Intelligent traffic signaling system based on vehicle demand for excessively populated developing countries

Iftekhar Mahmud Towhid, Nishu Nath, Nusrat Jahan Chowdhury

Abstract— Developing countries like Bangladesh use fixed cycle-fixed split scheme for signaling which is a very inefficient way and results in delay at the intersection, poor throughput and traffic congestion. So our research was focused on reducing traffic congestion in urban roads of Bangladesh and the end result proposes a customized traffic signaling scheme with indulgent phase design that allocates varying and adequate green time to any phase based on actual traffic flow demand. It emphasizes on optimizing uninterrupted traffic flow, minimizing delay time at the intersection and maximizing system throughput. This model collects real time data from traffic nodes using detection devices, designs suitable phases by efficiently calculating movement demands and chooses the right phase, cycle time and split times. At the end of the paper, it is shown that the proposed model works better than other orthodox models.

Index Terms— Demand based split time allocation, Traffic Management, Traffic Signaling, Traffic Phase design, Vehicle detection

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1 INTRODUCTION

BANGLADESH is a densely populated developing country. To meet the transportation need of its large population, the number of vehicles have increased to a great extent and still it is increasing at an excessive rate. As a result, road traffic conditions are becoming alarmingly complicated, crowded and chaotic [1] [2] [3]. The existing conventional traffic signaling system is proved to be inappropriate to control the huge scale of traffic. At transport nodes traffic flow gets interrupted for a long period of time due to uncoordinated signaling scheme and traffic congestion. Traffic flow is not constant and it varies at different time of a day. Some phase of an intersection get too much traffic flow and other phases get less traffic flow, but due to the fixed cycle and split time, each phase gets exactly the same time span to operate, this misuses the split time and phase. For this inappropriate traffic signaling scheme, vehicles have to wait longer period of time at the intersection and traffic flow throughput becomes minimal. Moreover, phase selection is made based on a fixed model ignoring the phase demand.

The proposed model is mainly based on the limitations of Bangladeshi Traffic system and its economy. Our research mostly focused on finding optimum solution using the least resource which a developing country like Bangladeshi traffic infrastructure can afford. In addition, this proposed work automatically figured out the problem caused by inconsiderate phase selection and fixed split timing.

2 PROPOSED MODEL

To solve traffic problems around the world, many intelligent traffic system have been proposed in recent years. Those ITS system are not suitable for Bangladesh because considering the traffic system of Bangladesh we found that there are too many challenging factors. In developing countries like Bangladesh and India, there are different types of transport of varying speed, either motorized or non-motorized. The percentage of public vehicle is far too greater than privates. Maximum roads of cities don’t follow any specific lane, so the traffic police needs to work a lot to control different types of vehicles. Roads here in Bangladesh are narrow and there is hardly any scope to expand them. The specialty of the proposed model is that it considered all these factors and introduced some terms to optimize the model.

This research design is a unique and single case study of Bangladesh but can be applicable for further analysis of other developing countries.

The system considers the intersections of any traffic system. The flexibility of the system is, it is suitable for the roads that are not divided into lanes. Detection scheme is adopted to find real time data of vehicles like speed, size of vehicles, and traffic volume at stop line etc. For this research we chose to use RFID tags and Infrared detectors for detection scheme as they are both effective and economical. The model observes real time data and predicts future vehicle demand and movement based on the synthesized data. And according to the vehicle demand and movement ratio, it choses which phase selection will optimize traffic flow through an intersection. Finally traffic flow is calculated from real time data to find out split time of particular phase.

The advantage of the model is, it uses real time data and demand and transforms the rigid traffic system into an automated intelligent system and optimizes uninterrupted traffic flow with minimum delay time at transport nodes. Moreover,

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it considers all the important fact of traffic problems in Bangladesh and proposes the model in such a way which is both cost effective and efficient.

3 METHODOLOGY

3.1 Modeling Traffic flow at Intersections

In Bangladesh, like other South Asian counties, vehicles drive on left hand side. Thus, for this paper, we modeled the system as left hand drive, but this is not necessarily a constraint, as it is similarly applicable for right hand drive traffics.

Road intersections are generally either three-way or four-way. Here we modeled a four-way intersection and this model can be generalized for three-way intersections. In a four-way intersection there are four entry corridors and four exit corridors. We denote the entry corridors *e1*, *e2*, *e3* and *e4* respectively and the exit corridors as *x1*, *x2*, *x3* and *x4* respectively as shown in figure 1:

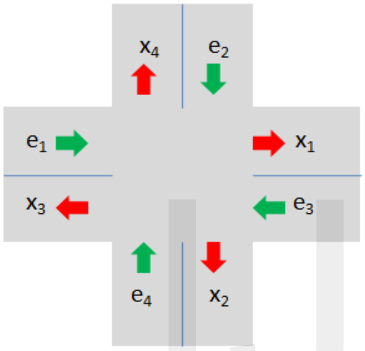

Figure 1: A four-way intersection for left driving lanes

There are three possible movements from any of the corridor of four way intersection. These are through movement, left turn movement and right turn movement. Figure 2 illustrates these movements with respect to the driver's position.

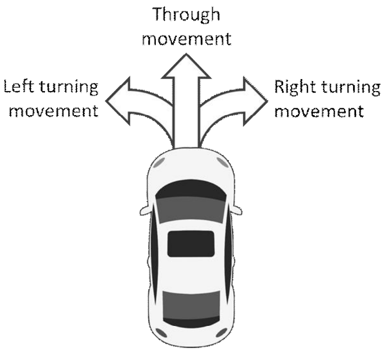

Figure 2: Through, Left turning and right turning movement

3.2 Collecting Data through Detectors

The proposed system takes some important characteristics of vehicles into account. Such as number of vehicles on a passage, the ratio of through, left turning and right turning movement, speed of vehicles and length of vehicles. To Determine these parameters vehicle detection schemes are needed. Considering the economic condition of Bangladesh, we choose detection schemes that are economical and highly compatible for the vehicles here. In Bangladesh, currently most of the motor-driven vehicles are required to install passive RFID tags. This makes the choice of using RFID detectors more compelling as RFID detectors are low cost and easy to install. However, in our proposed system we recommend the use of both the IR detectors and RFID detectors. RFID makes the detection more efficient, but to know other parameters like speed and length of vehicle, we need to make use of IR detectors.

In our model, however RFID plays an important role rather than just detecting the presence of the vehicles. According to our proposed system, RFID will also be used to predict vehicle movement using statistical data. In our model, all entry and exit corridors are equipped with RFID detectors. Each vehicle with a RFID have a unique ID. So we can log all the vehicles movement- for example, a vehicle which enters at *e1* and exits using *x2* has a right turning movement. So we can log how many vehicles at a specific entry had through movement, how many turned left and how many turned right in a specific previous time frame like one hour. Using instantaneous data, along with historical data we can predict the possible movement of the vehicles waiting at a stop.

For example, suppose there are 100 vehicles waiting at a stop line for next green time. If the next green time allows only through movement, but if a significant number of vehicles want to go right, traditional models would not count that and in demand based models, the phase time will be calculated as if all the vehicles are likely to move through. This problem is addressed in our model by using cheap RFID detectors.

Let, in a time period T, N vehicles enters an entry e and N_t of them moved through, N_l turned left and N_r turned right. Then we have,

Probability of moving through, $\rho_t = \dfrac{N_t}{N_t + N_l + N_r} = \dfrac{N_t}{N}$

Probability of turning left, $\rho_l = \dfrac{N_l}{N}$

Probability of turning right, $\rho_r = \dfrac{N_r}{N}$

As only these three movement are possible,

$$\rho_t + \rho_l + \rho_r = 1$$

As different part of day may have different traffic loads and weekday has also important impact on traffic loads, instead of using just instantaneous data, in our model we introduce historical bias for calculating movement probabilities. For example, in our model the realized probability of through movement is calculated as

$$\rho'_t = \alpha_1\rho_t^{T1} + \alpha_2\rho_t^{T2} + \alpha_3\rho_t^{T3}$$

Where, α_1, α_2 and α_3 fractional numbers and

$$\alpha_1 + \alpha_2 + \alpha_3 = 1$$

We select the amount of historical bias by adjusting the values of α_1, α_2 and α_3. Here ρ_t^{T1} is through moving probability in the previous T time, ρ_t^{T2} is average through moving probability at the exact hour throughout previous week and ρ_t^{T3} is average through moving probability of this weekday at the exact hour. Also we have

So our model is different from other demand based models in that, where other models merely calculate demand based on the number of vehicles waiting at the stop line and do not care about movement probabilities, where as our model takes this important aspect into account and offers a cheap solution for the problem.

3.3 Phase design

The MUTCD [14] defines a signal phase as the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements.

The objective of phase design is to separate the conflicting movements in an intersection into various phases, so that movements in a phase should have no conflicts. If all the movements are to be separated with no conflicts, then a large number of phases are required. In such a situation, the objective is to design phases with minimum conflicts or with less severe conflicts. Running as many compatible movements as possible during each phase, restricting each phase to non-conflicting movements & allowing each movement to run in as many phases as possible are also important considerations of these model.

Usually a phase design is guided by the geometry of the intersection, flow pattern especially the turning movements, the relative magnitudes of flow. Therefore a trial and error procedure is often adopted. We considered a phase design that leverages all parameters relating to phase design and has the advantage of changing the cycle time and green time according to flow pattern.

Generally, in a four way intersection, the phases are designed such that each cycle contains four splits, which occur alternately one after another, the split times may vary according to demand, however the secqunce and type of splits remain same. However, we have found out that, this is partly responsible of systems using demand based split time schemes being inefficient. This is because, in these systems, the detectors detect vehicle count at each stop, but have no idea about the vehicle movement. This significantly degrades the system utilization and throughput.

In our proposed system, to design a true demand based phasing system, we recommend the phases sequence not to be fixed, and rather phases will also be selected according to demand.

To accomodate varying arrival rates and movement probabilities at the entry corridors, we have designed 8 phases as shown in figure 3. These includes conventional phases that are in use at intersections throughout the world.

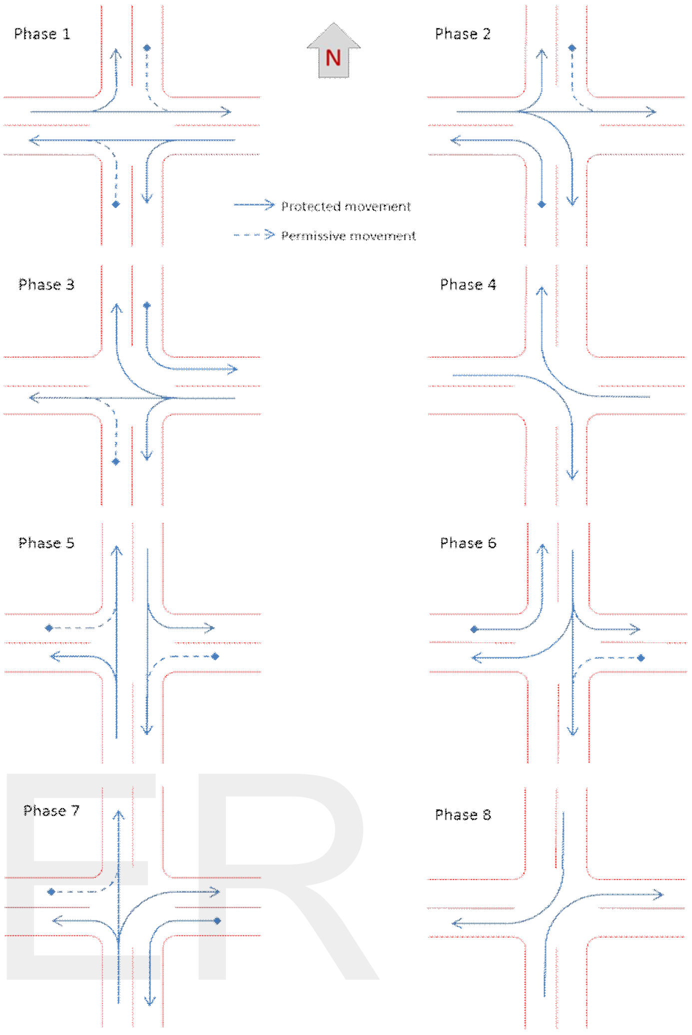

Figure 3: All phases of the proposed phasing scheme

3.4 Phase selection

Among the eight phases shown in figure 3, our system chooses any four depending on the movement demands.

Modern U.S. practice for signal control organizes phases by grouping them in a continuous loop (or ring) and separating the crossing or conflicting traffic streams with time between when they are allowed to operate, either by making the movements sequential or adding a barrier between the movements. The ring model separates phases that may operate sequentially one after another and typically conflicting phases are organized in a particular order. For instance, it may be desirable to separate the traffic traveling through the intersection in the northbound direction from the southbound left turn movement. Considering the conditions of developing countries like Bangladesh we have adopted the “ring barrier model” to synchronize the phases. The main purpose of this ring barrier model is to separate conflicting phases placing a logical barrier between non-conflicting phases and conflicting phases. The time sequences of phases are synchronized based on the traffic flow demand.

Some common rules for numbering of phases at an intersection (which are applicable to the diagram) are provided in the following list, which assumes leading left turns and separate left-turn phases.

- Phases 1, 2, 3, and 4 are assigned to Ring 1. Phases 5, 6, 7, and 8 are assigned to Ring 2.
- Phases 1, 2, 5, and 6 are assigned to Barrier 1. Phases 3, 4, 7, and 8 are assigned to Barrier 2.

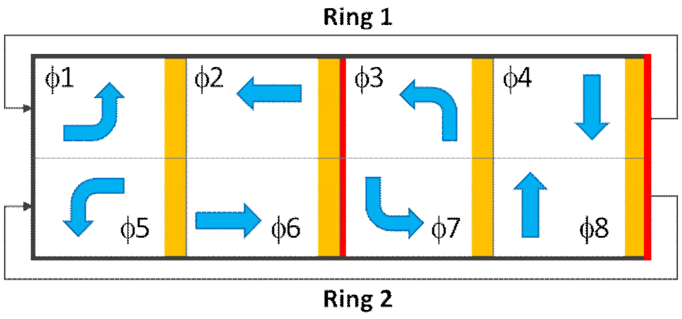

Figure 4: Ring Barrier diagram

An example ring diagram is shown in figure 4. The figure illustrates a ring and barrier diagram corresponding to a typical four legged intersection. There are 8 movements assigned number 1-8. The figure appears as a two row by four column matrix. Each column in each row represents a sequential operating phase of the respective ring. Two barriers, demarked by red and yellow parallel vertical lines, are shown after the second and fourth columns. These barriers represent where the rings must be synchronized to avoid conflicting movements. We'll have to select phases either from barrier -1 or barrier -2 and only one phase from each ring can be selected at a time. For example, we can select two phases from 1, 2, 5, 6 and either 1or 2 can be selected from ring one at a time, and either 5 or 6 can be selected from two. Maintaining these rules a split can be formed using phase 1+5, 1+6, 2+5, and 2+6. For barrier two selection of these split time can be 3+7, 3+8, 4+7, and 4+8. A phase pair contains two phases within the same ring and barrier that cannot be displayed concurrently. Phase pairs within the same barrier must end simultaneously (i.e., end at the barrier). For example, phase pairs 1+5 and 5+6 must end simultaneously at the end of barrier 1 and phase pairs 3+4 and 7+8 must end simultaneously at the end of barrier 2. Phase pair 1+5 can operate concurrently with phase pair 2+6. These phase pairs are also known as concurrency groups because they can time together.

3.5 Modeling movement demand

Among the eight phases shown in figure 3, our system chooses any four depending on the movement demands. The eight movements shown in the ring-barrier diagram of figure 4 can construct the eight phases shown in our proposed phasing scheme in figure 3 by taking a movement from ring 1 and another from ring 2, given that both lie in from same barrier. We can easily ignore left turning vehicles as they can move irrespective of the phase.

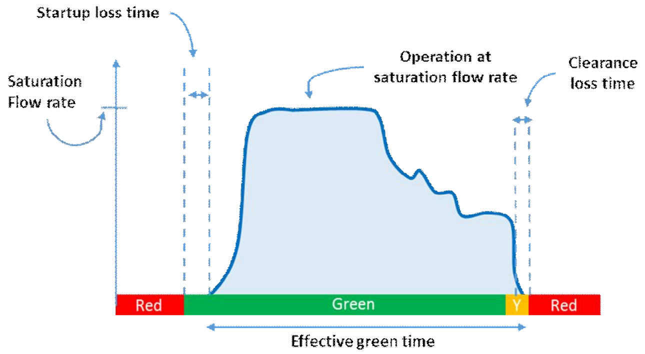

Figure 5: Traffic do not flow at saturation during all of the green phase.

As shown in figure 5 during a green phase the vehicles reach the saturation flow rate. The ideal saturation flow rate may not be achieved (observed) or sustained during each signal cycle. There are numerous situations where actual flow rates will not reach the average saturation flow rate on an approach including situations where demand is not able to reach the stop bar; queues are less than five vehicles in a lane, or during cycles with a high proportion of heavy vehicles. To achieve optimal efficiency and maximize vehicular throughput at the signalized intersection, traffic flow must be sustained at or near saturation flow rate on each approach. In most analyses, the value of saturation flow rate is a constant based on the parameters input by the user, but in reality, this is a value that varies depending on the cycle by cycle variation of situations and users.

It is observed that through going movement has much higher saturation flow rate than right or left turning movements. Again the mix of different types of vehicles affects the saturation flow rate. Thus in this paper, we have introduced a new parameter called demand grade (*G*) for individual movements which is the basis of phase selection.

The parameter Demand grade (*G*) can be expressed for through movement as

$$G_t = N_t^{\exp} \; / \; q_t^{sat} \tag{1}$$

Where $N_t^{\exp}$ = Total vehicle at stop line × turning ratio (ρ_t)

And q_t^{sat} = saturation flow rate for through movement

G is a unit less value. For simplicity, all the movement demand grades are normalized between 0 and 1.

Here $N_t^{\exp}$ has the unit Vehicle Unit per hour, to calculate this, the instantaneous arrival rate in certain window size (5 minutes/10 minutes) are extrapolated for 1 hour. The window size depends on the fluctuation of arrival rate.

In our proposed system, we select proper phases depending on the demand grade of each individual movement at each entry corridor. From the ring barrier diagram, inside each barrier, we chose the pair of movement with highest demand grade, each from a ring. Then the other two movements constructs the other phase. The obvious advantage is, this way we can acieve the maximum throughput, because in a phase, if the demand grade of two corresponding movement differs significantly, the utilization of minor movement will degrade noticably.

For example in barrier 1, let us consider the demand grade of phase 1, 2, 5 and 6 are .5, .3, .6 and .1 respectively. The demand grade of phase 5 (from ring 1) and phase 1 (from ring 2) are the highest. As the phases 1 and 5 are from separate rings and within same barrier they can be selected for a particular phase for a given time. After successful completion of this split time, next split containing phase 2 and 6 can be started.

If the demand grade of any of these phases is zero, we will not take it under consideration. The allotted split time of two phases (of which one has zero demand) will now be given to the phase that has demand grade value. It increases the flexibility and efficiency of the system. If there is no traffic flow during a phase (zero demand grade) and still the split time is allotted to this phase, then the split time is wasted. To overcome this problem, this system utilizes time by adding split time of zero demand phases to another nonzero demand grade phase.

4 CALCULATION

4.1 Traffic flow for through movement

As stated above, one of the problems is calculating the saturation flow rate is vehicle mix. To overcome the problem in our proposed system, we consider 'Vehicle unit' instead of 'Vehicle'. Vehicle unit can be chosen as the size of most dominant vehicle type in a system.

Then vehicle density, the number of cars per mile (kilometer) is

$$\rho=1/(L+d) \tag{2}$$

Where L is the average length of the vehicles and d is the average distance between two conseutive vehicles:

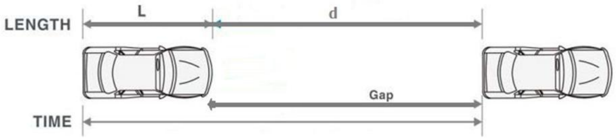

Figure 6: Traffic density equals the inverse of the spacing

And traffic flow or flux is [15]

traffic flow = density × velocity

$$q = \rho u \tag{3}$$

Let us describe some observed traffic phenomena. If traffic is sufficiently light, then the vehicles within the intersection can have the highest speed. As the traffic increases to a moderate level, the speed of moving traffic becomes slower. Hence the average speed of all the vehicles becomes less than expected speed. On the basis of this type of observation, a basic simplified assumption is introduced, at any point along the road the velocity of a car depends only on the density of the car [15].

$$u = u(\rho) \tag{4}$$

This assumption is depicted in figure 7.

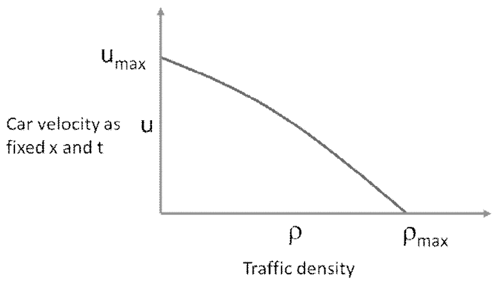

Figure 7: Car velocity diminishes as traffic density increases.

Lighthill and Whitham and independently Richardst in the mid 1950s proposed this type of mathematical model of traffic flow. [15]

If there is no other cars on the road (corresponding to very low traffic densities), then the vehicle would travel at the maximum speed umax.

$$u(0) = u_{max} \tag{5}$$

As the density increases further the velocity of the cars would continue to diminish. Thus at a certain density cars stand still. The maximum density ρ_{max}, usually called bumper-to-bumper traffic.

$$u(\rho_{max}) = 0 \tag{6}$$

At this state of hypothesis, we assumed a point somewhere in the graph as the saturation point named q_{sat} based on the relation of velocity and density. At the saturation point, our assumption is that maximum number of vehicles would get the average saturated velocity, usat at maximum average saturate density, ρsat.

$$q_{sat} = \rho_{sat} u_{sat} \tag{7}$$

There are many assumption involved in this hypothesis. It states that every driver drives at same velocity with same spacing. This is not clearly valid, though it may not be a very bad approximation. We introduce a model, in which it is proposed that at a certain density, some percentage of drivers drive at certain speeds and others driver are slightly different.

The velocity of a vehicle in traffic is linearly dependent on the density of the traffic at that point. When the density is equal to ρ_{max}, traffic will be unable to flow, so the velocity will be zero. This assumption is based on data on traffic density versus speed from [18]. We will therefore use the following equation for the velocity of the traffic flow:

$$u=u_{max}(1-\rho/\rho_{max}) \tag{8}$$

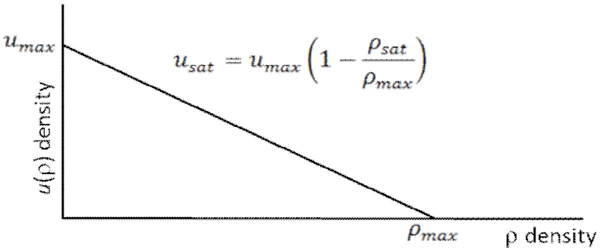

Figure 8: linear velocity-density graph

For maximum flow in our system it can be written as

$$u_{sat} = u_{max}(1-\rho_{sat}/\rho_{max}) \tag{9}$$

We have from [15],

$$\rho_{sat} = \rho_{max}/e \quad (10)$$

Substituting equation (9) in equation (10) we get,

$$u_{sat} = u_{max}\ (1-(\rho_{max}/e)/\rho_{max}) \quad (11)$$

We use V_{85} =85th-percentile speed, km/h (1 km/h = 0.621 mph) as the value of the maximum velocity u_{max}.

or, $u_{sat}=v_{85}\ (1-1/e)$ (12)

$$u_{sat}=v_{85}\times 0.632 \quad (13)$$

Again,

$$u=v_{85}\ (1-\rho/\rho_{max}) \quad (14)$$

Now, using equation (2) we have,

$$u=v_{85}\ (1-(1/(L+d))/(1/L)) \quad (15)$$

$$u=v_{85}\times d/(L+d) \quad (16)$$

So, for maximum performance of the system,

$$u_{sat}=v_{85}\times d/(L+d)$$

$$\Rightarrow d=1.717L \quad (17)$$

So, the total maximum traffic flow of our system is:

$$q_{sat}= u_{sat}\ \rho_{sat}$$

$$=v_{85}\times 0.632(1/(L+d\times b)) \quad (18)$$

Where, b = bunching ratio

b = Total vehicle unit / Total number of vehicle

This is the maximum traffic flow equation at average velocity and density for the through movements.

4.2 Measuring traffic flow rate for right turning movement

Using the regression relation in a National Cooperative High Research Program Report [16] relating maximum speed to radius [17]:

$$u_{max} = 2.41\ r^{0.372} \quad (19)$$

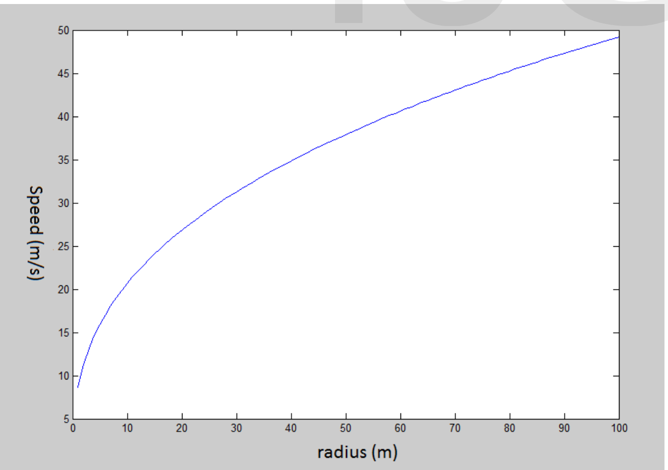

Figure 8: linear velocity-density curve

For right turning movement,

$$u_{max} = 2.41\ r^{0.372}$$

$$u_{sat} = v_{85}\ \times 0.632$$

$$=u_{max}\times 0.632$$

$$\Rightarrow \quad u_{sat} =2.41 \times r^{0.372} \times 0.632 \quad (20)$$

So, the maximum traffic flow rate for right turning movement,

$$q_{sat} =\rho_{sat} \times u_{sat}$$

$$q_{sat} = (1/(L(1+1.717b)))\times 2.41\times r^{0.372}\times 0.632 \quad (21)$$

4.3 Determining individual split time for a phase

As stated above, ease phase is constructed of two major movements that have almost similar demands. This approach increases the utilization of our proposed system. However the two movements may differ significantly in some cases. In our system individual split time depend on the critical movement between the two in a phase. To calculate the split time of a phase, we only consider the critical movement. To find out the split time we consider the following things:

- Loss times should be included.
- Split time increases as demand increases.

For our system we adopt the following equation:

Split time, $T =t_L + t_p/(1-\sqrt{}(v_c/q_{sat}))$ (22)

Here v_c is critical movement demand which can be found from [19]. t_p is the optimal passage time, this is an empirical value which can be fine tuned for increasing the performance of the system. Our final equation for split time is,

$$T = \begin{cases} 0 & for\ v_c = 0 \\ \min(t_L + \dfrac{t_p}{1+\sqrt{\dfrac{v_c}{q_{sat}}}}, g_{max}) & for\ 0 < v_c < q_{sat} \\ & otherwise \end{cases} \quad (23)$$

Where, lost time, $t_L = L_{start\text{-}up} + L_{clearance}$, g_{max} is maximum green time.

4.4 Formula for calculating number of virtual lanes

As in the developing countries, there are enormous vehicles on the road and they don't follow lane, we here derived an equation to calculate the number of lane that can be followed by a vehicle virtually through our proposed system.

$$N_{lane}=W_{lane}/\ W_{vehicle}\ + Safety\ margin \quad (24)$$

Where, W_{lane} = width of a lane,

$W_{vehicle}$ = width of a vehicle unit.

5 SIMULATION AND ANALYSES

5.1 Tools

There are many commercial and open source simulators for traffic modeling. We tried some open source traffic simulators like SUMO, VISSIM etc, but each of them has certain incapability which refrain us from using them. So for modeling our proposed system and comparing with existing system, we used MATLAB.

5.2 Simulation Settings

We implemented and simulated our proposed system along with three existing popular systems to compare the performance of each system. The existing systems are:

- Intersection using basic phasing scheme 1 (consisting of phase 2, 3, 6 and 7 in figure 3) with fixed split times of 60 seconds.
- Intersection using basic phasing scheme 1 with actuated split times and fixed cycle time of 240 seconds.
- Intersection using basic phasing scheme 2 (consisting of phase 1, 4, 5 and 8 in figure 3) with fixed split times of 60 seconds.

For simplification of simulation we ignored left turning movements. We assumed two lanes for each corridor.

We simulated each system for different arrival rates ranging from 1500 to 5000. We also simulated for different movement ratios. For the simulation, we assumed following parameters

TABLE 1
SIMULATION PARAMETERS

Parameter	Definition	Value
VU.Length	Length of Vehicle unit	5 meter
VU.Width	Width of vehicle unit	2 meter
gmax	Maximum green phase	120 second
Movement.through.tl	Loss time for through movement	4 second
Movement.right.tl	Loss time for right turning movement	6 second
window	Arrival window	300 second

5.3 Performance metrics

We implemented and simulated our proposed system along with three existing popular systems to compare the performance of each system. We used two performance metrics for the comparison:

Throughput: The number of vehicles that is served by the system is a unit time period (1 hour). The higher the throughput, the better is the system.

Average waiting time: The average time the vehicles waited at stop line before getting served. The lower the average waiting time, the better is the system.

5.4 Performance analysis

We simulated our systems twice, using

- ρ_t=.5 and ρ_r=.5
- ρ_t=.66 and ρ_r=.33

Figure 9 shows the comparison of system throughput for ρ_t=.5 and ρ_r=.5

Figure 10 shows the comparison of system throughput for ρ_t=.66 and ρ_r=.33

Figure 11 shows the comparison of average waiting time for ρ_t=.5 and ρ_r=.5

Figure 12 shows the comparison of average waiting time for ρ_t=.66 and ρ_r=.33

From the figures, we can see that our proposed system outperforms the other models in each case.

6 CONCLUSION

This paper provides a noble way to reduce waiting time of vehicles at intersections so that they can reach to their destination in least time. It is different from other models in the way that, it takes the various conditions into consideration that only applies for developing countries where roads are not properly designed and driver psychology is generally aggressive. The system indulge the phase design and determines the phases and their sequence based on predicted demands whereas in other models it is fixed. It also addresses the fact that turning movements are slower than through movement. Also it determines the demand by not directly counting the number of vehicles at stop line but it calculates each movement probability, which is a significant factor in calculating actual demand. Finally it suggests the optimum green time for each phases which is supported by the simulation results.

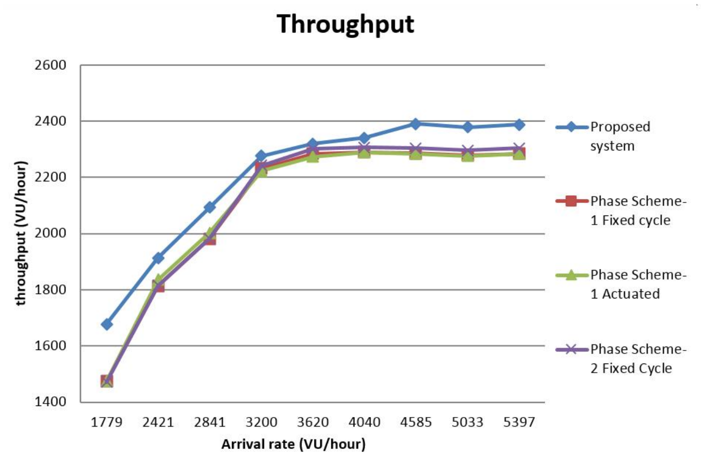

Figure 9: Comparison of system throughput for ρ_t=.5 and ρ_r=.5 (higher throughput is better)

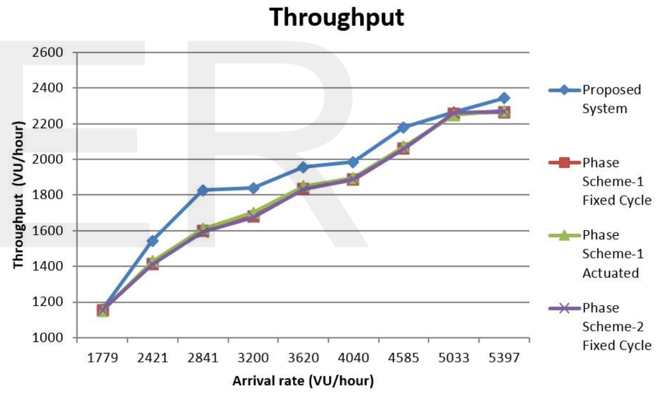

Figure 10: Comparison of system throughput for ρ_t=.66 and ρ_r=.33

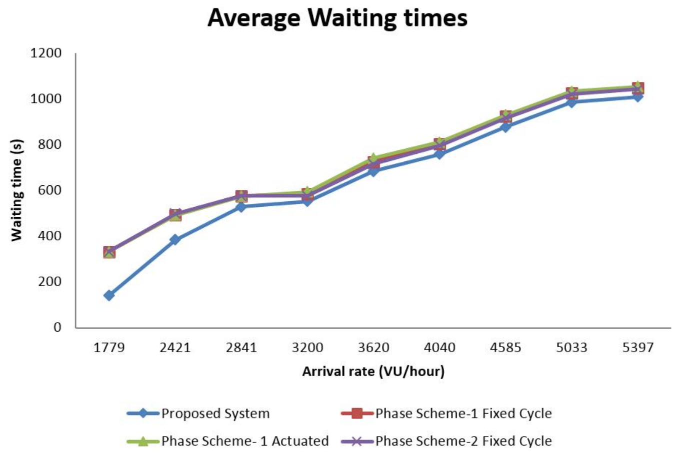

Figure 11: Comparison of average waiting time for ρ_t=.5 and ρ_r=.5 (lower is better)

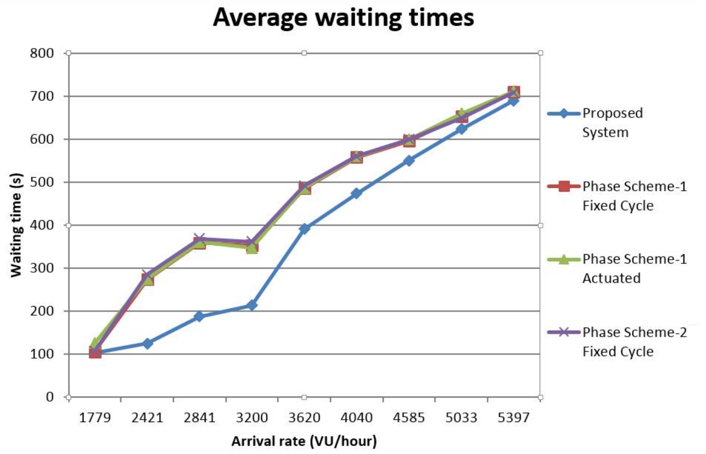

Figure 12: Comparison of average waiting time for ρ_t=.66 and ρ_r=.33

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