A dynamic offset model based on stop line detector information

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Abstract

Existing traffic networks have to be controlled and regulated efficiently before trying to build new transportation facilities, with an aim to reduce the growing traffic congestion. One of the effective options is signal coordination which helps in improving the uninterrupted flow of traffic. The offset provided for traffic signal coordination is often static assuming constant link travel time making it unfit for varying traffic flows. Present study is aimed at building a dynamic offset model, based on the flow rate and the link length between the intersections meant for coordination. Estimation of travel time required for the vehicles to travel from one intersection to another forms the basis of the offset calculation. The underlying assumption is that the travel time increases with an increase in the rate of vehicular flow, as well as the distance between the intersections. This can be captured by a vehicle detector typically placed at stop line. The relation between travel time and vehicular flow has been verified by conducting studies in congested corridors in Mumbai, India, during peak and off peak hours. An algorithm similar to a vehicle actuated algorithm, but terminate at some common cycle length is used in the development of the models and evaluated using a robust traffic simulator. A non-linear dynamic offset model is hence built, which caters to the real time fluctuating traffic conditions. However, the estimation of vehicular flow rate from the detectors in the field is sometimes difficult and erroneous. To address this limitation, a second model is proposed based on the assumption that the green time provided by the algorithm can be used as a proxy for the detector output and consequently the level of congestion. Accordingly, a dynamic offset model is developed which gives the value of the offset to be implemented based on the green time used and the link length. The models developed are compared with the independent vehicle actuated control and constant offset control. The average delay and travel time are considered as the performance indicator. It is observed that the dynamic offset is successful in improving the coordination efficiency of corridors, even for heterogeneous traffic conditions.

Keywords: Dynamic offset; travel time estimation; stop line detection; vehicle actuated signals

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doi:10.1016/j.sbspro.2013.11.142
1. Introduction

Transportation networks form an integral part of the infrastructure responsible for the growth of any country. An efficiently working transportation system of a region ensures comfort, safety, profit and its overall development. The major problem the highway networks experience at present is congestion. The roads must be designed to cater to the existing, as well as, future traffic demands. Similarly, management of the existing road facilities is also equally essential. Various traffic control devices such as signs, signals and road markings can be used to manage the traffic in the desired manner. These devices help in reducing the accidents and control the flow of traffic in such a manner that there is minimum congestion. One of the cheapest and most efficient tools for the management of traffic networks is the traffic signal. The defect with the existing signal control systems is that most of them run on a fixed time, and fail to meet the fluctuating traffic demands. In contrast to pre-timed signals, actuated signals have the capability to respond to the presence of vehicles or pedestrians at the intersection. Actuated control consists of intervals that are called and extended in response to vehicle detectors. The controllers are capable of not only varying the cycle length & green times in response to detector actuations, but of altering the order and sequence of phases. Though there have been advances in the field of vehicle actuated signal control, it is yet unable to control the high variations in the vehicular demands, thereby causing the deterioration of the transportation systems. These problems can be rectified by the introduction of an adaptive traffic control system, which adapts itself to the oscillations in the traffic demand. They collect the data by means of downstream or upstream detectors, predict the flow at the downstream intersection and plan the signal timings accordingly. Many innovative methodologies have been introduced, which use an online algorithm to measure the real time traffic flow and adopt suitable signal timings. The transportation networks are formed by a number of interconnecting roads and intersections. It is important that these intersections work in harmony, in order to ensure the smooth flow of vehicles with minimum delay. The traffic signals along a corridor are synchronized by means of traffic signal coordination.

Coordination is achieved by providing offsets. The offsets offered are usually fixed in nature, whose ideal value is determined based on the distance between the intersections and the link speed. The offset is hence derived from a constant value of the minimum travel time required by the vehicles to traverse the link between the intersections. But in reality, the travel time between the intersections will never be a constant and differs according to the flow. Therefore, the offset to be provided should be dynamic, which changes according to the requirement in flow, along the coordinated corridor of intersections. Also, most of the current adaptive control strategies make use of upstream detection of vehicles to predict the flow profile at the downstream intersection. This results in an erroneous estimation due to vehicle dispersion, and heterogeneity of traffic. The requirement is hence that of an adaptive control system which uses data from downstream detection. In the present study, the detectors are placed just after the stop line. The stop line detectors at an intersection can obtain the discharge at that intersection for every cycle. For vehicle actuated signals, this discharge information is necessary for giving the optimum signal green times to various approaches. Also, the discharge at an upstream intersection is used in the coordination with the ensuing downstream intersections. The present study focuses on the offset as a function of traffic flow and link length. Accordingly, a model is proposed in the study which gives the value of offset based on the traffic conditions and the distance between the intersections.

2. Background

The estimation of travel time proves to be one of the building blocks of adaptive signal controls. The control works by giving the required green times for the vehicles, based on the estimated time required for the vehicles to reach the intersection. The topic of travel time estimation is under constant development. New methods and advances are being made daily for a better and efficient travel time estimation system. Coifman and Cassidy (2001) proposed an algorithm for vehicle reidentification and travel time estimation using detector data, in congested freeways. The vehicle reidentification is done based on the vehicle lengths. The travel time of the
vehicles are calculated from their difference in arrival times on each of the detector sections. Hence, it can be used to extract travel time data without the need for new detector technologies. Even though the algorithm is capable of identifying vehicles and estimating travel times efficiently, it failed to give reasonable outputs when the vehicle changed lanes over the detector. Also, erroneous outputs may be obtained when one of the detector sections of the dual loop detector system malfunctions. These limitations were overcome by Benjamin Coifman and Krishnamurthy (2007) in their study of vehicle reidentification and travel time estimation using existing detector infrastructure. In addition to the previous work on dual loop detectors, the algorithm is extended to single loop detectors as well. The algorithm is capable of vehicle reidentification during lane changes, as well as, across merges and diverges. The same algorithm can also be applicable for other modes of vehicle detection.

The travel time function given by Bureau of Public Roads (BPR) is widely used for planning and estimation, due to its accuracy and simplicity. The equation gives the travel time as a function of flow. The generalized form of the equation is given as:

\[ t = t_0 \left(1 + \alpha \left(\frac{q}{M}\right)^\beta\right) \] (1)

where, \( t \) is the total travel time in seconds, \( t_0 \) is the free flow travel time in seconds, \( M \) is the practical capacity of the link (as given in HCM 2000) in veh/hr, \( q \) is the link flow in veh/hr, and \( \alpha \) and \( \beta \) are the calibration parameters.

Recent studies in the field of signal coordination have introduced various algorithms which help in the offset estimation and optimization. A major offset optimization model proposed by Ying, Guang and Jian (2008) uses two different approaches for the optimization process. The first approach involves the maximization of bandwidth for vehicle progression along the arterials, whereas, the second one deals with the minimization of stops and delays. In the study, two models are proposed – the first based on the arrival time and departure times of the vehicles, and the second on vehicle platoon dispersion. The arriving and departing of the vehicles was assumed to follow a uniform distribution. Also, Robertson’s fundamental platoon dispersion equation was used for the second model. The models consider an unsaturated traffic with a steady flow. Simulations were done using VISSIM. It was observed that the first model performed better than the second one, as the parameters of the second model are difficult to determine. Yin, Li and Skabardonis (2007) came up with a method to refine the offset offline in a coordinated actuated signal control system. It addresses the problem of uncertain starts or ends of the green in the determination of offsets for coordinated actuated signal control. It can work for both one way and two way coordination. The study succeeds in managing the early return to green too.

It can be concluded from the above review that most of the studies considered only the long term traffic variations. Most of the research done in the field of offset optimization was based on bandwidth maximization as the main objective assuming steady or constant flow. Further, existing optimization techniques require high computing time and memory as they make use of the archived traffic data. It is hence essential to develop a simple procedure to determine an offset taking into account the minor as well as major changes in the traffic conditions. Hence, in this study, travel time functions were first developed which uses stop line detector information as a proxy for the flow and link length. These functions were used to compute dynamic offset values and implemented in a signal coordination algorithm. In order to evaluate the model, the single control algorithm is interfaced with a robust traffic simulator which implements the dynamic offset model. The simulator provided performance indices such as delay and travel time to be compared with static offset system and conventional vehicle actuated system. The section below establishes the effect of flow on link travel time from filed data.

3. Field Experiment
A field experiment was conducted to investigate the vehicular flow – travel time relation. Videos were captured for duration of 4 hours, from 3.30 p.m. to 7.30 p.m., at two congested locations in Mumbai, India (Godrej intersection on the Eastern Express Highway and IIT junction on the JVLR). It incorporated different kinds of vehicular flow during the peak and off peak hours. The locations for the field experiment were selected based on the amount of traffic it carried. Also, the sections were selected such that there was a provision for capturing the videos easily. Foot-over bridges at the locations were used for capturing the videos. The data collection section at the first intersection was approximately 185 m in length, whereas the road section itself was 4 lanes wide. The second intersection has four lanes and approximately 120 m in length.

Initially, the vehicular discharge at the sections, for each signal cycle was noted down. The traffic was divided into different vehicle classifications such as Car, Bike, 3 Wheeler, HGV and Bus. The discharge for each of these vehicles was then obtained. The discharge for each cycle was then converted in terms of Passenger Car Units (PCU). Over the 4 hour duration of the video data collected, varying values of discharge were considered for travel time calculation, such that the flow varied from low to high. 25 samples of varying flow were selected from the Godrej intersection, and 16 from the IITB intersection. For each of these samples, the travel time required for each classification of vehicles to traverse the section was calculated manually. A sample of 20 vehicles, from each of the flow sample was considered for calculating the travel time. The average travel time for each vehicle classification was also calculated. The travel time was for all the vehicles in the sample were also averaged. The variation in travel time with the discharge in PCU for every cycle is given in Fig.1 for both the sites considered.

Fig.1. (a) Variation of Travel time with discharge (Godrej Intersection); (b) Variation in Travel time with Discharge (IITB intersection).

The graphs show that the travel time increases as the flow increases. It is thus proved that there exists a strong relation between the vehicular flow and travel time, where the travel time increases with the flow. This relationship has already been used in various mathematical models and algorithms for travel time estimation and in the field of signal coordination. The field experiment thus reinforces the assumption made prior to the present study case, about how the flow influences the travel time.

4. Vehicle Actuated Control Systems

From among the numerous adaptive traffic control methodologies being used to compute the optimal signal timings, vehicle actuated (VA) control is preferred in many of the cases. This is because VA signal controller is capable to handle the random fluctuations in traffic and has the ability to quickly dissipate the accumulated traffic at the junctions. It acquires the real time information and the same real time information is given as input to the VA logic. In vehicle actuated control, green time is continued until the queued vehicles from that phase group have been cleared. The green time is extended in finite steps based on the real-time demand, with constraint on
maximum green time. Most of the vehicle actuated controls work on principle of v/c ratio, but in real-time conditions it is difficult to derive this ratio. So gap identification logic is implemented to take decisions regarding the phase termination or extension with in pre-determined minimum and maximum constraint on green time. The gap indicates the inter-departure times between vehicles from the detector. The terminating gap will be longer than the gap that is encountered when the queue is being served. If the vehicle arrival is continuous such that the system does not find a gap long enough to terminate the phase, the green time is terminated only at the configured maximum green; or if the system does not identify any demand, the phase is terminated at the minimum green. The average green time may be estimated as the sum of the queue service time and the phase extension time. In the VA algorithm developed, the minimum and maximum greens are taken as 10 s and 46 s respectively. These values are derived from the optimum maximum cycle time obtained from the extensive hit and trials done for the coordinated control. The green time is extended by 3s based on the real time demand. The threshold gap considered is 3s. The phase is terminated based on these three termination criteria.

The essential simulations were carried out with the help of the microscopic multi-modal traffic flow simulation software VISSIM 5.10. The software is capable of simulating the existing or hypothetical traffic network conditions, collecting necessary data and analyzing the same. It can also incorporate various kinds of signal control design strategies. The algorithms were implemented with the help of Microsoft Visual Studio 2010, coded in the C++ language. The algorithm coded was integrated and implemented with VISSIM COM API. VISSIM provides a well developed Application Programming Interface (API) for users to apply their own logic in traffic signal control.

The Vehicle Actuated (VA) algorithm was introduced to improve the efficiency of the traffic signals and hence the road networks. The algorithm suggests that the green time provided to the vehicles will be according to the intensity of traffic flow. It ensures that no green time is wasted (i.e., green time is not provided when there is no vehicle on the highway), and sufficient green is provided to the highway with the maximum traffic. Thus, it aims to reduce the delays and queuing and helps the vehicles to maintain a desired speed. A test case was conducted to investigate the efficiency of the VA control logic developed. An arbitrary traffic corridor consisting of 2 intersections, each comprising of 4 approaches, 3 lanes wide, was used for the testing and evaluation of the VA control logic proposed. The layout of the corridor is given in Fig.2.a, whereas the flow profile provided is given in Fig.2.b.

![VISSIM geometry used for VA test case](image1)

![Phase plan provided at the intersections for test case VA network](image2)

**Fig.2.** (a) VISSIM geometry used for VA test case; (b) Phase plan provided at the intersections for test case VA network
A varying input flow was used in the test case. The flow profile for the coordinated and non coordinated links is given in Fig. 3.a. The major advantage of the Vehicle Actuated algorithm is that it caters to the changing demands of the vehicular traffic. It provides green time to the signals based on the amount of discharge it captures from the detectors. The following figures, Fig. 3.b and 3.c show the trends in discharge and green time for any junction, as the demand changes. It implies that the algorithm successfully collects the discharge data as it corresponds to the input flow provided. Also, the trend in green time matches that of the input flow provided, as well as the ensuing discharge. This proves that the VA algorithm is capable of providing green time as per the traffic demand. Since it is seen that the green time is provided according to the discharge, the green must increase with an increase in flow and decrease when there is low flow. This relation is given in Fig. 3.d. The curve follows a rising trend indicating that the green time increases with the discharge. The curve reaches a saturation point at 46 s of green time, as that is the maximum green provided.

Since the VA algorithm terminates based on the gap, it can cause difficulties when the headway is higher than the threshold headway, even when the flow is high. The major aim is hence to provide a means, which allows identifying the approach with the maximum flow and providing green time such that there is a continuous flow of traffic. This can be attained through signal coordination. The offset provided during coordination must be according to the flow, and therefore a dynamic offset can be presumed as the immediate solution.
5. Dynamic Offset Models

Recent studies have shown that independently, coordinated or adaptive control cannot solve the problems at the intersections. The best option is to develop an adaptive coordinated system of control. The offset to be provided for the coordination depends upon the traffic flow, speed and travel time of the vehicles. It also depends on the spacing between the signals. The offset provided must be capable of letting the vehicles move through the corridor without any stops. In this paper, two different models are proposed, which give the real time value of offset based on the traffic conditions and the spacing between the intersections.

5.1 Development of the models

Nine geometries of various lengths ranging from 200m to 1400m, and 3 lanes wide with 3.5m widths each, were used for the simulations in VISSIM. An increasing flow of 0 to 1200 veh/hr for the coordinated approach, and 0 to 600 veh/hr for the non coordinated approaches, was used as the input for the simulation. The phase plan given is similar to the one provided in Fig. 1.b. The geometries are provided with data collection points, detectors and travel time sections, for extracting and evaluating the data. The data collection points and detectors offer the discharge information every second, whereas the travel time sections give us details about the travel times for each kind of vehicle and the delays occurring.

![Fig.4. (a) Location of travel time section in the geometry used; (b) Location of stop line detectors; (c) Location of data collection points.](image)

The type of traffic considered in the development of the model includes both the homogeneous and heterogeneous traffic. The homogeneous traffic consisted of cars with an average speed of 50 km/hr. The vehicle composition used in the heterogeneous traffic condition is given in Table.1.

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Proportion</th>
<th>Average Speed (km/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>0.6</td>
<td>50</td>
</tr>
<tr>
<td>Bike</td>
<td>0.2</td>
<td>60</td>
</tr>
<tr>
<td>Bus</td>
<td>0.1</td>
<td>30</td>
</tr>
<tr>
<td>HCV</td>
<td>0.1</td>
<td>25</td>
</tr>
</tbody>
</table>

The data collection sections and detectors are placed at the stop line to obtain the discharge of vehicles during every green signal. This discharge has to be converted to the flow rate in veh/hr, during the model development. Travel time sections are placed from the stop line of the upstream intersection to the end of queue of the downstream intersection. This is to avoid the intrusion of the queuing effect on the calculation of travel time data,
which may lead to erroneous outputs. The location of data collection points, detectors and travel time sections (shaded area) in the VISSIM network are given in Fig. 4.

5.2. Model 1: Dynamic Offset from Flow Rate and Link Length

A dataset was created from the simulations carried out with the different geometries and varying flows. The dataset included the link length in meters, the rate of flow in veh/hr and the travel time in seconds. The independent relations between the travel time, flow rate and link length were studied thoroughly. The saturation rate of the lane was obtained, from which the capacity is calculated. From the relations studied, it was evident that the function of offset is a non linear bivariate function of flow rate and link length. Statistical analysis and curve fitting on the dataset gave the required travel time as a function of the flow rate and link length. The equation for both the homogeneous and heterogeneous conditions is given below in Equations 2 and 3:

For homogeneous traffic condition:

$$\text{Offset} = \frac{LL}{V_f} \left( 1 + 0.089 \left( \frac{FR}{c} \right)^{2.045} \right)$$  (2)

For heterogeneous traffic condition:

$$\text{Offset} = \frac{LL}{V_f} \left( 1 + 0.157 \left( \frac{FR}{c} \right)^{3.412} \right)$$  (3)

where, LL is the link length between the intersections in m, Vf is the free flow speed (m/s), FR is the flow rate in veh/hr and c is the Capacity of the link in veh/hr. The free flow speeds for homogeneous and heterogeneous traffic conditions were obtained as 13.89 m/s and 14.14 m/s, respectively. Similarly, the capacities of the link for homogeneous and heterogeneous traffic conditions were correspondingly obtained as 1920 veh/hr and 1440 veh/hr.

The minimum and maximum values of the offsets were obtained from the minimum and free flow speeds of the vehicles during various levels of flow. The minimum speed was obtained as 5 km/hr (1.389 m/sec) and the free flow speed was taken as the maximum speed. The limiting values offsets are given below:

Minimum Offset, \(O_{\text{max}}\) (in sec) = Link Length/ 1.389  (4)

Maximum Offset, \(O_{\text{min}}\) (in sec) = Link Length/ 13.89 (for homogeneous traffic) = Link Length/ 14.14 (for heterogeneous traffic)  (5)

5.3. Model 2: Dynamic Offset from Green Time and Link Length

From the test case carried out to ascertain the efficiency of the VA control logic, it was observed that, the control provides green time according to the flow. The trend in green time was similar to the trend in the discharge. The value of green time provided by the signal control will be in accordance with the actual discharge of vehicles through the intersection. In conclusion, it can be assumed that the green time can act as a proxy for the discharge information obtained through the detectors. Hence, an alternative model is proposed, which gives the real time value of offset based on the green time utilized every cycle by the vehicles and the link length between the intersections of the corridor.

The same flow profile and geometries used in the primary dynamic model were used in the alternate model as well. The simulations were carried out for geometries of different lengths and under varying flow conditions. The dataset was created with elements consisting of the green time, travel time and link lengths. Statistical analysis and curve fitting on the dataset gave the required travel time as a function of the flow rate and link length. The equation for both the homogeneous and heterogeneous conditions is given below in Equations 7 and 8:
For homogeneous traffic condition:  
\[ \text{Offset} = \frac{LL}{V_f} \left(1 + 0.004e^{0.125G}\right) \]  
(7)

For heterogeneous traffic condition:  
\[ \text{Offset} = \frac{LL}{V_f} \left[1 + 0.125/\left(\frac{46 - G}{G}\right)^{0.985}\right] \]  
(8)

where, LL is the link length between the intersections in m, Vfr is the free flow speed (m/s), G is the green time utilized for every cycle and c is the Capacity of the link in veh/hr. The values of Vfr and c are calculated akin to the first model.

5.4. Comparative Evaluation of the Models

For the validation of the model developed, a comparative evaluation of the model was done against other offset conditions, such as when there is no offset and when the offset is constant. For the test, initially, the VISSIM networks of different link lengths were simulated using only the Vehicle Actuated logic. Here, the intersections of the corridor ran independent of each other, each working on the VA algorithm. The average delays and travel times for each case was obtained. Next, the same set of simulations was done for a constant offset. The constant offset was taken as the ideal offset, which is the ratio of the distance between the intersections and the design speed of the link. Thus, the ideal offset remained constant for a particular link length. Using the same link lengths and flow conditions, the test was then done for the dynamic offset, as given by the models.

Fig.5. Comparative Evaluation of Offsets for Homogeneous Traffic Conditions for Performance Indices (a) Travel Time; (b) Delay

Fig.6. Comparative Evaluation of Offsets for Heterogeneous Traffic Conditions for Performance Indices (a) Travel Time; (b) Delay
For each of these cases, the delays and travel times were measured, and used as the performance indices. The comparison in terms of the performance indices are given in Fig. 5 and Fig. 6 for the homogeneous and heterogeneous traffic conditions, respectively. From the results obtained, it is clearly visible that the dynamic offset model is successful in reducing the delays and travel times for the intersections of a corridor.

6. Conclusions

The dynamic offset model proposed in this study gives real time offset value when the link travel time changes as a result of variations in the traffic flow which is detected by the vehicle sensors located at stop line. The important contribution of this study is the establishment of the dynamic offset concept from reasonably accurate link travel time estimation using the stop line detector information, a proxy for the link flow. The dynamic offset helps in improving the performance of the signalized intersection in terms of travel time and delay. The reduction in travel time is in the order of 27 to 53 % and delay is in the order of 40 to 66 % for the proposed dynamic offset model when compared to vehicle actuated algorithm. An alternate dynamic offset model is proposed where the link travel time modeled as a function of utilized green time and the link length. Offset obtained from the alternate model also improves the efficiency of the signalized intersections, even though the first model gives better progress. The reduction in travel time is in the order of 32 to 47 % and that in delay is in the order of 38 to 59 % for the proposed dynamic offset model when compared to vehicle actuated algorithm. Although, the present study exhibits the advantages of a dynamic offset using stop line detection, the dynamic offset function was developed solely based on results obtained from simulation under limited traffic and geometric conditions. Recalibration of the proposed functions using extensive field data is definitely required before any real implementation.

Acknowledgements

We are highly indebted to Mr. Ashutosh Bajpai and Mr. Tanmay Shah in their contribution in coding the algorithms and implementing the model. We are also grateful to Mr. Freddy Antony for his help in the collection and extraction of the field data required for the study.

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