle is standing on the road due to a certain event like a red traffic signal and vehicle engine is running. In order to calculate correct CO2 emission SUMO simulator uses HBEFA v3.1 based emission model [24] which includes Euro-6 vehicles. The HBEFA v3.1 is a new model for calculating emission factors including new models of MotorCycle (MC), Personal Car (PC) and Light Commercial Vehicles (LCV). It also differentiates between Diesel Cars with diesel particulate filter (DPF) or without DPF. It also considers emission reducing technologies like exhaust gas recirculation (EGR) and selective catalytic reduction (SCR). This model also includes new fuel types: CNG, PNG and E85 for emission factor calculation.

Figure 4 shows average CO2 emission for fixed interval traffic light and variable interval traffic light duration for different vehicle density ranging from 500 to 5000 vehicles. In each vehicle density scenario, for each vehicle we count CO2 emission to reach vehicle source to destination and then make a total of all vehicle CO2 emission. From the above graph it has been observed that when we have fewer vehicles (500 to 2500 vehicles/hr) the total CO2 emission for fixed interval traffic light and variable interval traffic light is almost similar. As the vehicle density increase further (2501 – 5000 veh/hr) road gets congested in fixed interval traffic light scenario and increase in CO2 emission is observed whereas in variable traffic light scenario it permits lower CO2 emission using more realistic vehicle density value. The reason behind that is, variable traffic light duration algorithm allows more number of vehicles to be passed from cross section by taking some extra time duration from less dense road and reduces overall average waiting time at cross section and travelling duration of each vehicle and thus reducing CO2 gases emission. The reduction of 6 to 28% in average CO2 gases emission observed in variable traffic light duration scenario.



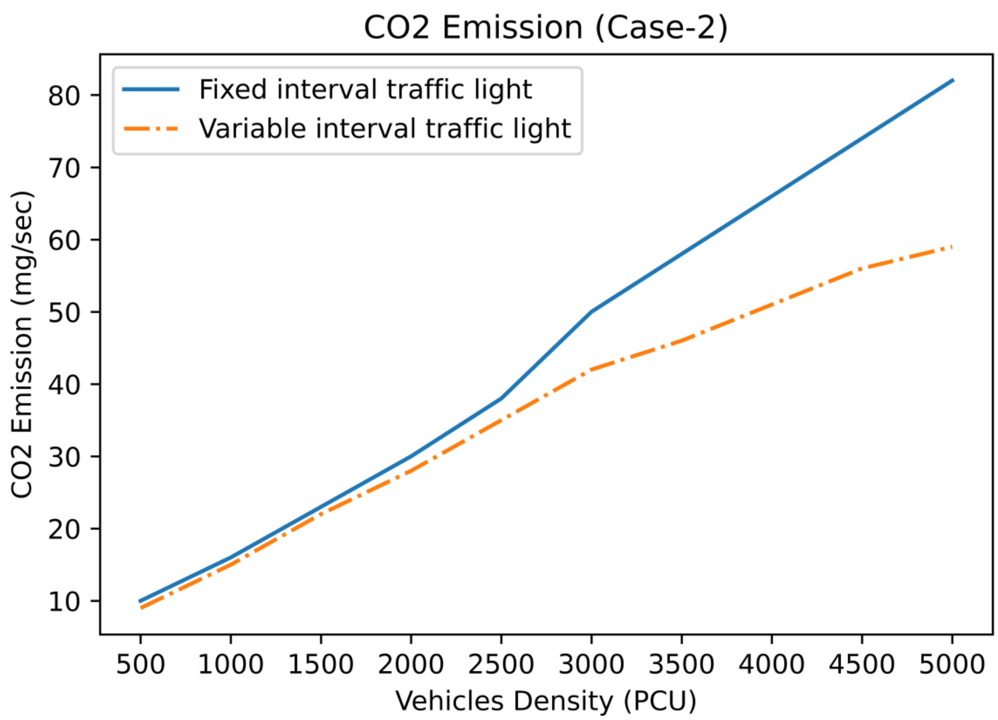


Figure 4: CO2 Emission versus Vehicle Density

The scatter plot illustrates the relationship between vehicle density (500–5000 PCU) and CO_2 emission levels for both the fixed-interval traffic signal and the proposed adaptive control method. As expected, CO_2 emissions increase with higher traffic density under both control strategies due to greater congestion and longer idling times. However, across all traffic demand levels, the proposed method consistently produces lower CO_2 emission rates compared to the fixed-time approach.

At lower densities (around 500–1500 PCU), the improvement is modest but noticeable, with reductions of approximately 1–3 mg/sec. As density intensifies toward peak levels (3000–5000 PCU), the performance gap widens significantly: the proposed algorithm achieves reductions of 5–7 mg/sec, demonstrating its ability to adapt green times effectively and reduce prolonged queue buildup. This consistent downward shift in emission values confirms that incorporating real-time vehicle density and waiting time enables more efficient traffic flow, minimizing unnecessary idling and stop-and-go movement.

Overall, the results show that the adaptive strategy delivers meaningful environmental benefits, particularly under medium to high congestion, validating the effectiveness of dynamic signal timing in reducing CO_2 emissions in urban intersections.

7. CONCLUSION

This paper summarizes different categories of traffic light control technologies. Authors proposed an intelligent traffic light scheduling algorithm based on real time vehicle density. In each phase this algorithm calculates vehicle density in each flow of cross road junction and based on the rank it updates default time duration of the traffic light timings for each direction by subtracting certain amount of time from low rank traffic flow direction and add same amount of time in high rank traffic flow direction keeping complete 1 phase time constant. Algorithm also make sure that if the difference in vehicle density in each direction is approximately equal (<20%), traffic light timings will not be updated. From the experimental results, we conclude that the proposed variable duration traffic light scheduling algorithm achieves better performance compared to traditional traffic light timings. Average trip duration reduced by 28%, Fuel consumption reduced by 25% and CO2 gas emission reduced by 28%.

FUTURE WORK

Intelligent traffic light scheduling algorithm proposed here is experimented at isolated cross junctions. Implementing the same algorithm to arterial traffic flow to take into account the behaviour of traffic patterns is a promising enhancement to the current research.

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