IMPROVING ATSPM'S APPROACH DELAY CALCULATION

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Word count: 6,850 words text + 2 table x 250 words (each) = 7,350 words

Submission Date: May 15, 2019

Abstract

There are more than 330,000 traffic signals in the United States, at least 75% of which could be significantly improved by updating their equipment or timing plans, reducing unnecessary delay to motorists. A major reason for this excess delay is poor traffic signal timings that account for nearly 300 million vehicle-hours on major roadways alone. Automated Traffic Signal Performance Measures (ATSPM) is a recent development which provides performance measures that can be used for decision making and selection of more effective operational strategies that could reduce the total delay and cost. However, the delay estimation method of ATSPM is extremely simplified and ignores some of the fundamental components of delay experienced by motorists at a traffic signal. The team proposes three alternative methodologies for estimation of approach delay, each of which addresses one or more of the drawbacks currently present in the ATSPM framework. The cumulative arrival/departure method uses upstream and downstream detection and incorporates the stop, deceleration, and the acceleration delays into the approach delay. Departure-only method uses the actuations at the departure detectors to estimate the approach delay that are comprised of the stop and initial queue delays. The shockwave method uses arrival and departure detections to estimate the approach delay. Stop component of the approach delay is fully incorporated in the estimates by this method. Results of the proposed methodologies reveal promising improvements over ATSPM's conventional delay framework.

Keywords: Approach Delay, Arrival/departure Curves, Shockwave, ATSPM, Detector

INTRODUCTION

With increase in human population, there is an increase in transportation demand. As a result, transportation facilities are used more and eventually there is an increase in traffic on roads. For efficient and safe travels, it is important to manage traffic. For effective traffic management, traffic signals are installed at intersections. Traffic signals control opposing flow and hence enhances intersection performance. As a result, commuting becomes safe and efficient for travelers. In the United States, first traffic signal was installed in 1914 and at present there are more than 330, 000 traffic signals according to United States Access Board. Though the traffic signals make travelling efficient and safe especially at intersections, there are drawbacks of this traffic control device. It causes issues such as congestion and as a result delay is caused. Recently it has been discovered that traffic signals are one of the dominating sources for congestion. In the US, on an average a driver spends 42 hours a year at signalized intersections during peak hours. Also there are safety concerns; about 19% of the crashes occur at signalized intersections. Hence it is of vital importance to study and analyze signalized intersections to improve its performance.

To study signalized intersections, there are several performance measures such as delay, queue length, number of stops etc. These performance measures are linked to each other explicitly or implicitly. Delay is defined as the amount of time consumed in passing through the intersection: the difference between the arrival time and departure time wherein this can be calculated using myriad methods. Queuing is referred to as the number of vehicles stopped on an approach behind stop line during red phase of a signal. Stops refer to the number of vehicles or percentage stopped at the signal. Thus by estimation of any single performance measure, expected trends of another can be easily known. Though this performance measures can provide an accurate picture of intersection performance, estimating them is a difficult task. Several methods are developed for their estimation but there are certain assumptions and limitations to each of the methods. Out of all the performance measures, delay estimation serves as the better out of all as it directly yields the time spent at the intersection when the vehicle is stationary. There are several components of delays such as acceleration delay, deceleration delay and control delay.

Quality of data used in delay estimation models is the key pin everything hinges on! Precision and accuracy of any model is highly dependent on the type of data used. With the development of technology, use of sensors and detectors is done to collect several data at the intersection. With the use of such technologies, high resolution data within different time intervals can be obtained. This data can be utilized to estimate delays and in a way that optimizes the performance of signalized intersections.

Automated Traffic Signal Performance Measures (ATSPM) dataset is one such source which can provide high resolution data. ATSPM helps in better management of traffic signals by generating performance metrics based on the high resolution data. These performance metrics helps in better decision making and selection of more effective operational strategies which reduces congestion and cost. There are several performance metrics in ATSPM such as: approach delay, approach volume, approach speed, arrivals on red, purdue split failure and similar other. There are advantages and limitations of each performance metrics.

Out of all the performance metrics, ‘Approach Delay’ is one of the most critical performance metrics of all. Delay can provide a comprehensive estimate of time during which vehicles are not moving. Secondly, delay is largely a function of capacity utilization; It is measured by utilizing volume-to-capacity ratio and performing relevant calculations. An accurate estimate of delay provides clear picture on capacity unutilized and thus can help in better implementation of operational strategies for traffic management. Total delay is the summation of several components of delay such as control delay, acceleration delay, deceleration delay and few others which implicitly or explicitly impact delay.

In ATSPM, one of the most poorly functioning performance metrics out of all is approach delay with reference to traffic flow theory. ATSPM provides information regarding the delay experienced on any approach to an intersection. Though the ATSPM dataset provides delay measurements, it does not account for all the components of delay. ATSPM delay measurement does not account for: start-up delay, deceleration delay, queue length that exceeds detection zone, initial queue length, right turn on red, travel time detector and stop bar. As the delay estimates does not account for all these components, delay calculated is mostly an under-estimate of actual delay. In this study, some of these missing components of delay are addressed and three algorithms are developed, capable of estimating delay more accurately than ATSPM. These three algorithms are then compared with the ATSPM delay estimates and conclusions are drawn.

High resolution traffic data from Utah DOT was provided for two corridors, corridor-1: 3 I00W (US-89) and corridor-2: 700E (UT-71). Corridor-1 had 10 intersections and corridor-2 had 12 intersections and the signal data for the year 2018 was provided. With the use of this data, 2 models for delay estimation are developed one being microscopic and macroscopic. One approach is based on cumulative arrival and departures of vehicles (microscopic) and another is based on shockwave analysis (macroscopic). Each method is discussed in detail in later sections.

Next portion of this report discusses literature review and summary. Microscopic and macroscopic methodologies developed are discussed in the section after literature review. Guidelines on its implementation and important assumptions associated are also listed. In the last section, concluding remarks with limitations of the model are mentioned and scope for future work is reported.

LITERATURE REVIEW

As discussed before, delay can serve as an important performance measure to evaluate intersections' performance but its estimation is challenging and difficult. It is a common practice to calculate delay based on the vehicle queue length. Majority of the queue length estimation methods can be classified into 2 classes: input-output models and shockwave based models. Input-output models basically involves analysis of vehicle accumulation just before the intersection i.e. at the stop line. Shockwave models are based on the variation of traffic stream properties during queue formation and dissipation. These shockwave models can account for temporal and spatial information for the queuing process.

Research based on shockwave theory to estimate queue lengths and delays began since the early 1980s. In (Panos G. Michalopolous, 1981) , a real time control policy minimizing total intersection delays based on queue length constraints was developed. An isolated intersection was studied in this paper rather than a system of signalized intersections. Proposed model or policy was tested with real world data and it was observed that during peak hours, suggested method can generate accurate results. In another study in 1981 (Pisharody, 1981) , analytical and mathematical procedures to estimate delays for system of coordinated signalized intersections were developed. It was also shown with numerical examples that he shockwave models or macroscopic models in general yield more accurate results than conventional input-output models.

With the advancement in technology, models utilizing detector data for delay estimation began developing. Use of ATSPM is gaining popularity in terms of using high resolution data at signalized intersection for performance measurements and is used frequently. In a report by Georgia DOT (America, 2016) , detailed discussion on reporting results of ATSPM is mentioned. Interpretation for all the attributes of performance measures in ATSPM is reported. In (Liu, Wu, Ma, & Hu, 2009) , use of high resolution data collected from SMART-SIGNAL in Minnesota was done to estimate real time queue lengths. This paper suggests three models, one classical Lighthill-Whitham-Richards (LWR) model and two with minor changes in this basic model. It was observed that the classical LWR model yields most accurate results when used in combination with high resolution data. MAPE of around 7% for classical model was observed and that for two modified models was 15% and 21%. Though this model yield minimum error, data hungriness of this model makes its use limited. In a study, (Cheng, Qin, Jin, & Anderson, 2011) a methodology for cycle by cycle queue length estimation for signalized intersection was proposed. Vehicle trajectory data is used as an input and Critical Points (CP) are defined based on this trajectory data. These critical points represent different states of vehicle in queue and it is used for queue length estimation. The methodology is tested with real world data and Mean Absolute Percentage Error (MAPE) of 20% is observed on an average. This model is simple to implement and can be used in the real world but the error is unreasonably high. In cases of oversaturation, error up to 25% was reported. In essence, there is no model without limitations; results are highly dependent on the type of data and assumptions related to it.

Incremental Queue Accumulation (IQA) Method

The performance measure of an intersection depends on several criteria such as the delay, queue length and the number of stops, among which delay is considered to be the most important. One of the most widely used methods for delay estimation is the Queue Accumulation Polygon (QAP) method suggested in the Highway Capacity Manual (HCM). With the uniform term of delay equation, the HCM method assumes that the QAP must have a triangular shape (shown in Figure 1). However, the assumption does not hold true in real-world scenarios as the vehicle arrivals and departures may vary in a cycle. To improve the limitation, the previous studies developed several alternative methods that accounts for the non-uniform pattern of arrivals and departures of vehicles.

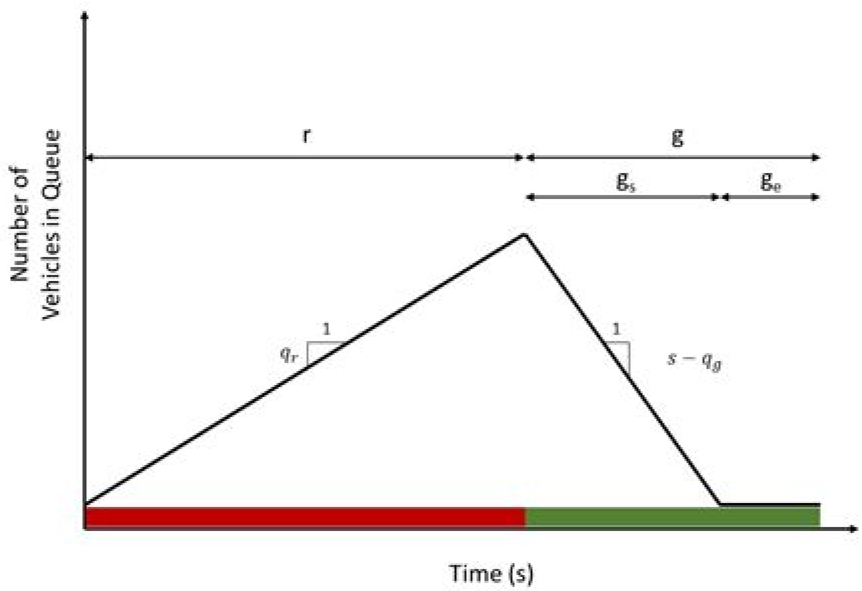


Figure 1: Queue Accumulation Polygon (QAP) in HCM

Robertson (1969) first proposed an analytical framework to account for the pattern of arrivals and departures at a signalized intersection. The suggested method uses a flow profile diagram which can be drawn by the arrivals and departures with the short time steps.

Strong et al. (2005) modified the flow profile diagram and proposed the Incremental Queue Accumulation (IQA) method, which is an alternative calculation method for HCM first-term delay model. IQA method is to calculate the areas of time short time slices of the QAP rather than using the formula to calculate the triangle area of QAP. So, the IQA method can lift the limiting assumption of the QAP formula. The study proved IQA method yields more understandable, accurate, and applicable results for delay calculation over a broader range of conditions.

Strong and Rouphail (2006) proposed an extended approach of IQA method that can account for the non-uniform arrival rates affected by the platooned arrivals. The study showed that the proposed method has higher accuracy and flexibility in implementing the treatment than the progression factor method suggested in the HCM.

Kyte et al. (2008) provided validation of IQA method using NGSIM dataset and compared delay estimates with field measurement and HCM method. Delay from field measurement was estimated using travel time of each vehicle between the arrival (entry point at the intersection) and departure (exit point at intersection) points. IQA method estimates delay using a queue accumulation polygon by calculating the number of vehicles in a queue for each time period of vehicle arrival. The method incorporates the non-uniform arrival rate by matching the vehicles upstream (upstream detector) and downstream (stop bar detector) which provides more accurate results as compared to HCM delay method.

METHODOLOGY

Data Preparation

The dataset provided as part of ATSPM project has a high-resolution vehicle detection data. This data is provided from Utah DOT for two corridors: corridor-1: 300W (US-89) and corridor-2: 700E (UT-71). Data is prepared for a section of corridor 2 at 700 East at 500 South using detector data and signal timing (phase) data. This data has event-based time stamps with the accuracy of 0.1 seconds consists of two variables i.e. event parameter and event code. Event parameter represents a detector or phase ID and Event code represents the condition of detector or a phase whether it is "on" or "off". Using these two variables, a R script is used to extract the cycle by cycle data of arrivals and departures of vehicles.

Method 1: Cumulative Curves Based Approach

Basic Principles of IQA

The IQA method estimates the length of queue using the arrivals and departures information with short time steps. The method adds and subtracts the vehicle arrivals and departures during each time step to the queue at the start of the time step. Figure 2 illustrates the queue length computed at time step i, which is the difference between accumulated vehicle arrivals and departures. The time steps are defined whenever a vehicle arrive or depart so that there is a change of status in the queue.

Then, the total delay (D1) experienced in a cycle can be calculated by adding up all the products of queue and time steps. The corresponding average delay per cycle (d1) can be computed by dividing the total delay by the number of vehicle arrivals in a cycle. As such, the IQA method computes the QAP area of trapezoids representing the total time during the cycle where the inflow and outflow rates are not equal.

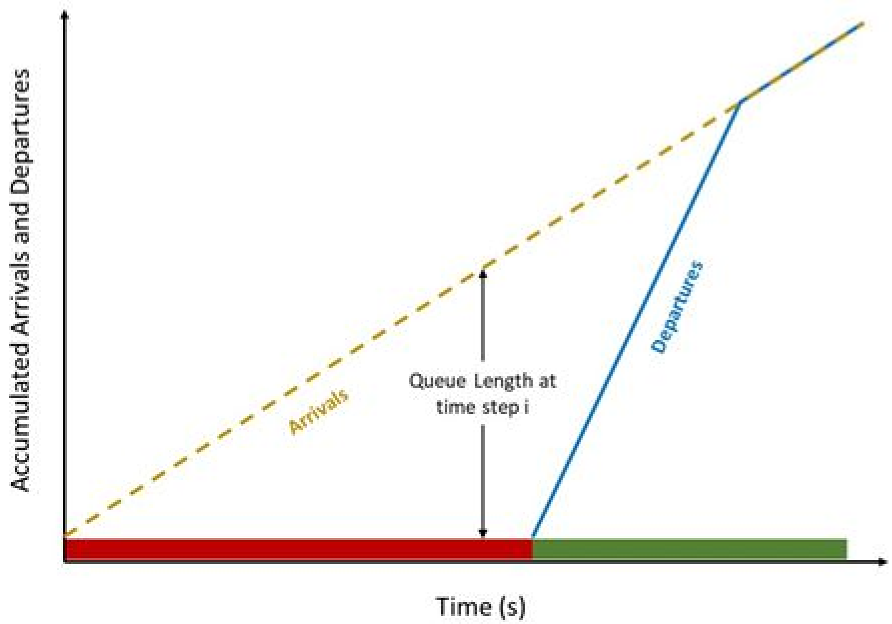


Figure 2: Queue Length during Time Step (i)

Application with ATSPM Data

Prior to the application of IQA method with ATSPM data, it is necessary to identify what types of data are available to use. Figure 3 is the time-space diagram that shows the vehicle trajectories approaching toward an intersection. The figure can be drawn only when every vehicle trajectory is recorded. The ATSPM data, however, includes only the vehicle observation records detected at the upstream and stop-bar detectors which are shown as dotted lines in the figure. As such, for IQA method, it is essential to tie the observations at upstream and stop-bar detectors.

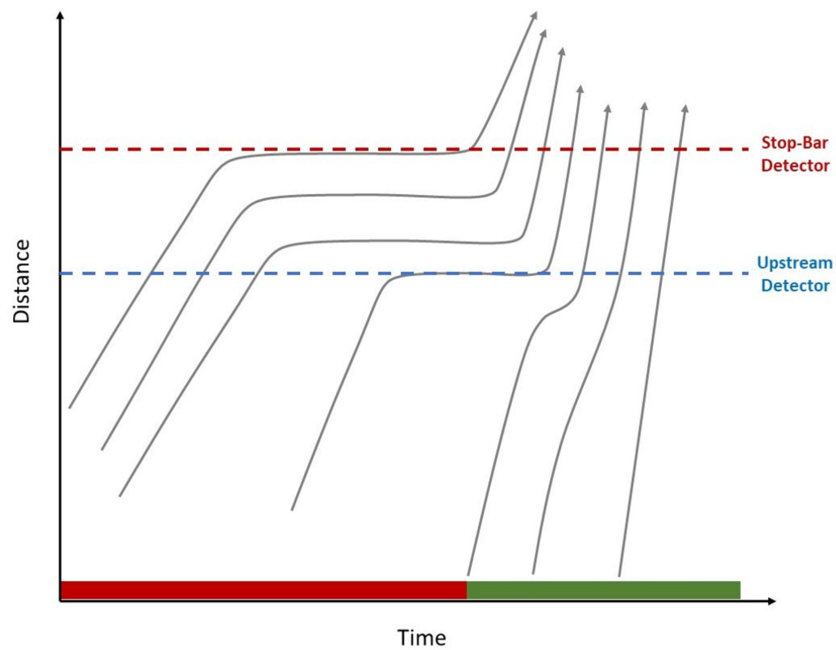


Figure 3: Time-Space Diagram for Vehicle Trajectories

This methodology assumes stable operations of the traffic signal (i.e. departure curve catches up with the arrival curve before the end of a cycle). Hence, there will be no vehicles present at the end of a cycle. It further assumes that arrivals and departures obey the FIFO (first-in-first-out) principle. This means that vehicles depart from the stop bar in the same order as they had arrived at the upstream detector. These assumptions enable the analyst to tie the arrivals at the upstream to the departures from the stop bar.

With the refined data, the vehicle arrivals-departures curve can be drawn as Figure 4, which illustrates the accumulated vehicle arrivals to time. In the figure, the yellow dashed line and blue line are the vehicle arrivals detected at upstream and stop-bar, respectively. The horizontal time gap between two lines is the travel time of vehicle from upstream to stop bar. To compute the delay for vehicle using the arrival and departure time, the appropriate free-flow travel time needs to be determined.

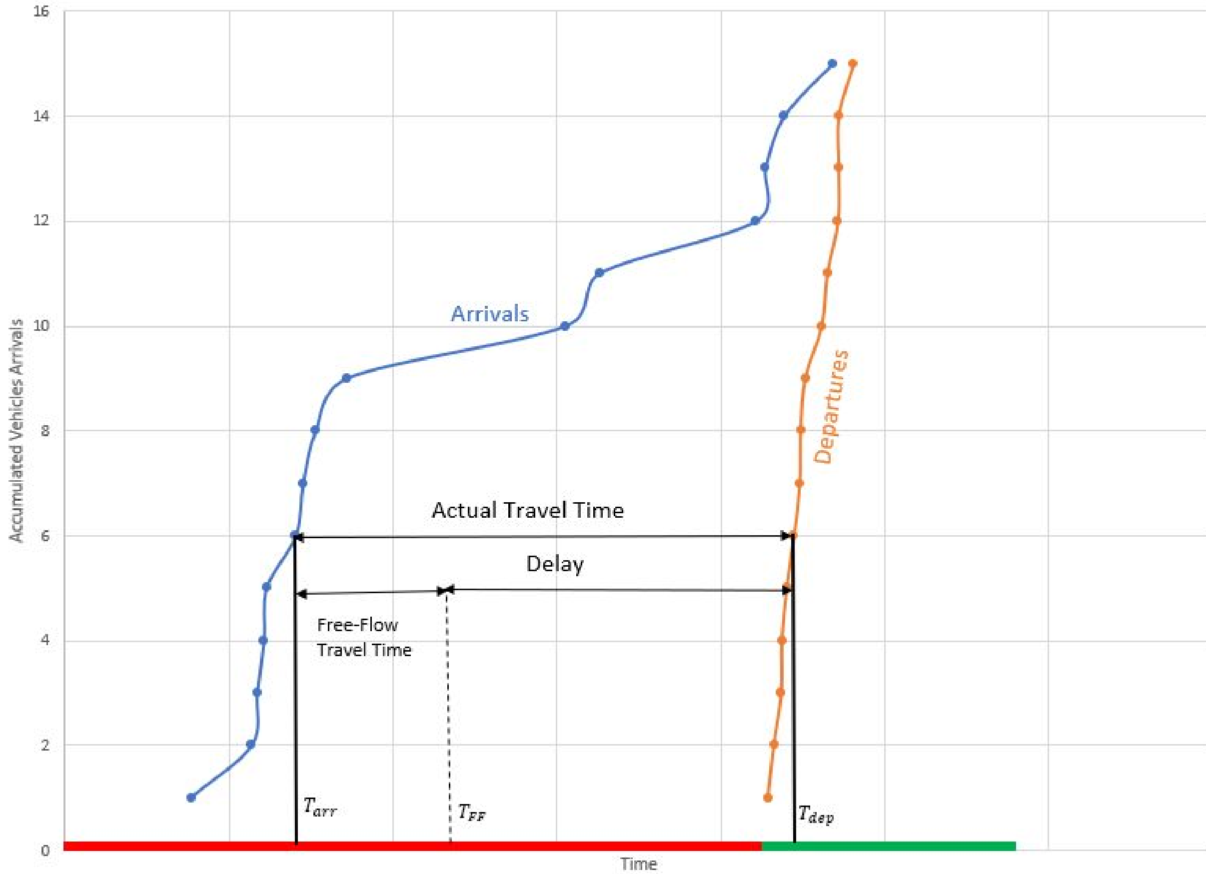


Figure 4: Accumulated Vehicle Arrival and Departure Time

To estimate the delays for individual vehicles, the expected departure time for free-flow condition is calculated by adding the free-flow travel time to the observed arrival time (see Figure 4). Free flow travel time is estimated for each vehicle as described below:

$$T_{FF} = \frac{L}{Speed\ Limit}$$

Where,

T_{FF} = Free flow travel time (in seconds)
L = length between upstream and downstream detectors (ft)
Speed Limit = Posted Speed (mph)

Then, the delay can be computed by subtracting the expected free-flow departure time from the observed departure time as shown in the figure. The total experienced delay can be computed by adding up all the delays and the average experienced delay per vehicle can be calculated by dividing the total delay by the number of vehicle arrivals.

METHOD 2: BASED ON EXIT SENSOR DATA ONLY

This method employs actuation data only from the lane-by-lane detectors located at or just downstream of the stop line of an intersection. It leverages the changes in headway of departing vehicles when all queued vehicles are served and the unqueued vehicles start arriving at the intersection. Two thresholds are implemented to classify queued and unqueued vehicles that enable the estimation total delay per cycle and average delay per vehicle based on reasonable assumptions.

<u>Assumptions:</u>

1. Vehicles departing from a queue are likely to have inter-departure times or headways that are close to the saturation headway.
2. A large gap between two successive departures indicates that the queue has cleared and the remaining vehicles will not experience any delay.
3. The arrival rate is uniform during green and red period except for some special cases that are described separately.
4. Multiple lanes of a movement group are operating independently.
5. No queue spilling back from any downstream intersection

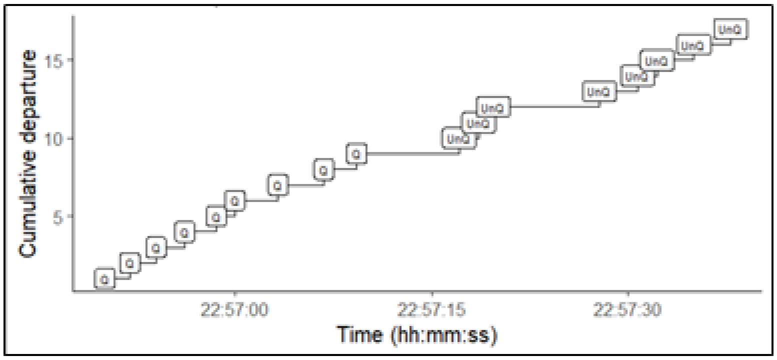
Inputs

At the end of each cycle, we archive the phase time information and actuation (detector "on") events from the stop bar detectors.

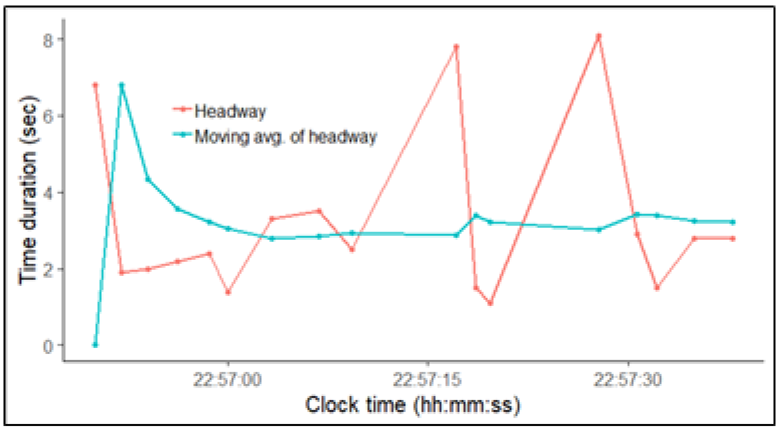
Process

In the subsections below, the steps to apply this method to each lane of a movement group are described. It assumes that there is no residual queue and both queued and unqueued vehicles are served by the lane during its green time. Following this, the applicability of this method to some special cases are discussed when any of these conditions are violated.

Step 1: Queued And Unqueued Vehicle Identification: Figure 5(a) shows a typical cumulative departure plot for a lane within a cycle. It is evident that, had the first vehicle departed from a queue, the queue cleared with the departure event circled red. However, this classification of queued and unqueued vehicles is not trivial because the saturation headway of queued vehicles is a stochastic parameter. To address this issue, the moving average of headways of the departing vehicles are calculated as shown by the cyan line in Figure 5(b). Queue clearance is declared when the difference between this moving average and observed headway (red line in Figure 5(b)) exceeds a threshold.



(a)



(b)

Figure 5:(a) Cumulative departure of queued and unqueued vehicles from a lane during green time for that movement (b) Variation of headway and moving average headway during green time

If the Nq is the number of queued vehicles, then the time to clear the queue from the start of the green (gq) is estimated using the following equation.

$$g_q = h_{av} + \sum_{i=1}^{N_q} h_i$$

Where, is the average headway of the queued vehicles.

i=1, 2, 3 ,… count of departing vehicles.

Here, the headway of the first vehicle is calculated as the time difference between the start of the green time and its departure time. A large value for this headway would indicate that this vehicle arrived during green and all the vehicles on this lane did not experience any delay in that cycle. Another threshold is used to identify such cases when vehicles on a lane experience no delay. The reason for using a different threshold is that unlike for other vehicles' headway, the headway of the first vehicle is sensitive to detector latency. Moreover, the presence of a queue from a closely spaced downstream intersection may affect the selection of these thresholds.

Step 2: Arrival Rate Estimation: Figure 6 shows the cumulative arrival of vehicles during red and green (dashed lines) and the departure (solid line) from a lane within a cycle. Since only departure events are known, the solid lines are measured from those events while the dashed lines need to be estimated. The saturation flow rate (s) can be calculated as the inverse of the average headways for all the queued vehicles.
The arrival rate during green (qg) is estimated using the following equation.

$$q_g = N_f / g_u$$

Where, N_f = count of vehicles departing from an unqueued condition,
g_u = remaining green time after the last queued vehicle departs.
The arrival rate during red (q_r) is estimated using the following equation:

$$q_r = \min\left(\frac{N - Q_i - q_g * g}{r}, 0\right)$$

Where, N = total vehicle departing in a cycle, and g and r are the green and red time for that cycle, respectively.
= initial queue or the residuals from the preceding cycle. Note that $Q_i = 0$ for the first cycle in the analysis period.

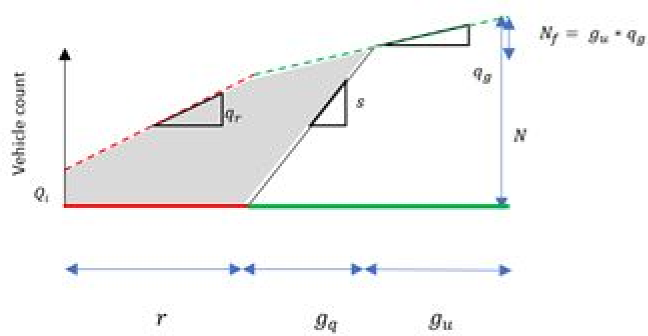


Figure 6: Estimation of arrival rate during red and green for a lane within a cycle

Step 3: Performance Measure Estimation: The shaded area in Figure 6 represents the total delay within that cycle, which is estimated using the following equation

$$Delay\ per\ cycle, D = \left(\frac{1}{2}\right) * r * (r * q_r + Q_i) + \left(\frac{1}{2}\right) * q_r * r * g_q$$

Delay per vehicle and percentage arrival on red can be estimated as:

$$Delay\ per\ vehicle, d = \frac{D}{N}$$

$$AR\% = q_r * r / N * 100$$

This performance measures calculated for each cycle and each lane of a movement are then averaged over multiple lanes weighted by the volumes served by each lane.

Special Cases

The method described above will not work if the cycle is oversaturated or if there are no unqueued vehicles. However, with some additional, rational assumptions, we can provide decent estimates of delays and overflow queues for such cases as described below.

Oversaturated Cycle: Figure 7 below shows the arrival-departure plot for successive oversaturated cycles followed by an undersaturated one. The arrival rate (*q*) is assumed to be uniform throughout all these cycles which is estimated as the slope of the dashed line.

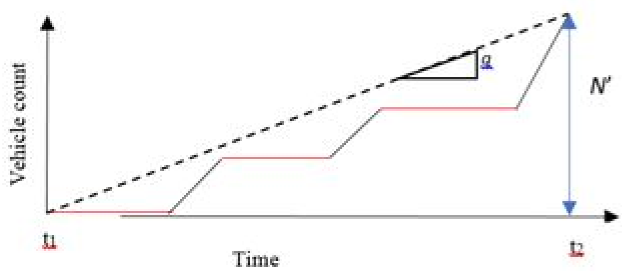


Figure 7: Estimation of average arrival rate for successive oversaturated cycles

$$Average\ arrival\ flow\ rate, q = N'/(t_2 - t_1)$$

Where N'is the total vehicle departing between the start of the first oversaturated cycle and the end of the first undersaturated cycle after that. t_1 and t_2 mark these start and end times.

For each oversaturated cycle, the overflow queue size is estimated as:

$$Q = Qi + qC - sG$$

The delay for each cycle is estimated as:

$$D = 0.5 * q * r * C + 0.5 * (Q_i * r + Q * g)$$

Undersaturated Cycle with No Unqueued Vehicles: Figure 8 shows the arrival-departure plot for an undersaturated cycle where no unqueued vehicles departed after the queue was cleared.

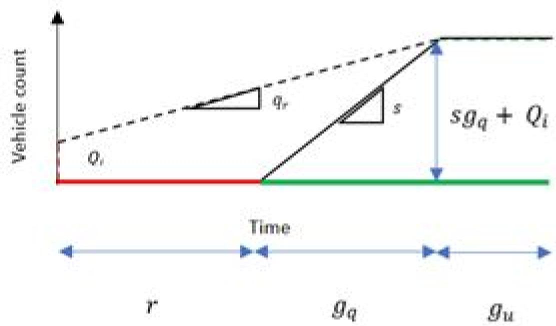


Figure 8: Arrival rate estimation for a lane within a cycle with no unqueued vehicle

Here, we assume that the arrival rate is uniform from the start of the cycle to the end of The average arrival flow rate is estimated as:

$q = (s * g_q - Q_i) / (r + g_q)$

Delay measurements are estimated using the following equations.

$Total\ delay, D = 0.5 * (Q_i * r + q_r * r * (r + g_q))$

Note that the formula for delay per vehicle and percentage arrival on red remain same for these special cases.

Limitations

1. Platoon of vehicles arriving right after the queue clearance may cause erroneous classification of queued and unqueued vehicles
2. In case for closely spaced intersections, queue from a downstream intersection may affect the identification of queued and unqueued vehicles
3. It does not account for lane changes induced by lane imbalance at an intersection

Method 3: Traffic Shockwave Approach

Shockwave analysis dates back to original theories and observations by Lighthill and Whitham (1955) which utilizes a basic flow density relationship to track flow state boundaries for various conditions. This work has been extended for traffic signals to include additional conditions for deceleration and acceleration which began with Michalpopoulos et al (1981) and has seen innovations throughout recent decades. Many of these methods rely on accurate traffic state measurements which are difficult to obtain under traditional traffic signal detection layouts. Intersections with inductive loop or other point sensors must be instrumented upstream and downstream of the stop bar in positions which can capture arriving and departing traffic, however these are typically not used to track individual vehicles and lose fidelity when lane by lane data are aggregated for an approach.

The application of this method for improved delay estimation for ATSPM adopts a set of assumptions in order to develop cycle-by-cycle average arrival and departure flow states including uniform arrivals and equally distributed traffic across lanes. Additionally, the method assumes a triangular flow-density relationship as shown in Figure 9 and does not consider acceleration or deceleration delays or initial queue delay. Shockwave speeds can be estimated by measuring the slope of lines connecting two transition points on the flow-density plot. The key points to calibrate per site are the density and flow at capacity and the jam density. Then the ATSPM data can be used to measure the traffic states of interest and track the red phase for the signal. It is important to note that this method assumes that there are no split failures as no information is tracked across multiple cycles.

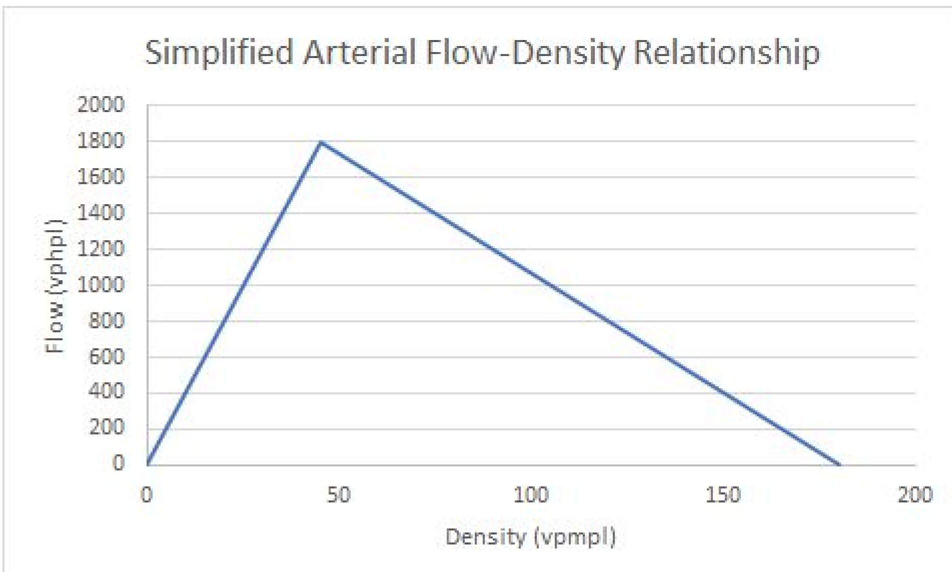


Figure 9: Simplified Arterial Flow-Density Relationship

Figure 10 shows the expected flow states and shockwaves. Shockwave (a) is the transition from the free-flowing arrivals (I) to the queued state (II). Shockwave (b) is the transition from queue (II) to departures (III). Shockwave (c) is the transition between departures at saturation flow and the arrivals which continue through the intersection without delay. Shockwaves (a) and (b) always begin at the start and end of the red phase respectively, while shockwave (c) continues from the point where (a) and (b) meet downstream at the free flow speed. In this example graphic, the following data were used:

- Free Flow Speed: 40 mph
- Arrival Flow Rate: 800 vphpl
- Jam Density: 180 vpmpl
- Green Phase: 30 s

- Saturation Flow Rate: 1800 vphpl
- Cycle: 60 s

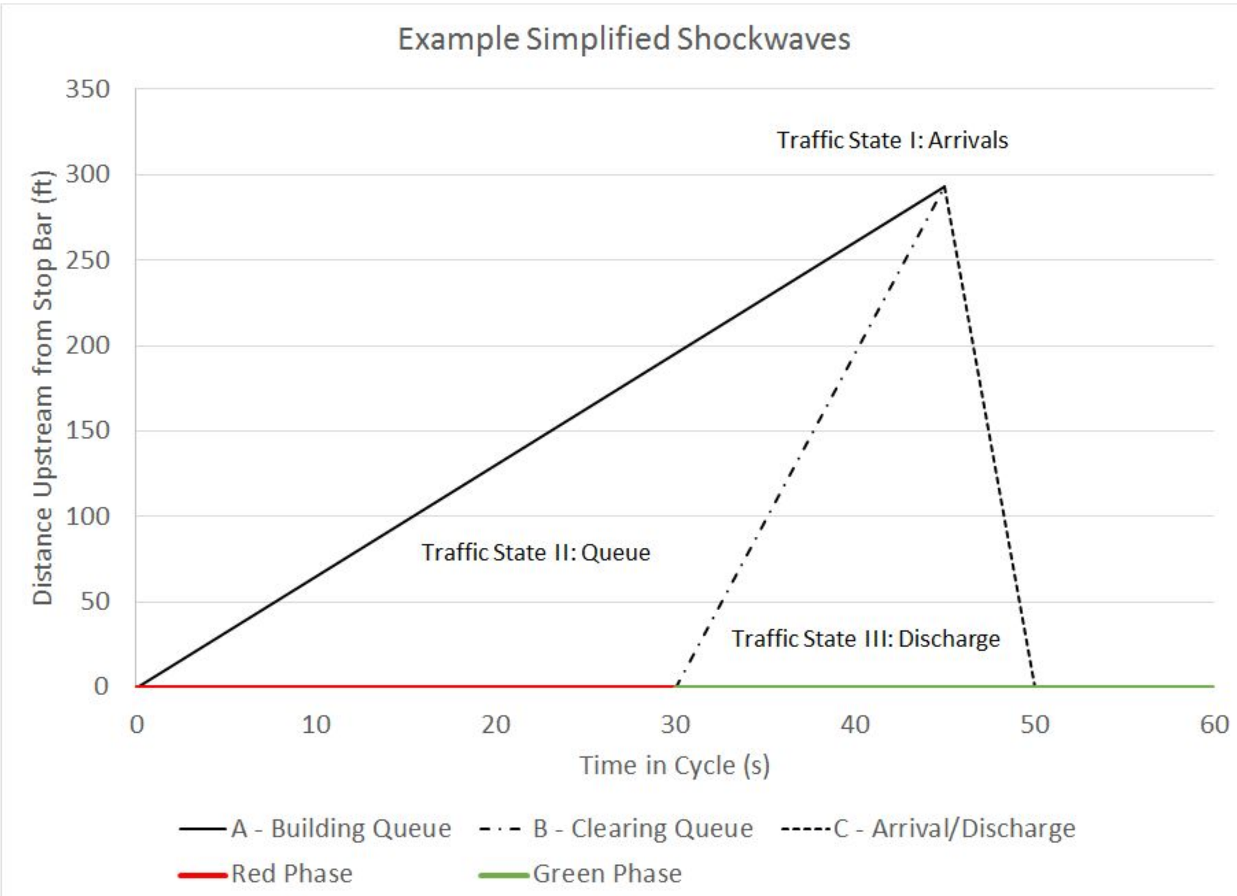


Figure 10: Example Simplified Shockwaves

Once all traffic states and shockwaves are estimated, average delay per vehicle can be estimated under the assumption of uniform arrivals however with ATSPM we have actuations from actual arrivals which can be used to estimate their trajectories and therefore estimate delay. In this case, we have a detection at a distance upstream where the advanced detector is located which can be projected downstream at the free flow speed until it either crosses shockwave (a) or passes the stop bar undelayed. Trajectories which cross shockwave (a) experience stop delay equal to the horizontal time between (a) and (b) at this distance. An example is shown in Figure 11 where a vehicle is detected 350 ft upstream at t=0 in the cycle. This results in a stop at 35 ft upstream and 26.4 seconds of stop delay. This method is repeated for each actuation and can be aggregated to per cycle or time period delay by direct averaging of all individual vehicle delays.

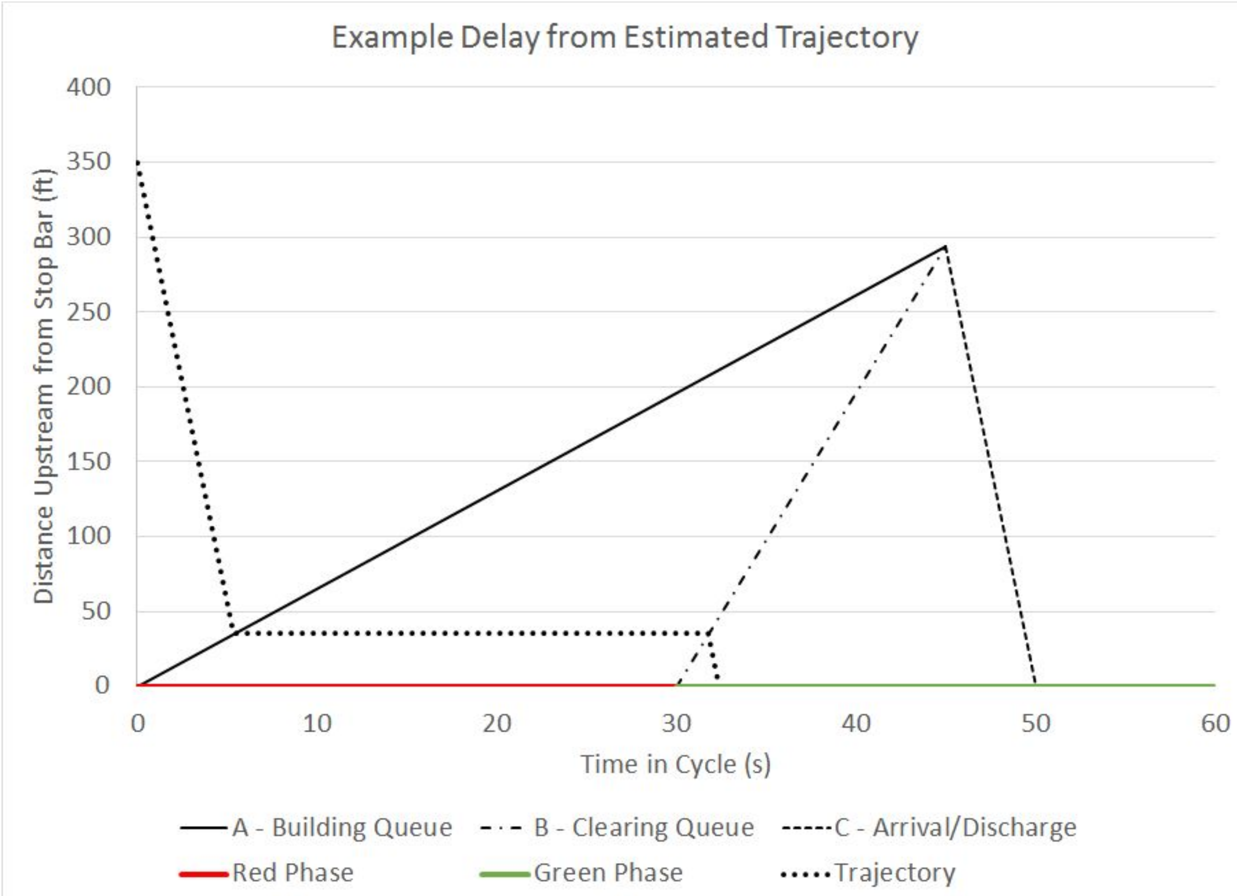


Figure 11: Example Delay from Estimated Trajectory

Method 4: ATSPM's Approach

ATSPM provides a simplified approach delay experienced by vehicles approaching and entering the intersection. Both the average delay per vehicle and total delay are calculated as part of this process. Individual delay per each actuations of the upstream detector is calculated and the reported approach delay is aggregated in bins of 5 minutes or 15 minutes. This method uses traffic signal timing data along with upstream detector actuation to obtain the approach delay.

The ATSPM method calculates the approach delay as the time between a detector activation during the red portion of the phase, and when that phase turns green. Figure 12 shows the delay for one arrival during red. The total approach delay for a typical cycle can be obtained as follows:

$$Cycle\ delay = \sum_{i}^{n}(T_G - T_{FF_i} - T_{arr_i})$$

Where T_G is the start of green for the cycle, T_{FF_i} is the free flow travel time for vehicle i estimated using equation 1, and T_{arr_i} is the time when vehicle i arrives at the upstream detector.

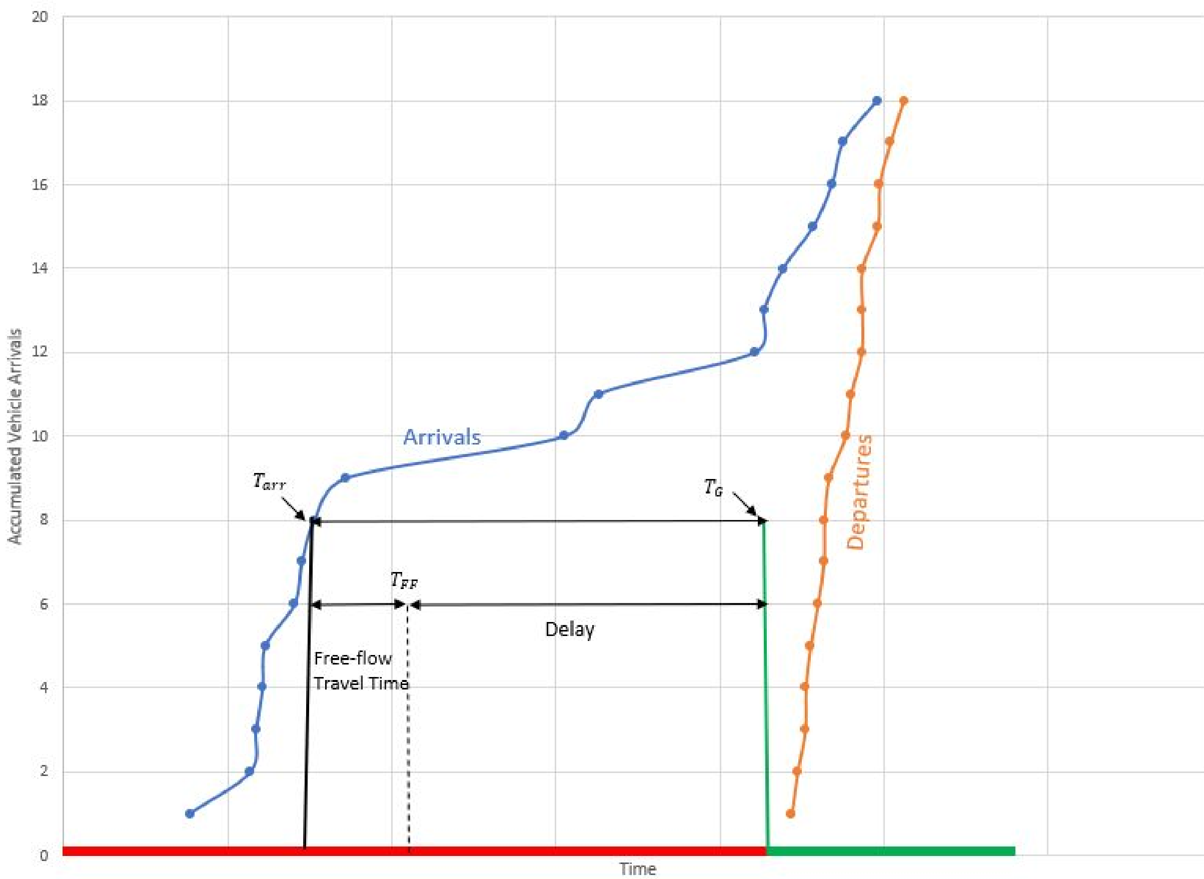


Figure 12: ATSPM's method of estimating approach delay for a typical vehicle arriving in red

The approach delay calculated by this method fails to account for start-up delay, acceleration delay, deceleration delay, or queue length exceeding the detection zone.

CASE STUDY

In order to adequately test the four delay methods in this report, the team identified three critical data points needed at a candidate approach for case study. First, the signal timing data must be available in the ATSPM dataset, which is true for all of the sites provided. Secondly, the approach must have upstream detection in order to count arrivals. Finally, a downstream detector is needed for methods 1 and 3 in order to ensure arrival and departures in a cycle are balanced. All Signal IDs were entered in the UDOT ATSPM website in order to determine which performance measures and associated detector data were available. The team required that the following reports were available and the table below documents the data availability: 1) Purdue Split Failure, 2) Turning Movement Counts, 3) Approach Delay, 4) Approach Speed.

Table 1: Data Availability

Signal ID	Purdue Split Failure	Turning Movt. Counts	Approach Delay	Approach Speed
7122	Y	Y		
7123	Y		Y	Y
7124	Y		Y	Y
7342				
7125	Y	Y		
7126	Y			
7127	Y			
7128				
7129	Y			
7241	Y	Y		
7180	Y			
7181	Y	Y	Y	Y
7182	Y	Y	Y	
7183	Y	Y	Y	
7184	Y	Y	Y	
7185	Y	Y	Y	Y*
7186	Y	Y	Y	Y*
7187	Y	Y	Y	
7076			Y	Y
7188	Y		Y	Y
7189	Y		Y	Y
7190	Y	Y		

*Not available for all major street approaches

The team selected Signal ID 7181 based on data availability and established the event enumerations of interest in the raw data file based on the Southbound approproach and turning movement count detectors as well as the corresponding Phase 6 signal data. During data exploration, the team discovered that the turning movement count detectors were all active beginning in October 2018, so only data beyond this point was reviewed. In order to reduce data cleaning activities, a single day of Tuesday November 6, 2018 was selected for use in all four methods. In addition to the selection of events of interest in the log, an additional field was added in processing in advance of use for each method to establish a common cycle ID based on the start of the red for Phase 6 in each cycle.

Figure 13 shows the layout of detectors for the selected signal. Detector 4 is an advanced count detector located 390ft from stop bar and used for keeping track of arrivals. Detectors 43, 42, and 41 are lane-by-lane stop bar count detectors used for keeping track of departures from the intersection. Methods 1 (arrival/departure curve) and 3 (shockwave) use actuations of detectors

4, 41,42, and 43 for calculation of approach delay, while method 2 (departure-only) uses detector 41,42, and 43 for this purpose.

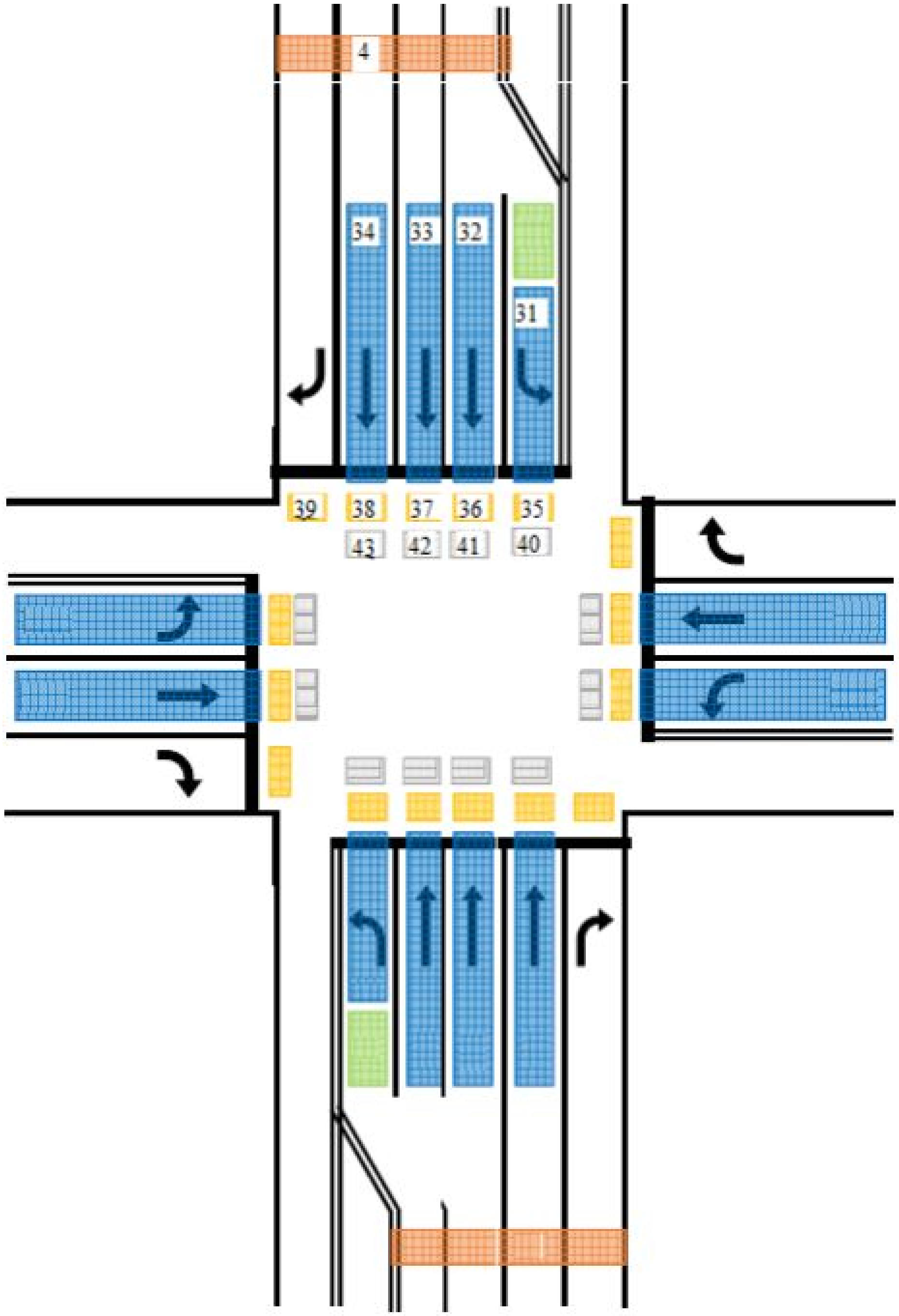


Figure 13: Detection setup for signal ID 7181

ANALYSIS AND RESULTS

This section provides the analysis and results pertaining to all of the four methods for estimating the delay on a cycle-by-cycle, 5-minutes and, 15-minutes aggregated basis for November 6, 2018. Figure 14 shows the results of intersection average delay per vehicle by all four methods and is aggregated at a cycle-by-cycle level. A two hour period is highlighted in Figure 15 to allow for direct comparison during the peak period. Comparison of results show that the delay estimated by the Method 1 is always greater than that estimated by ATSPM. This is expected because Method 1, in addition to incorporating stop delay, includes deceleration delay and a portion of the full acceleration delay profile of vehicles. Method 2 shows high variability with higher maximum cycle average delays due to the method including different green and red arrival rates. Method 3 and the Method 4 using both raw or adjusted arrivials show similar trends for each cycle. This is due to the assumptions being very similar in the two methods. Aggregation to five minutes (Figure 16) or 15 minutes (Figure 17) show that these trends also occur in aggregate with two unique patterns emerging. First, Method 1 has the highest maximum delay values which are exaggerated in very low flow conditions. This is most likely due to long cycles where "rebalanced" arrivals create very long travel times before the observed departure happens. Secondly, Method 3 seems to be the only method which shows a delay trend that tracks with the overall approach volume. This southbound approach has a higher PM peak than AM peak volume with every peak hour cycle showing split failure for the Southbound Phase 6 however the other methods show fairly flat delay trends over time. This delay pattern is promising as one major limitation to the current Method 4 ATSPM approach delay tends to not track the overall congestion time of day trend in many other locations the authors have studied.

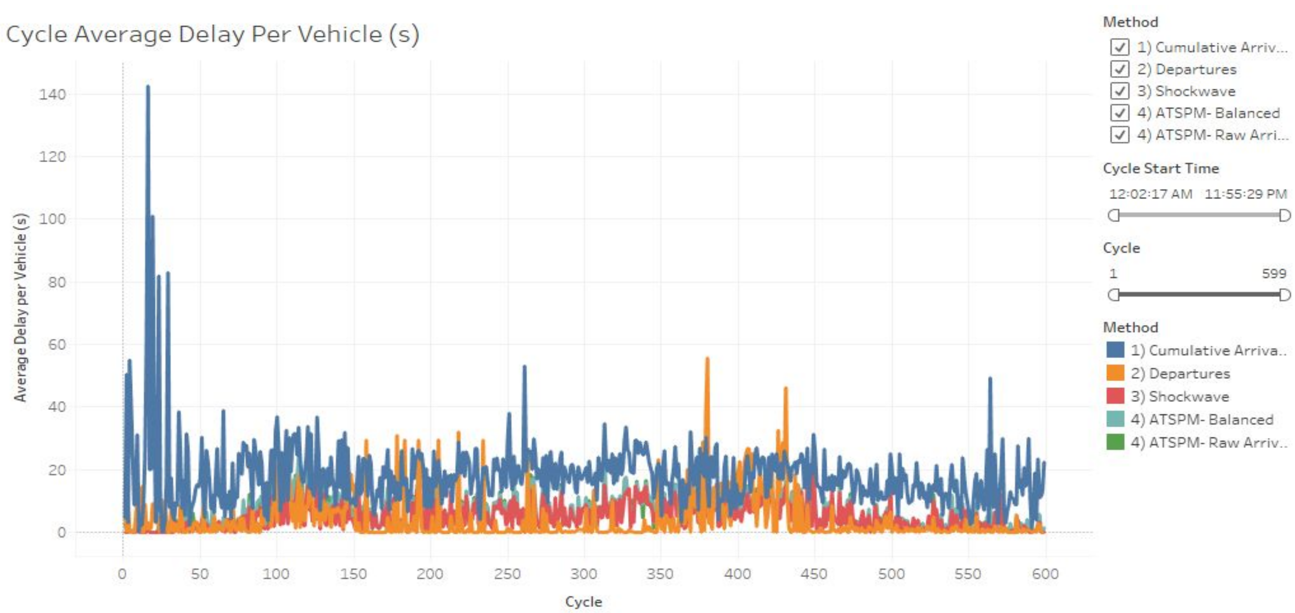


Figure 14: Cycle Average Delay per Vehicle

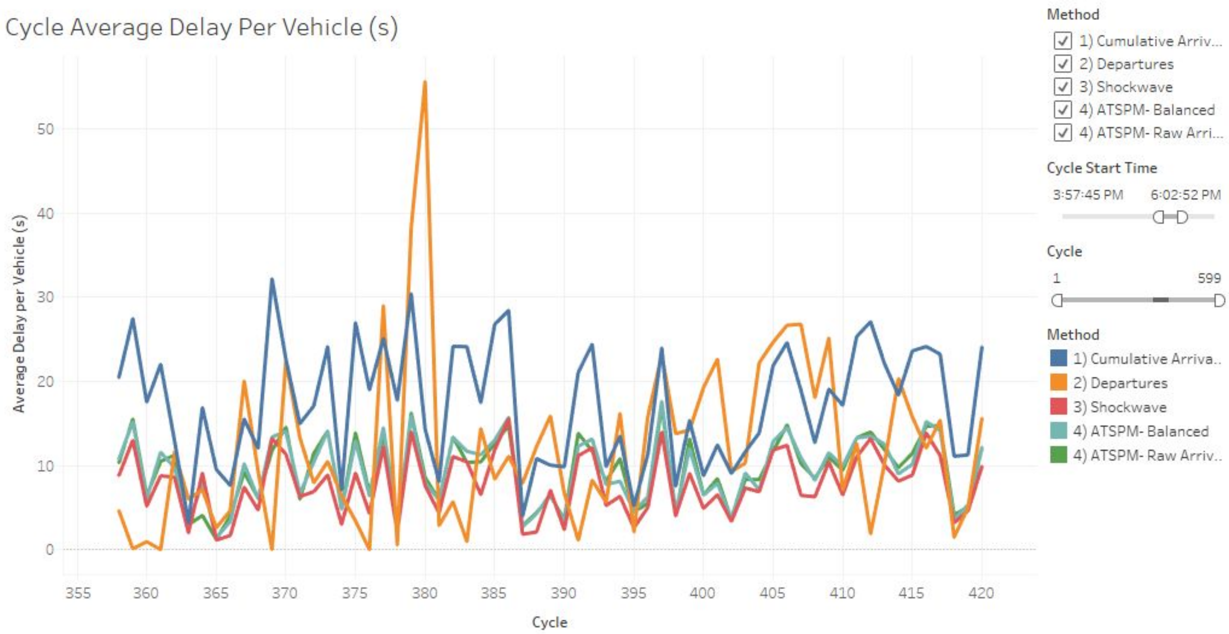


Figure 15: Cycle Average Delay per Vehicle - 4PM to 6PM

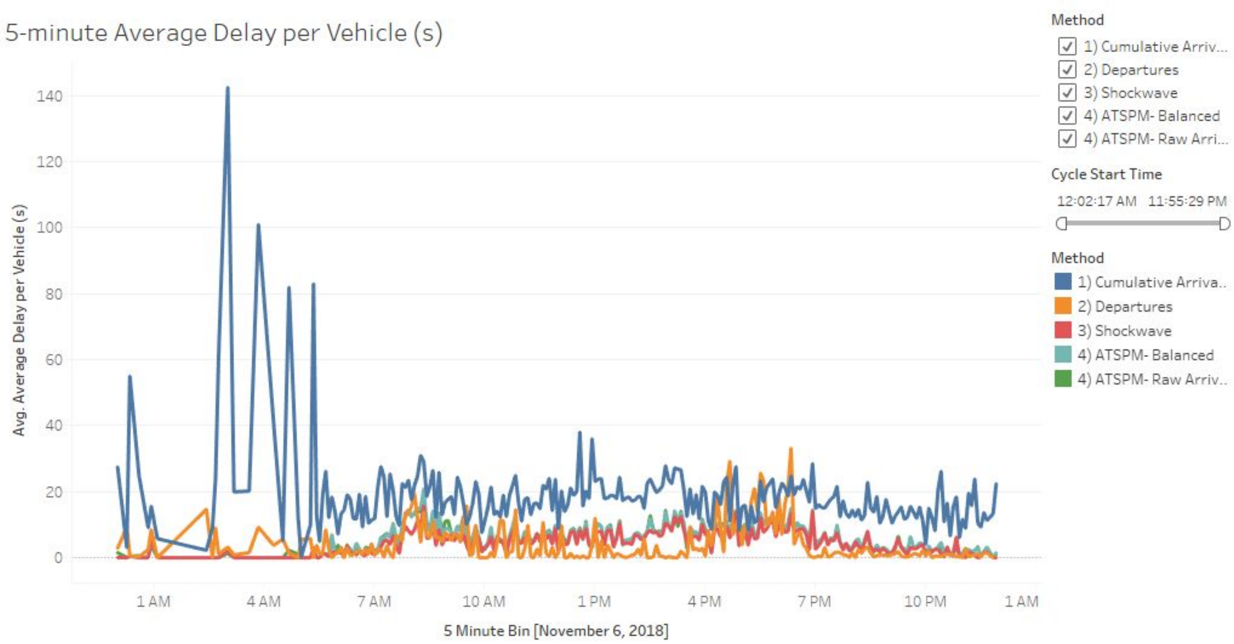


Figure 16: 5-minute Average Delay per Vehicle

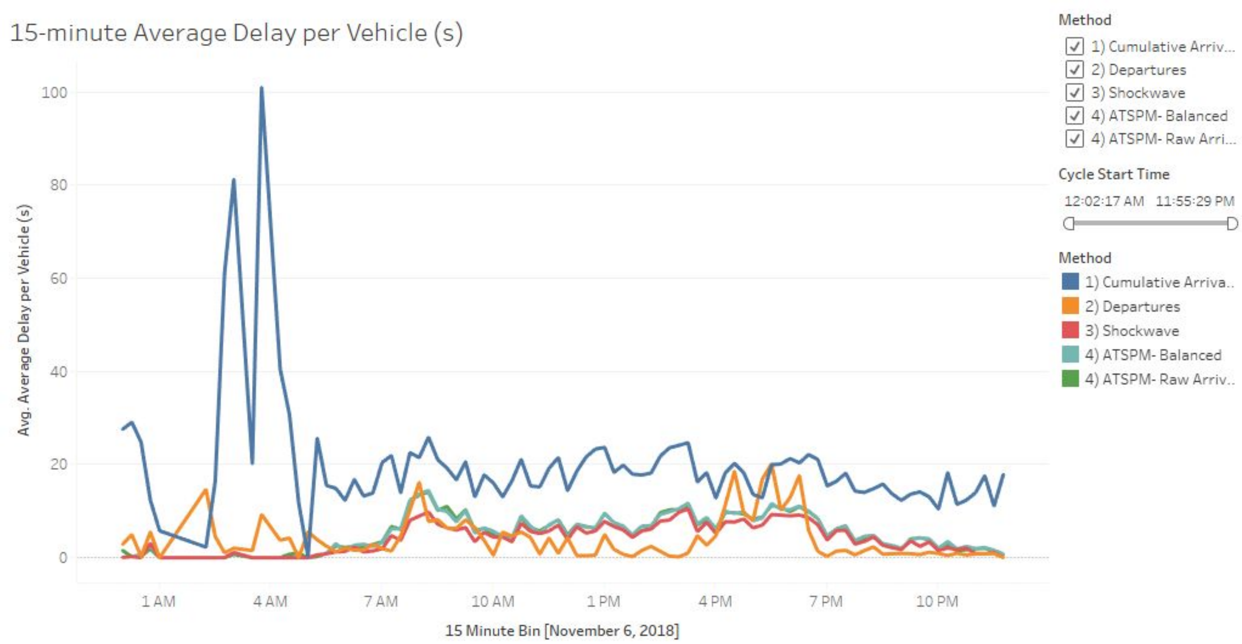


Figure 17: 15-minute Average Delay per Vehicle

CONCLUSIONS AND RECOMMENDATIONS

More than 330,000 traffic signals are being used to control traffic in the United States and more than ¾ of these could be significantly improved by updating their equipment or timing plans (FHWA-HRT-05-002). Unnecessary delay to motorists and pedestrians is one of the significant side effects of these control devices. A major reason for this unnecessary delay is poor traffic signal timings that account for nearly 300 million vehicle-hours on major roadways alone (TTI Urban Mobility Report). ATSPM is one of the recent developments that helps in better management of traffic signals by providing performance metrics based on high resolution datasets. These performance metrics help in better decision making and selection of more effective operational strategies to reduce delay and cost.

Although ATSPM provides a measure for assessing the delay experienced at an approach to an intersection, it is a simplified outlook and ignores some of the fundamental components of delay. This report proposes three alternative methodologies for estimating the approach delay at an intersection, each of which addresses one or more of the drawbacks currently present in the ATSPM framework.

The first method named the "cumulative arrival/departure method" uses arrival, departure, and traffic signal timing data to estimate the approach delay. Out of the four components of delay, this method fully incorporates the stop and deceleration delays, but includes the acceleration delay partially (only includes acceleration delay incurred prior to the downstream detector). However, the delay estimated by this method does not include the initial queue delay.

The second method termed the "departure-only method" uses the departure actuations and the traffic signal timing data to estimate the approach delay. This method fully incorporates the stop component of the delay. Furthermore, it includes the initial queue delay – estimated with the assumption of uniform arrival rate that spans through all consecutive cycles with split failure. Acceleration and deceleration components of the approach delay are not considered in this method, however.

The third proposed method, shockwave, uses arrival, departure, and traffic signal timing data to estimate the approach delay. Stop component of the approach delay is fully incorporated in the estimates by this method. This method, however, does not include the initial queue, acceleration and deceleration components of the approach delay.

Table 2 provides a list of assumptions and/or limitations for each methodology. Method 1 assumes, in addition to the assumptions listed under Table 2, a first-in-first-out (FIFO) principle for vehicles that arrive at the upstream detector and depart from the downstream detector. Table 3 provides a graphical depiction of delay components covered under the estimation of each methodology.

Table 2: Model Limitations or Assumptions

Limitation or Assumption	**Method 1**	**Method 2**	**Method 3**	**Method 4**
Needs Arrivals	Yes	No	Yes	Yes
Needs Departures	Yes	Yes	Yes	No
Adjust Arrivals	Yes	No	Yes	No
Constant Speed	Yes	Yes	Yes	Yes
Assumes Stable Operation	Yes	No	Yes	Yes
Assumes Uniform Arrival Rate	No	Yes	No	No
Processing time (sec)	14.5	20	15	-

*Processing time for data preparation and cycle division: 225 seconds.

Table 3: Aspects of Control Delay Included in Estimate

Method	Stop	Deceleration	Acceleration	Initial
1: Cumulative Arrival/Departure			i	
2: Departure-Only				ii
3: Shockwave				
4: Current ATSPM	iii			

i) Acceleration delays incurred prior to the downstream detector are included
ii) Initial queues are estimated using a uniform arrival rate which spans all consecutive cycles with split failure
iii) Stop delay is minimally estimated with a "vertical queue"

Overall, all four methods showed unique trends for certain time of day traffic conditions. Table 5 shows the distribution of cycle average delay per vehicle seen across the study day. Methods 3 and 4 followed very similar trends, however the unique time of day pattern seen in Method 2 is especially promising for future study.

Table 4: Cycle Average Delay per Vehicle Descriptive Statistics

Method	Minimum	Average	Maximum	Standard Deviation
Cumulative Arrival/Departure	0	18.06	142.55	10.81
Departures	0	4.08	55.66	7.14
Shockwave	0	5.02	19.20	4.26
ATSPM- Balanced	0	6.25	24.70	5.05
ATSPM- Raw Arrivals	0	6.19	26.04	5.02

Each method comes with critical assumptions or limitations, many of which may be addressed through future research. The authors note that Method 1 should always provide higher delays than the base ATSPM Method 4 due to the inclusion of all deceleration and some acceleration delay. However this method relies heavily on consistent actuations upstream and downstream which cannot be achieved when the upstream detector includes additional turning movements. Thus, future work on Method 1 should include more defensible and realistic addition or subtraction of upstream actuations as well as consider split failure conditions where departures are lower than arrivals for one or more cycles.

Method 2 is the only method which includes initial queue delay, though the current method assumes a constant arrival rate for consecutive cycles with split failure. This provides a minimal estimate of initial queue delay that may be better calibrated using upstream arrival distributions. This is also the only method which requires solely downstream detection. Other candidate improvements identified include detection of plattoned vs discharging flows, handling downstream spillback, and initial headway thresholds during low flow conditions.

Finally, Method 3 has the largest combination of data needs and assumptions resulting in many limitations to the methodology. Full additions of upstream arrival rates and more realistic discharge rates will improve the delay estimate, however this may lead to the method becoming a generalized case of Method 2. Due to the ease of estimation, this method may be best left as a comparison method for future work on one of the other two proposed methods.

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