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Anuj Sharma
University of Nebraska - Lincoln, anujs@iastate.edu

Darcy M. Bullock
Purdue University, darcy@purdue.edu

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FIELD EVALUATION OF ALTERNATIVE REAL-TIME METHODS FOR ESTIMATING APPROACH DELAY AT SIGNALIZED INTERSECTIONS

Anuj Sharma[1], Darcy M. Bullock[2]

ABSTRACT. Vehicle delay at a signalized intersection is among the widely used performance measures of efficiency at a signalized intersection. The Highway Capacity Manual (HCM) uses this performance measure to report the level of service at a signalized intersection. This performance measure is also used to estimate travel time along the arterials. With the advent of technological advances in the field of vehicle detection, real-time measurement of delay at a signalized intersection has become economically and computationally feasible. This paper compares three emerging techniques for estimating approach delay: an Input Output technique (IO), a Hybrid technique, and the HCM delay equation. The techniques were tested under varying traffic conditions at the instrumented intersection in Noblesville, IN.

INTRODUCTION

Vehicular delay is a quantitative measure for evaluating performance of a signalized intersection. This information is important for both the users of the intersection as well as a traffic engineer. The traffic engineer can use the information as a measure of effectiveness for the operation of intersection and signal retiming. The real-time delay information can be used by the commuters to estimate their travel time and choosing a travel route. The performance measure can also be used for a range of real-time applications, such as: real-time signal control, incident management, traveller information, and congestion pricing.

Numerous methods have been proposed in past literature (Sokofidis et al., 1973; Robertson et al., 1976; Bonneson, 1992; Powell, 1998; Son, 1999; Dion et al., 2004) for measuring intersection delay. There exists a trade-off between accuracy and cost in using these measures. IO technique and Hybrid technique were developed by Sharma et al. (2007). These techniques are highly accurate and estimate delay at a microscopic level. Because delay of each

[1] PhD Candidate, School of Civil Engineering, Purdue University, West-Lafayette, Indiana, USA, e-mail: sharma23@purdue.edu
[2] Professor, School of Civil Engineering, Purdue University, West-Lafayette, Indiana, USA, e-mail: darcy@purdue.edu

Sharma, 2009- , University of Nebraska-Lincoln, asharma3@unl.edu

individual vehicle is estimated the techniques become computationally intensive requiring higher processing speed and memory space. These techniques are beneficial for urban and sub-urban intersections that require highly accurate and discrete data and also have the resources to collect such data. Rural intersection typically lack resources for such accurate data collection. Typically in such areas a trade-off can be made between accuracy and feasibility.

In this paper the author uses HCM equation estimating average delay at a macroscopic level. This approach estimates the delay for every 15 minute interval. The delay computed by HCM equation is then compared against the delay estimated by IO technique, Hybrid technique and ground truth delay.

OVERVIEW OF IO AND HYBRID TECHNIQUES

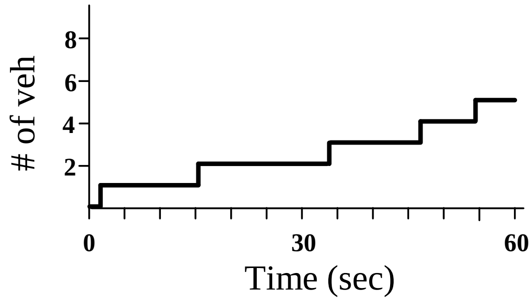
The IO technique uses advance detector actuations, phase change data, and parametric data (e.g., saturation headway, storage capacity, etc.) as model inputs. The advance detector actuations are used to track arrivals at the intersection approach over time. The phase change and saturation headway data are used to estimate the number of departures from the stop line over time. These two flow profiles are combined to estimate the queue accumulation on the intersection approach. The time in queue is used to estimate the delay.

The Hybrid technique uses advance detector actuations, stop bar detector actuations, phase change data, and parametric data (e.g., storage capacity) as model inputs. The advance detector actuations are used in a manner similar to the IO technique. The stop bar detector actuations are used with the phase change data to measure the number of departures from the stop line over time. As with the IO technique, these two flow profiles are combined to determine if there is a queue accumulation on the intersection approach and to estimate queue length and delay.

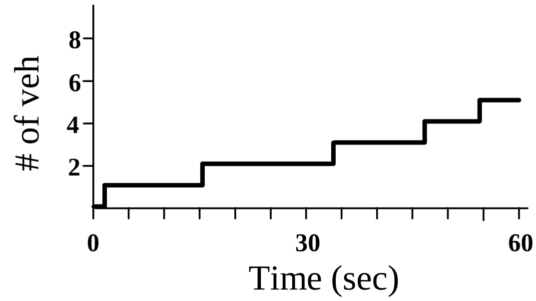
In contrast to the IO technique, the Hybrid technique requires additional detection at the stop bar. A vehicle signature identification technique available from inductive loop detectors (ILD) is used to count the number of departures with the stop bar detectors. ILD vehicle signature identification techniques have been used (Grenard et al, 2001; Smaglik, 2005) to count vehicles crossing the stop line. The stop bar count detection provides real-time information about the departure rate. In contrast, this rate is a simple parametric input in the IO technique. The real-time information about the departure rate is intended to make the Hybrid technique more accurate than the IO technique particularly during inclement weather when the saturation flow rate decreases. For both techniques, delay and maximum queue length are estimated once for each signal cycle. The techniques rely on the assumption that vehicles do not change lanes after they cross the advance detectors. The first in/first out (FIFO) principle (i.e., the first vehicle to enter the queue departs first) is also assumed to hold for vehicles in queue on the intersection approach.

Estimation of Arrival Profile

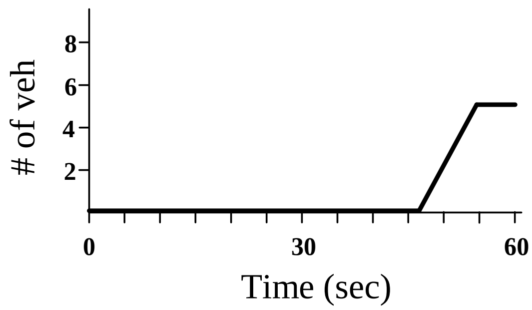
Figure 1a and Figure 1b show example arrival flow profiles for the IO and Hybrid techniques, respectively. This profile represents the count of vehicles measured at the advance detector. The stair-stepped nature of the profile reflects the arrival of individual vehicles to the detector at the corresponding time. For example, in Figure 1a, the first arrival occurs at time t =2.0 s;



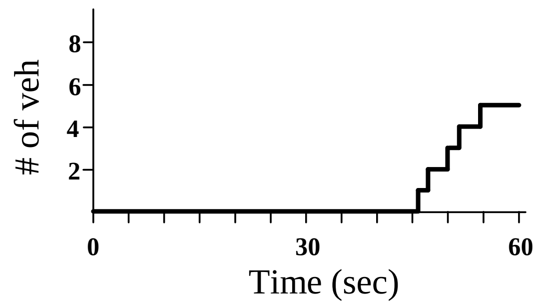
a) IO arrival profile



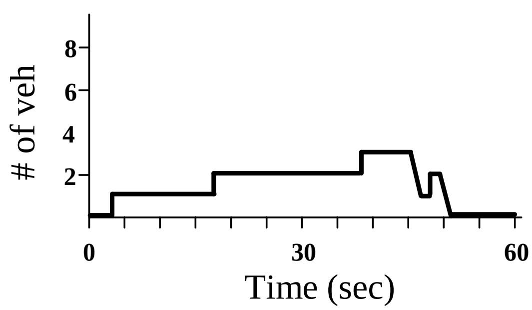
b) Hybrid arrival profile



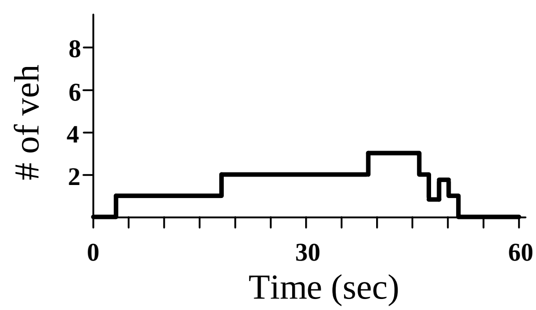
c) IO departure profile



d) Hybrid departure profile



e) IO queue profile for computing delay



f) Hybrid queue profile for computing delay

Figure 1 Comparison of delay measurement techniques.

the second arrival occurs at time t = 16 s; and so on, until a sixth vehicle arrives at time t =55 s.

Estimation of Departure Profile

The IO technique uses the start-up lost time, saturation headway, and phase change data to estimate the departure profile. Figure 1c shows the departure profile estimate for this technique. The trend line shown indicates that the signal indication is red until time t = 45 s.

At this time, the signal indication changes to green; however, departures do not occur until time t = 47 s due to a 2.0 s start-up lost time. The departure profile is estimated only until the queue is discharged. The smooth line in Figure 1c represents the fact that departure profile is a calculated projection, not a real-time estimate. The slope of the departure profile from time t = 47 s to t = 55 s equals the input saturation headway.

Figure 1d shows the departure profile for the Hybrid technique. This departure profile is measured in real-time using the count detector at stop bar and represents a more accurate representation of the departure profile for the current signal cycle. This additional measurement is the fundamental difference between the two techniques.

Delay and Queue Estimation Using Queue Polygon

A queue polygon is obtained by superposing the departure and arrival profiles. The area within the polygon is the total delay incurred by vehicles for that cycle. The curve that defines the polygon indicates the number of vehicles in queue at any time in the cycle. Thus, maximum queue length can be obtained from the queue polygon by finding the ordinate at start of green plus start up lost time. Figure 1e and Figure 1f illustrate the queue polygons obtained using the IO and Hybrid technique, respectively.

Figure 1e indicates the queue length is one vehicle from time t = 3 to t = 18 s; it increases to two vehicles at that time and remains at two vehicles until time t = 39 s. The maximum queue of three vehicles occurs from t = 39 to t = 47 s. The area under the polygon can be computed as 89 veh-s total delay. When divided by the six vehicle arrivals during the cycle, the average delay is computed as 14. 8 s (=89/6). The first vehicle to arrive at t = 3 s did not depart until t = 48 s, hence, it incurred the maximum delay of 45 s.

Detailed algorithms for implementing IO techniques and Hybrid technique can be found in paper by Sharma et al. (2007)

OVERVIEW OF HCM TECHNIQUE

The HCM (1997) procedure offers the following equation for estimating the delay at through movement as the result of the signal (i.e., through delay)

$$d = d_1(PF) + d_2 + d_3 \tag{1}$$

$$d_1 = \frac{0.5C\left(1 - g/C\right)^2}{1 - \min(1, X)\, g/C} \tag{2}$$

$$d_2 = 900T\left(\left(X - 1\right) + \sqrt{\left(X - 1\right)^2 + \frac{8kIX}{cT}}\right) \tag{3}$$

where:

d: control delay to the through movement, s/veh;

d_1: uniform delay, s/veh;

d_2: incremental delay, s/veh;

d_3: initial queue delay, s/veh;

PF: progression adjustment factor;

X: volume to capacity ratio for the through lane group;
C: cycle length, s;
c: capacity of the lane group, veh/h;
g: effective green time for the through lane group, s;
T: duration of analysis period, h;
k: incremental delay adjustment for actuated control; and
I: incremental delay adjustment for filtering by upstream signal.

The HCM methodology for estimating delay is useful in calculating the aggregate delay over a time period like 15 minutes. This methodology assumes a uniform flow over this time period and calculates the term d_1. The effect of variation between arrivals on green and arrivals on red is captured by the term progression factor PF. The second term d_2 gives incremental delay which might occur due to flow exceeding capacity either due to randomness or due to over saturation. Third term in the delay equation d_3 represents the initial queue delay. The HCM method is an aggregate method of estimating the delay in absence of actual arrival profile and departure profile.

The value of PF was determined using the following equation as given in chapter 16 of HCM:

$$PF = \frac{(1-P)f_{PA}}{1-\left(\frac{g}{C}\right)} \tag{4}$$

where:
PF: progression adjustment factor
P: proportion of vehicles arriving on green
g/C: proportion of green time available
f_{PA}: supplemental adjustment factor for platoon arriving during green

HCM Exhibits 16-11 and 16-12 are used to determine the arrival type and f_{PA} for given volume condition and vehicle distribution over green time.

For this technique, the initial queue was assumed to be zero at the start of each 15 minute period.

TECHNOLOGY REQUIREMENTS

This section describes the hardware and software requirements for the IO, Hybrid and HCM techniques.

Sensor Requirements

All the three techniques require a set of advance detectors. IO and Hybrid techniques use the advance detectors to construct of arrival profiles whereas HCM use this to estimate average flow rates and arrival types.

The inductive loop detector is the most likely sensor to be used to implement these technologies, given its relatively low installation cost and proven reliability. However, any sensor that can count individual vehicles by lane with reasonable accuracy can be used. A recent review of sensor performance by Martin et al. (2003) indicates that magnetic, true-presence microwave, Doppler microwave, and video image vehicle detection system

(VIVDS) detectors are also suitable for all-weather applications on urban street segments. However, research by Rhodes et al. (2005) questions the use of VIVDS.

Processing Platform

The IO and Hybrid techniques process data and calculate delay for individual vehicles, whereas the HCM technique aggregates volume and arrival type for a 15 minute period and uses the HCM delay equation to calculate delay. The processor and memory requirements for the HCM technique are significantly lower than the other two techniques.

Technology Limitations

All three techniques require a set of advance detectors for measuring the arrival profile. The detectors should be located sufficiently far back from the intersection to avoid frequent spillback of queues behind them. The detectors will not be able to accurately count vehicle arrivals if the queue backs over the advance detectors. Based on typical cycle durations and peak hour flow rates, the location of this sensor would likely be 400 ft or more in advance of the intersection. However, the detector should not be located so distant from the intersection that driveway activity between the sensor and the stop line degrades the accuracy of the predicted arrival flow profile. This objective is often in conflict with the desire to locate the sensor back far enough to avoid queue spillback. In general, the further the detectors are set from the intersection, the more likely there will be mid-block traffic activity between the advance detectors and the intersection. The optimal sensor location will vary from site to site depending on the number of access points and their traffic volumes.

The Hybrid technique also needs a set of count detectors at the stop bar for real-time estimation of discharge profiles. If the stops bar count detectors provide inaccurate counts, the Hybrid technique might not perform as well as the IO and HCM techniques.

DATA COLLECTION PROCEDURE

Figure 2 shows the data collection site located at the signalized intersection of SR 37 and SR 38 in Noblesville, Indiana. This is an extensively instrumented intersection with capability of collecting detector actuations, signal states, and simultaneous video recording of the existing traffic condition.

The detectors that were used for data collection for low volume conditions include:

- NA8, NB8: Advanced detectors located 405 ft away from the stop bar. These detectors were used for estimating arrival flow profiles for both techniques.
- NA1, NA2, NA3, NA4, NB1, NB2, NB3, NB4: Stop bar detectors are used in combination with vehicle recognition logic to provide vehicle counts. These detectors were used in the Hybrid technique for real-time estimation of lane discharge.
- C2N: This is the camera used for recording the real-time video for ground truthing the delays and queue lengths estimated by the two techniques.

The detectors that were used for data collection for heavy volume conditions include:

- SA5, SB5: Advanced detectors located 405 ft away from the stop bar. These detectors were used for estimating arrival flow profiles for both techniques.

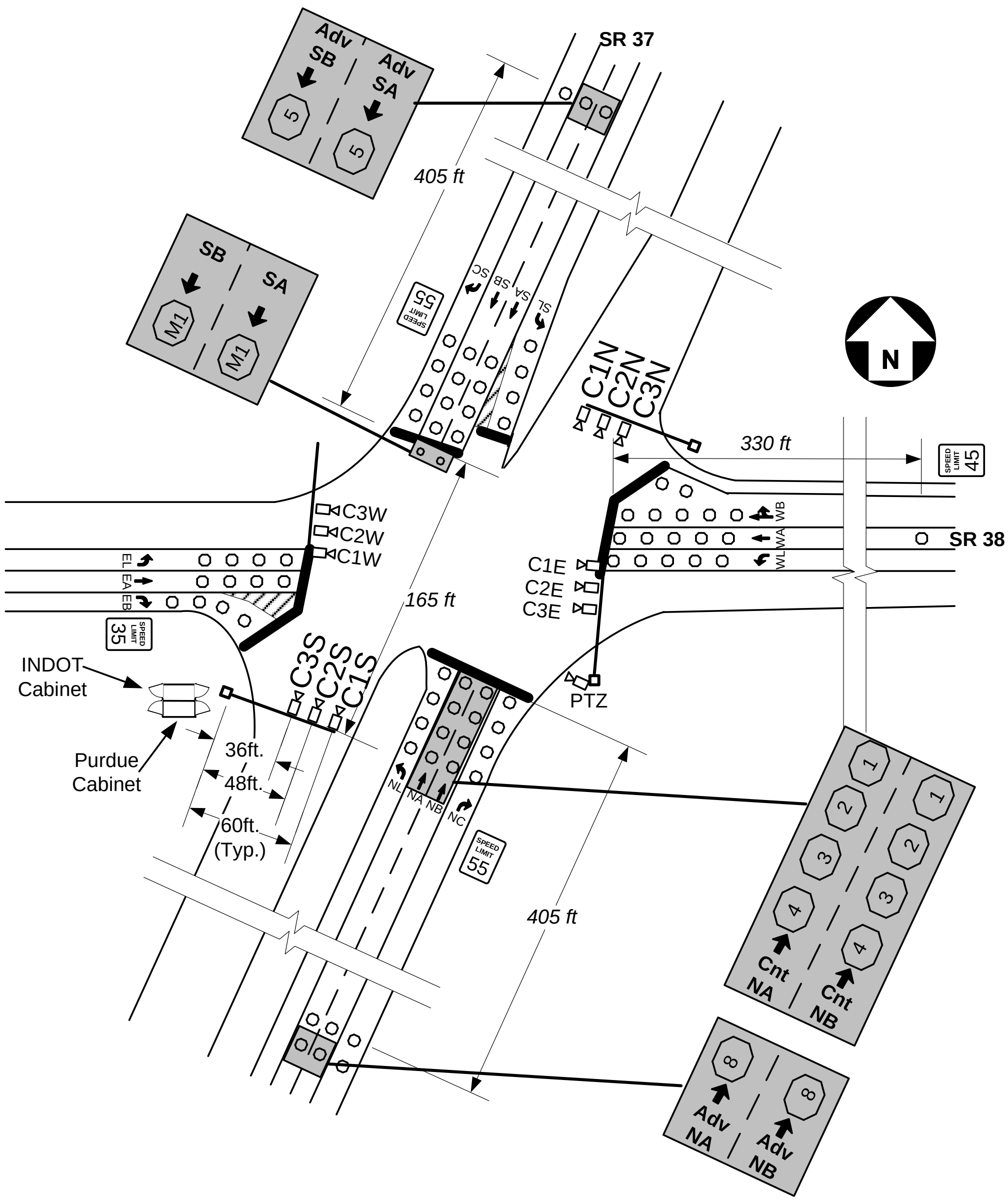


Figure 2 Data collection site at Noblesville,IN.

- SA-M1, SA-M2: Stop bar micro loop detectors were used in the Hybrid technique for real-time estimation of lane discharge.
- C2S: This is the camera used for recording the real-time video for ground truthing the delays and queue lengths estimated by the two techniques.

Stop bar detectors NA1 through NA4 are wired in series to function as one long detection zone in the inside through lane, just in advance of the stop line. This detection zone is referred to hereafter as “CntNA.” Similarly, stop bar detectors NB1 through NB4 are wired together to monitor the outside through lane and are referred to hereafter as “CntNB.”

The detector actuations and phase change data were recorded in a data file. These data have a resolution of 1/1000 of a second and are accurate to within approximately 1/100 of a second.

These data were used to estimate the arrival and discharge profile as described in previous sections.

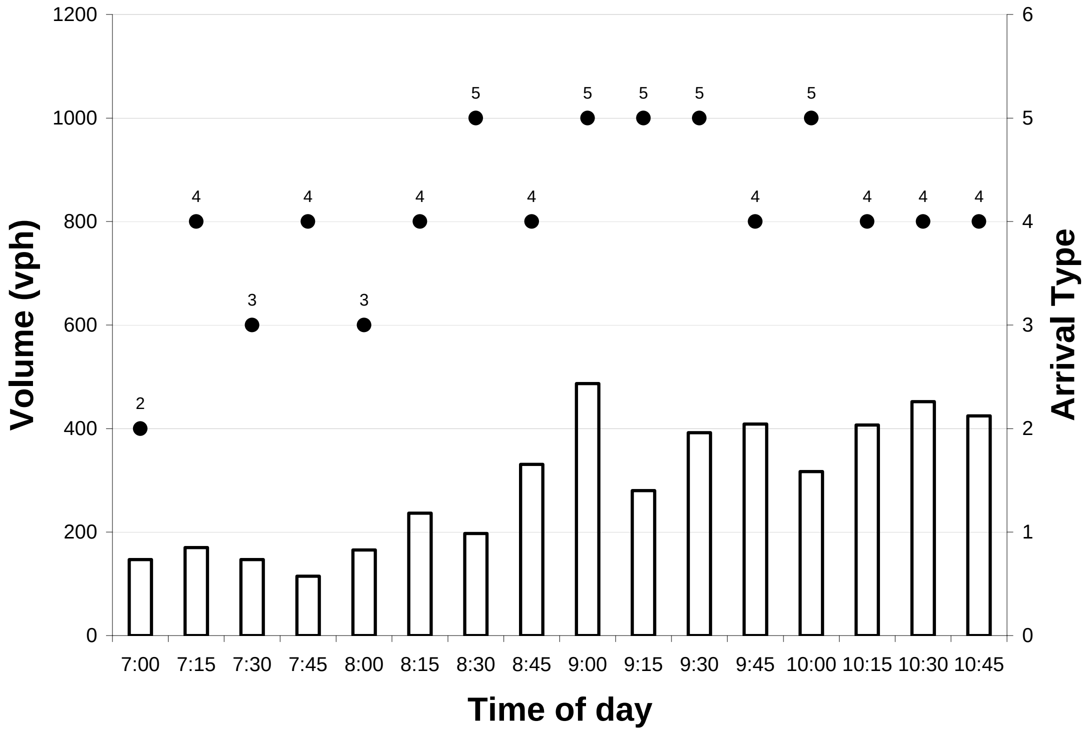
Four hours of data were collected on Sunday, October 30, 2005, from 7:00 A.M. to 11:00 A.M for the first phase of performance testing of the techniques under low volume conditions. Another four hours of data were collected Wednesday, June 21, 2006, from 2:00 P.M. to 6:00 P.M. Traffic events on the intersection approach were recorded during the study period using Camera C2N (Figure 7) and Camera C2S. The video recording was used to quantify ground truth vehicle arrival times and departure times, as well as the delay and maximum queue length for each cycle. These data were then used to evaluate the accuracy of both techniques.

RESULTS

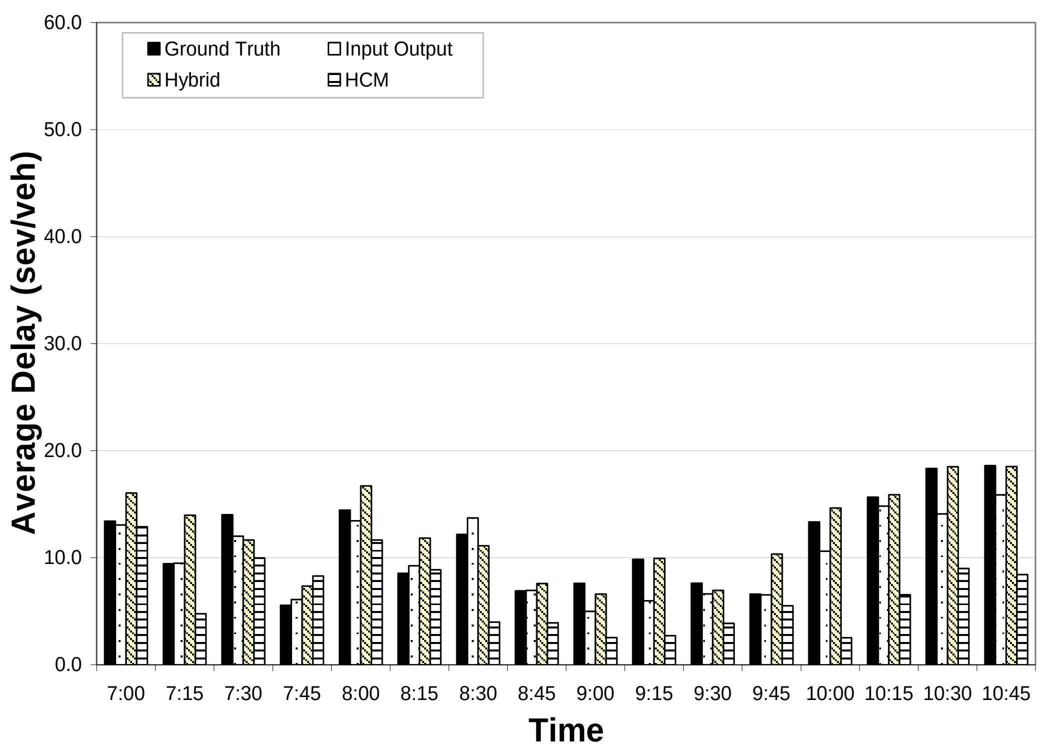
The Performance of the IO, Hybrid and HCM techniques was evaluated over fifteen minute periods. The total through volume varied from 115 vph to 490 vph during the first phase of the study whereas the total through volume ranged from 435 vph to 820 vph during the second phase of the study. Figure 3a shows the variation of volume and arrival type during the first phase of the study. Figure 3b compares the estimated and true value of average delay during this phase. The average delay for higher arrival type for same volume is lower. For example, the duration of 9:00 – 9:15 AM had an arrival type of 5 and average volume of approximately 500 vph. The average delay during this duration was 8 sec/veh. The duration of 7:00 – 7:15 AM had an arrival type of 2 and an average volume of approximately 150 vph. An average delay of 13 sec/veh was observed during this duration. This phenomenon is in accordance to our expectation. Higher arrival types correspond to better progression and thus reduced delay. The importance of arrival type as a performance measure at an intersection can be seen through this example.

Figure 4a shows the variation of volume and arrival type during the second phase of the study. Figure 4b compares the estimated and true values of average delay during this phase.

Table 1 and Table 2 lists the average delay and Table 3 and Table 4 lists error in estimation as given by the IO, Hybrid and HCM technique, averaged over a 15-minute period for low volume and high volume conditions respectively. The average root mean square error for IO technique was 2.01 seconds during low volumes and 3.88 seconds during heavy volumes condition. The average root mean square error for the Hybrid technique was 2.11 seconds for low volume conditions and 2.78 seconds for the second phase. The average root mean square error for HCM technique for was 4.46 seconds for low volume conditions and 4.13 seconds for the second phase. For heavy volumes, the Hybrid and the IO techniques have an increase in the root mean square errors. In contrast, the RMS for the HCM technique relatively remains constant. So, HCM technique can be used quite efficiently during medium to heavy conditions. For extremely low volume condition, accurate arrival type estimation is difficult and leads to higher estimation errors. The reported errors of all the three technique are small for both heavy and low volume conditions, and any of them could be implemented, based on the site feasibility.

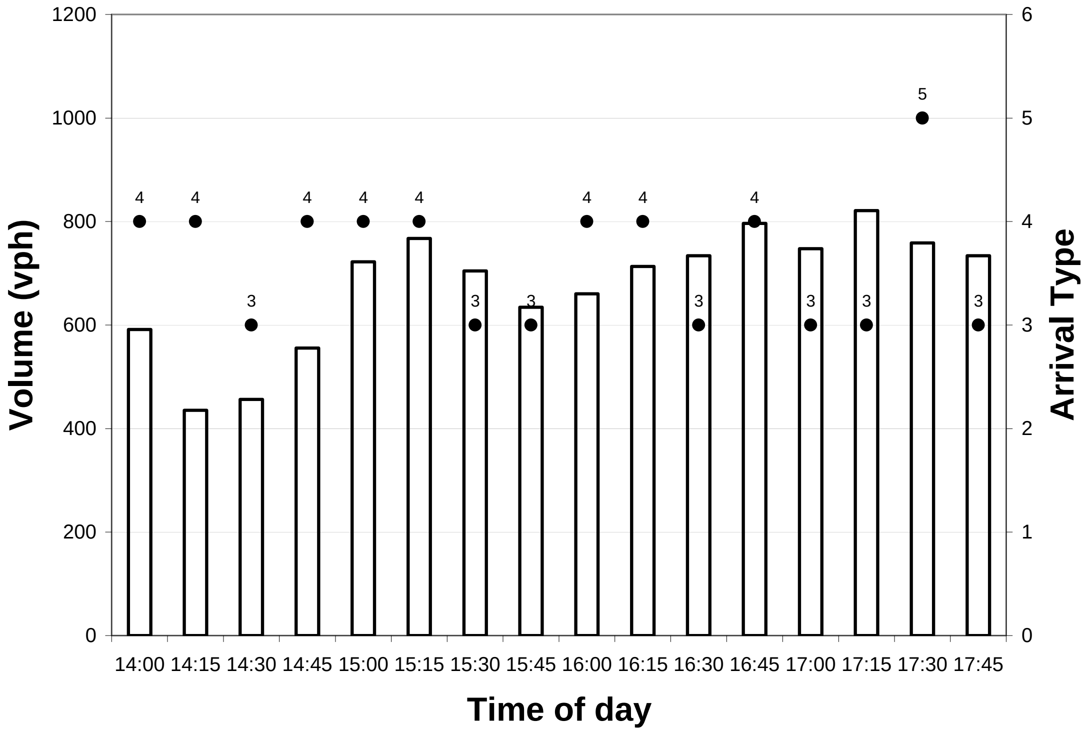


a) South Bound Approach, Volume (veh/hr) averaged over 15 min, 10/30/2005

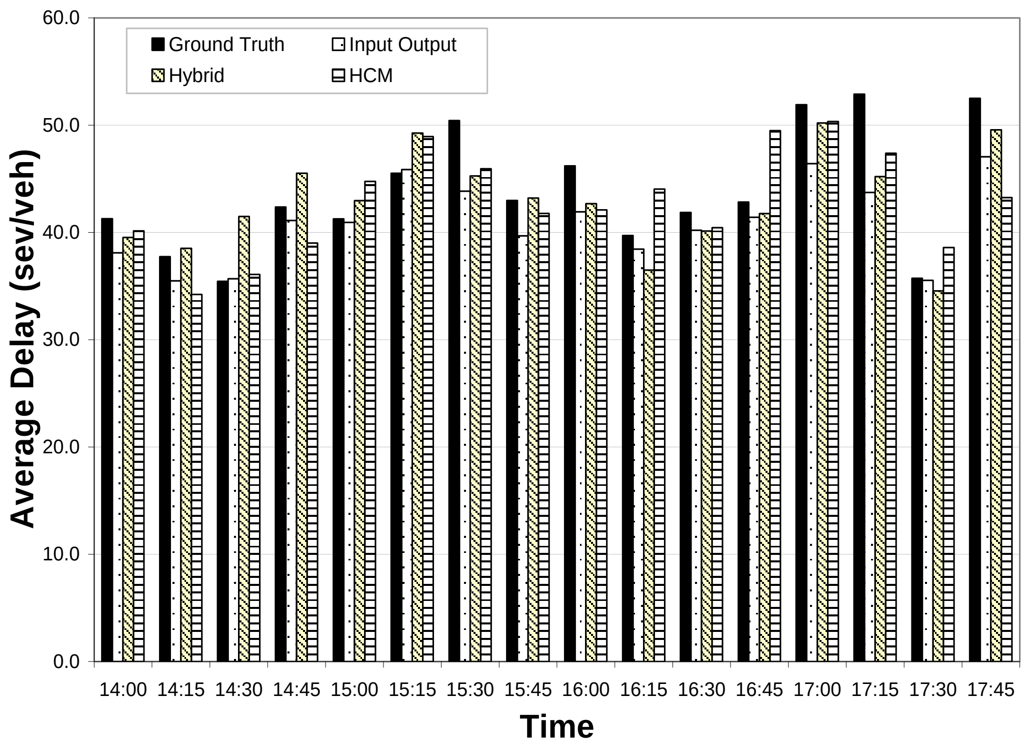


b) Southbound Approach, Delay(sec/veh) averaged over 15 min, 10/30/2005

Figure 3. Comparison of techniques for real-time estimation of delay low volume



a) South Bound Approach, Volume (veh/hr) averaged over 15 min, 06/21/2006



b) Southbound Approach, Delay(sec/veh) averaged over 15 min, 06/21/2006

Figure 4: Comparison of techniques for real-time estimation of delay high volume

Table 1. Comparison of techniques for real-time estimation of delay (low volume)

		Average Delay			
Start Time	End Time	True	IO	Hybrid	HCM
7:00:00	7:14:59	13.42	13.07	16.06	12.90
7:15:00	7:29:59	9.43	9.49	13.98	6.98
7:30:00	7:44:59	14.01	12.02	11.66	10.30
7:45:00	7:59:59	5.54	6.09	7.34	10.66
8:00:00	8:14:59	14.44	13.46	16.71	12.06
8:15:00	8:29:59	8.54	9.24	11.82	11.48
8:30:00	8:44:59	12.18	13.72	11.12	6.16
8:45:00	8:59:59	6.89	6.95	7.58	7.73
9:00:00	9:14:59	7.61	5.00	6.60	4.87
9:15:00	9:29:59	9.84	5.97	9.94	4.88
9:30:00	9:44:59	7.63	6.62	6.96	6.88
9:45:00	9:59:59	6.59	6.52	10.34	8.38
10:00:00	10:14:59	13.35	10.61	14.65	5.79
10:15:00	10:29:59	15.66	14.82	15.88	9.52
10:30:00	10:44:59	18.34	14.08	18.50	12.70
10:45:00	10:59:59	18.62	15.86	18.51	10.95

Table 2. Comparison of techniques for real-time estimation of delay (high volume)

		Average Delay			
Start Time	End Time	True	IO	Hybrid	HCM
14:00:00	14:14:59	41.3	38.1	39.5	40.2
14:15:00	14:29:59	37.7	35.5	38.5	34.2
14:30:00	14:44:59	35.5	35.7	41.5	36.1
14:45:00	14:59:59	42.4	41.1	45.5	39
15:00:00	15:14:59	41.3	40.9	43	44.8
15:15:00	15:29:59	45.5	45.8	49.3	48.9
15:30:00	15:44:59	50.4	43.8	45.3	45.9
15:45:00	15:59:59	43	39.7	43.2	41.8
16:00:00	16:14:59	46.2	41.9	42.7	42.1
16:15:00	16:29:59	39.7	38.4	36.5	44
16:30:00	16:44:59	41.9	40.2	40.1	40.4
16:45:00	16:59:59	42.8	41.4	41.8	49.5
17:00:00	17:14:59	51.9	46.4	50.2	50.3
17:15:00	17:29:59	52.9	43.7	45.2	47.4
17:30:00	17:44:59	35.7	35.5	34.6	38.6
17:45:00	17:59:59	52.5	47.1	49.6	43.3

Table 3. Error matrix of techniques for real-time estimation of delay (low volume)

Start Time	End Time	IO	Hybrid	HCM
7:00:00	7:14:59	-0.35	2.64	-0.52
7:15:00	7:29:59	0.06	4.55	-2.45
7:30:00	7:44:59	-1.99	-2.35	-3.71
7:45:00	7:59:59	0.55	1.80	5.12
8:00:00	8:14:59	-0.98	2.26	-2.38
8:15:00	8:29:59	0.70	3.28	2.94
8:30:00	8:44:59	1.53	-1.06	-6.02
8:45:00	8:59:59	0.07	0.69	0.84
9:00:00	9:14:59	-2.62	-1.01	-2.75
9:15:00	9:29:59	-3.87	0.10	-4.96
9:30:00	9:44:59	-1.01	-0.67	-0.74
9:45:00	9:59:59	-0.07	3.75	1.79
10:00:00	10:14:59	-2.74	1.30	-7.56
10:15:00	10:29:59	-0.84	0.22	-6.15
10:30:00	10:44:59	-4.25	0.16	-5.64
10:45:00	10:59:59	-2.76	-0.11	-7.67
Avg RMSE		2.01	2.11	4.46

Table 4. Error matrix of techniques for real-time estimation of delay (high volume)

Start Time	End Time	IO	Hybrid	HCM
14:00:00	14:14:59	-3.2	1.4	0.7
14:15:00	14:29:59	-2.2	3	-4.3
14:30:00	14:44:59	0.2	5.8	-5.4
14:45:00	14:59:59	-1.3	4.4	-6.5
15:00:00	15:14:59	-0.4	2.1	1.8
15:15:00	15:29:59	0.3	3.5	-0.4
15:30:00	15:44:59	-6.6	1.5	0.6
15:45:00	15:59:59	-3.3	3.5	-1.4
16:00:00	16:14:59	-4.3	0.8	-0.6
16:15:00	16:29:59	-1.3	-1.9	7.5
16:30:00	16:44:59	-1.7	-0.1	0.3
16:45:00	16:59:59	-1.4	0.4	7.7
17:00:00	17:14:59	-5.5	3.8	0.1
17:15:00	17:29:59	-9.2	1.5	2.2
17:30:00	17:44:59	-0.2	-0.9	4
17:45:00	17:59:59	-5.4	2.5	-6.3
Avg RMSE		3.88	2.78	4.13

CONCLUSIONS

The HCM technique performed satisfactorily in terms estimation accuracy when compared against the IO and the Hybrid techniques.

The HCM technique is computationally economical and should be the first choice for the traffic engineer unless some special conditions, as described below, exist to justify the higher accuracy. The trade-off between the microscopic delay and computational cost should be considered while trying to implement one of the three techniques. The IO technique should be the second choice as it is less costly than the Hybrid technique. The Hybrid technique might be beneficial for intersections having more inflow or outflow of traffic between the stop bar and the advance detector. The sites with huge variability in saturation flow rate (due to changing weather conditions) could gain substantially on the accuracy of the estimation by implementing Hybrid technique. The Hybrid technique should also be considered if there are frequent queue spillbacks over the advanced detector.

ACKNOWLEDGEMENTS

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