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Data Fusion Technique for Measuring Intersection Delay Using GPS-Enabled Probe Vehicles

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DATA FUSION TECHNIQUE FOR MEASURING INTERSECTION DELAY
USING GPS-ENABLED PROBE VEHICLES

by

Byung-Hee Han

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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Department of Civil and Construction Engineering

Western Michigan University
Kalamazoo, Michigan
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DATA FUSION TECHNIQUE FOR MEASURING INTERSECTION DELAY USING GPS-ENABLED PROBE VEHICLES

Byung-Hee Han, M.S. *

Western Michigan University, 2007

Intersection control delay is considered a primary measure for determining the level of service at signalized intersections. This thesis develops a technique estimating intersection delay using GPS data from GPS-enabled vehicles. First, this study analyzes existing methods that estimate control delays using GPS data and proposes an improved technique in response to the weakness of those methods. The proposed method estimates the control delay well with better accuracy covering the weaknesses. However, the control delay from the GPS data has a sample size problem for determining the level of service at signalized intersections. Therefore, this thesis proposes a data fusion technique using the data from both GPS devices and loop detectors in order to be able to estimate delays and the level of service at signalized intersections with the small number of GPS-enabled vehicles. The data fusion technique developed in this study improves the accuracy by 59.6% with one GPS-enabled vehicle.

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CHAPTER I

INTRODUCTION

Background

Delay reflects well drivers' inconvenience caused by traffic signals and can be also converted as a monetary value (Olzsewski 1993). More importantly, delay is a key factor in evaluating level of service at an intersection as adapted by Highway Capacity Manual (HCM).

There has been much effort to measure delay at a signalized intersection. A variety of devices and procedures including ground-based time-lapse photography (Buehler et al. 1976), aerial time-lapse photography (Benekohal 1991), and video (Benekohal et al. 1992) has been applied to measure intersection delay by tracing individual vehicle trajectories. Unfortunately, these techniques are either very expensive or labor intensive (Olszewski 1993). Olzewski (1993) and Mousa (2002) conducted delay studies by applying the screen lines on the roads based on field observation. The most common method in practice has been the vehicle-in-queue count technique (HCM2000) that measures the delay by a field observation. However, those techniques are still labor-intensive.

Recently, test car techniques using global positioning system (GPS) receivers were used by Quioroga and Bullock (1999) and Ko, Hunter, and Guensler

(2006). These techniques collecting traffic data using GPS have been proven very effective in respects of costs and labors. However, they only deal with the delay of individual vehicles and have some weaknesses in the procedures of generating delay from GPS data. This thesis focuses on techniques using GPS-enables probe vehicles..

In response to the weaknesses, the more effective and accurate method is needed in estimating delay from GPS data. Furthermore, such a GPS-based technique relies on the availability of GPS-enables vehicles. In order for the GPS-based technique to be usable as an alternative of vehicle-in-queue count technique, there should be enough vehicles equipped with GPS. As such, when using GPS-based technique, the sample size issue has to be addressed. This thesis suggests an effective and accurate method to measure the control delay using GPS data and addresses the sample size issue by employing data fusion technique.

Methodology

In this study, two different sets of data are used: one from micro simulation tool, and the other from actual field data. While the data from micro simulation tool, Paramics, are useful in comparing truthful delay at an intersection, the actual field data reflects reality of the real system. Using simulation data is unavoidable because it is not possible to equip all vehicles with GPS. For acquisition of actual GPS field data, several GPS-equipped vehicles are used along three intersections in the Oakland corridor in Kalamazoo, MI. or comparisons.

This thesis is divided into two parts. The first part is to develop a method estimating the control delay of individual vehicles using GPS data. After reviewing methods previously developed by Quiroga et al (1999) and Ko et al (2006), this study develops a new method. The performances are compared using the data from a 5 minute test run in Paramics and the actual field data from three intersections in the Oakland corridor. The second part is to develop a data fusion method that uses both GPS data and traffic sensor data. The data fusion method overcomes the inaccuracy problem under the small sample of GPS data.

CHAPTER II

LITERATURE REVIEW

Control Delay

Delay at a signalized intersection is defined and used in many different ways. Delays are often defined as stopped delay, approach delay, time-in-queue delay, travel time delay, and intersection control delay. Among those, the control delay is used when determining intersection level of service. The concept of control delay was developed in the 1994 Highway Capacity Manual (HCM 1994), and was included in the HCM 2000 (Roess et al. 2004). The criteria of level of service are shown in Table 1.

LOS	Control Delay per Vehicle (s/veh)
A	≤ 10
B	$> 10-20$
C	$> 20-35$
D	$> 35-55$
E	$> 55-80$
F	> 80

Table 1: Criteria of level of service

Control delay is defined as the delay caused by a control device, either a traffic signal or a STOP-sign. It is approximately equal to time-in-queue delay plus the acceleration-deceleration delay components (Roess et al. 2004). According to Quiroga and Bullock (1999), control delay includes deceleration-acceleration delay

and stopped delay. As differently defined above, stopped delay and time-in-queue delay can be considered the same as a component in control delay even if they have different definitions. In this thesis, control delay is considered as the sum of deceleration delay, stopped delay, and acceleration delay. Three components of control delay are defined below.

- Deceleration delay: the time needed by a vehicle to reduce its speed to stop.
- Stopped delay: the time that a vehicle is stopped in queue while waiting to pass through the intersection.
- Acceleration delay: time loss due to reacceleration back to the desired speed.

The components defined above can be computed mathematically in the space-time diagram in figure 1.

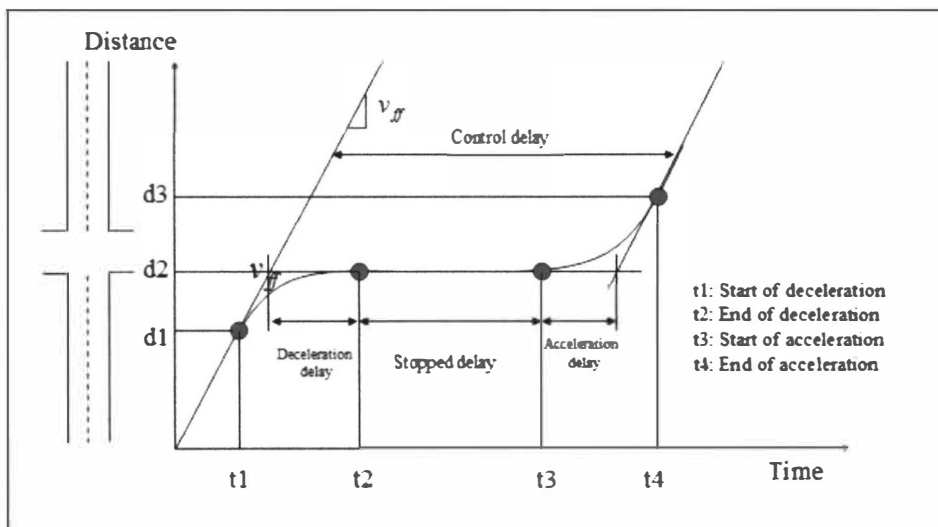


Figure 1: Space-time diagram

The computations of components of control delay are shown below.

$$\text{Deceleration Delay} = (t_1 - t_2) - \frac{d_2 - d_1}{v_{ff}} \quad (1)$$

$$\text{Stopped Delay} = t_3 - t_2 \quad (2)$$

$$\text{Acceleration Delay} = (t_4 - t_3) - \frac{d_3 - d_2}{v_{ff}} \quad (3)$$

$$\text{Control Delay} = d_d + d_s + d_a \quad (4)$$

Global Positioning System

GPS stands for Global Positioning System. It is defined as a network of satellites that continuously transmits coded information, which makes it possible to precisely identify locations on earth by measuring distance from the satellites (Garmin 2000). GPS has a variety of applications on land, at sea and in the air. Especially, GPS has been efficiently and effectively used for gathering traffic data. GPS consists of three major segments, space segment, control segment, and user segment. Those are the satellites, the ground stations, and user's GPS receivers respectively.

GPS works based on triangulation with three or four satellites. The location of a GPS receiver from a particular satellite can be calculated using the speed of light and the time delay of signal. And based on the distances obtained from 3 or 4 satellites, the location of the GPS receiver is determined by triangulating. Mathematically, 4 satellites are needed to have an exact point, but 3 satellites are able to produce an exact location since one of two points is a ridiculous answer that

is either too far from the earth or moving at an impossible velocity.

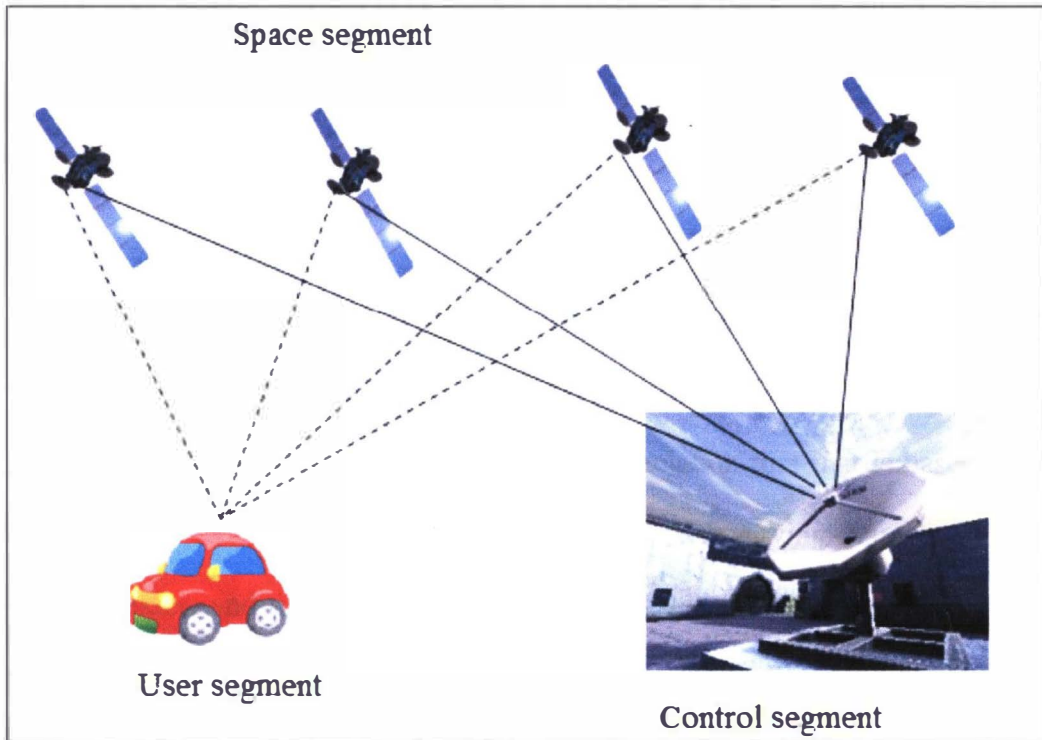


Figure 2: Three major segments of GPS

GPS has its own errors such as ionosphere and troposphere delays due to the signal slowing in the atmosphere, signal multi-path due to the reflection off objects, receiver clock errors, orbital errors, number of satellites visible, and satellite geometry. Also intentional degradation of the satellite signal called “Selective Availability” used to exist and turned off May 2, 2000 by the U.S. military (Garmin 2000). However, accuracy can be improved by combining the GPS receiver with a Differential GPS (DGPS) receiver, which can operate from several possible sources to help reduce some of the sources of errors described above.

Even though GPS has its own errors, it is getting improved and popularly used for collecting traffic data in many studies. The big advantage using GPS is that traffic data required can be easily collected at the time required with low initial costs.

Paramics

Paramics is a suite of high performance software tools used to model the movement and behavior of individual vehicles on urban and highway road networks (Quadstone Limited 2006). It is a microscopic simulation tool that is based on the movement of individual vehicles, vehicle by vehicle, with varying characteristics and multiple classes, and that vehicle positions are updated by car-following logic and lane changing rules including stochastic components.

Paramics consists of Modeller, Processor, Analyser, and Programmer. Among them, Modeller is used for this study. Paramics Modeller provides a visualization of road networks and traffic demands using a graphical user interface (GUI). Geographic and travel data is input to the program which then simulates the lane changing, gap acceptance, and car following behavior for each vehicle (Quadstone Limited 2006).

Paramics Modeller is best fit to this study not only because it uses a graphical user interface so that a behavior of individual vehicles can be observed as real, but also because GPS data can be obtained using an application program interface (API). Especially, the GPS Plugin is used for this study to get GPS data in

simulation as an API. This Plugin is designed to generate vehicle position data including coordinates, bearing and gradients for use in a visualization tool or for comparison with GPS data (Quadstone Limited 2006). Using GPS Plugin, the advantage that sufficient GPS data can be obtained in simulation is taken. The sufficient GPS data can be obtained to address the sample size problem mentioned usually in current studies.

CHAPTER III

METHODS GENERATING CONTROL DELAY

Delay of Individual Vehicles using GPS Data

The main problem in computing control delay components with GPS data is to find critical points, t_1 , t_2 , t_3 , and t_4 in Figure 1. It is relatively easier to find t_2 and t_3 when a vehicle ends decelerating and starts to accelerate respectively (i.e. when a vehicle stays stopped) using speed profile. However, the points when a vehicle starts to decelerate and ends accelerating, t_1 and t_4 respectively are very hard to be detected. Certain rules are required to proceed easily and automatically to find those critical points when dealing with large amount of data. Quiroga and Bullock (1999) introduced a method to detect those critical points, and Ko and Hunter (2006) also suggested a related method recently. The methods are described below.

Quiroga and Bullock's Method

Change of acceleration is used to detect critical points using forward and backward average acceleration algorithms.

Required input elements

- The speed profile

- The x and y coordinates used for locations
- Free Flow Speed

Steps

1. Compute acceleration profile with the speed profile using central average scheme

$$✓ \quad a_i = \frac{v_{i+1} - v_{i-1}}{t_{i+1} - t_{i-1}}$$

2. Detect critical points when a vehicle starts to decelerate and accelerate (t1, t3) using forward average acceleration algorithm.

$$✓ \quad \text{Filtering: } a_i = I \cdot a_i, \text{ where } I=1, \text{ if } \frac{1}{n} \left| \sum_i^{i+1} a_i \right| > threshold, \text{ otherwise } 0.$$

$$✓ \quad \text{Determine where the values become non-zero}(t1, t3)$$

3. Detect the critical points when a vehicle ends accelerating and decelerating (t2, t4) using backward average acceleration algorithm.

$$✓ \quad \text{Filtering: } a_i = I \cdot a_i, \text{ where } I=1, \text{ if } \frac{1}{n} \left| \sum_{i-1}^i a_i \right| > threshold, \text{ otherwise } 0.$$

$$✓ \quad \text{Determine where the values become zero}$$

4. Compute control delay components using the equations above.

Weaknesses

1. The acceleration profile from speed profile using central average scheme has bigger error than speed profile itself.
2. Even though the direct use of speed profile is more accurate and understandable to detect stopped delay, the acceleration profile is still used for t2, t3.

3. The number of points used for forward and backward average algorithms (n) was 10, and it seems to have problems. The sensitivity was done with the data obtained from a test run in Paramics

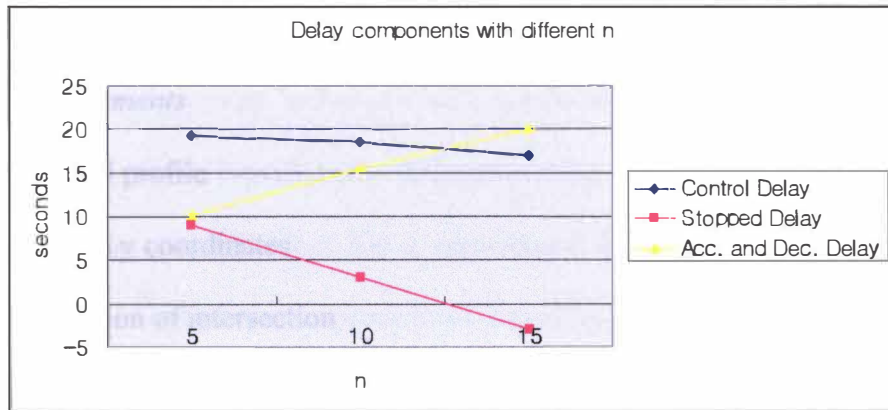


Figure 3: Sensitivity of application to changes in n

The control delay decreased as n increased, which could give the underestimated delay if larger n was used. It detected t_1 earlier and t_4 later than expected. It resulted in underestimated delay because the delay is a function of time and distance as shown above in the equation (1) and (3). Even though the time difference becomes bigger, the distance difference also becomes bigger still. When $n=15$ was used, the stopped delay became negative, which is not possible in the real world. According to the Figure 3, the number of points should be 5 although it still detects points earlier and later.

Ko and Hunter's Method

A local polynomial regression technique is used to de-noise speed profile and central average scheme used in Quiroga and Bullock's method is also used to generate acceleration profile.

Required input elements

- The speed profile
- The x and y coordinates
- The location of intersection
- The free flow speed

Steps

1. Smooth the speed profile creating a de-noised speed profile using a local polynomial regression technique
2. Compute the acceleration profile using central average scheme used in Quiroga and Bullock's method
3. Find the critical points for the stopped time interval (t_2 , t_3) using the de-noised speed profile
4. Search backward from t_2 to detect the critical point(t_1) when the acceleration is non-negative
5. Search forward from t_3 to detect the critical point(t_4) when the acceleration is non-positive
6. Compute the control delay components

Weaknesses

1. Points, t_1 and t_2 are obtained from acceleration profile generated by central average scheme that gives you more error than using speed profile only.
2. A local polynomial regression technique with a two-second bandwidth is used to smooth the speed profile. However, it seems that it is not necessary to use the regression technique with a two-second bandwidth since that doesn't give the significantly different values in control delay from the original speed profile that has a zero-second bandwidth according to the paper. It just makes the procedures complicated, and it seems that the original profile gives more accurate values since the computation of stopped delay with original speed profile is relatively more accurate and understandable. According to the paper, the stopped delay decreases, and acceleration and deceleration delay increase as the bandwidth increases. It results in underestimated stopped delay and overestimated acceleration and deceleration delay within the control delay.
3. It had also the same problem as Quiroga and Bullock's method. It detected t_1 and t_4 earlier or later than expected with the simulation data. That resulted in underestimated acceleration and deceleration delay.

Method Proposed

To avoid the error from the acceleration profile using central average scheme

used in both methods above, the original speed profile and the difference of speed between two adjacent points are used to detect critical points. For stopped delay, the problem to detect critical points is that vehicles may be crawling at certain speed even though they are in queue. Therefore, certain threshold to filter out the crawling vehicles has to be considered. Usually, previous studies showed that the speed thresholds, 2mph~3mph, were used (Ko et al 2006). In the proposed method, stopped delay is computed as the amount of time during which the velocity of a vehicle is below a given threshold, which is the same as Ko and Hunter's method.

For those critical points, t_1 and t_4 , speed difference between two adjacent points and a speed threshold filtering out unassociated points are used. The speed difference between two adjacent points determines whether the point associated is an acceleration point or a deceleration point. Applying the computation, $s_i - s_{i-1}$, represents that a negative value is a deceleration point and that a positive value is an acceleration point. However, a vehicle traveling may have acceleration points or the points with zero of acceleration value after starting to decelerate to stop at intersections. It may have deceleration points or the points with zero of deceleration value after starting to accelerate to reach a desired speed after passing intersections. The vehicle behavior described above leads to unexpected critical points that result in inaccurately estimated delay. To avoid the problem, a speed threshold is applied. In normal traffic conditions, vehicles tend to reach a certain speed such as speed limit, or free flow speed. Using the behavior, speed limit, or free flow speed can be the threshold. Otherwise, the threshold less than the speed limit can be applied

depending on a traffic condition of the study area.

Now the unassociated points less than the threshold are filtered out. The critical points can be smoothly detected by searching backward to the first non-negative point, t_1 , from t_2 , and by searching forward to the first non-positive point, t_4 , from t_3 . Keep in mind that any vehicle traveling less than the speed threshold applied is an abnormal vehicle so the GPS data related to the vehicle is invalid data. The method described above is summarized below

Required input elements

- The speed profile
- The x and y coordinates for locations
- The free flow speed
- The location of the intersection

Steps

1. Detect t_2 and t_3 for stopped delay with the same method used in Ko and Bullock's method.
 - ✓ The threshold, 2.5 mph is used as commonly used. If the value is less than or equal to the threshold, it is assumed to be stopped, 0.
 - ✓ The first 0 and the last 0 are t_2 and t_3 respectively.
2. Detect t_1 and t_4 using a speed threshold and speed difference between two adjacent points.
 - ✓ The speed threshold can be a criterion that filters out points unrelated to the critical points, t_1 and t_3 . Filter out the points less than the threshold.

- ✓ Compute the acceleration profile using two adjacent points.

$$S_i - S_{i-1} = a_i$$

- ✓ Search backward to detect t1, the first non-negative point from t2
- ✓ Search forward to detect t4, the first non-positive point from t3
- ✓ Compute the control delay components

Comparisons in Paramics

The traffic simulation tool, Paramics was used to compare the methods described above. Only the through movements from zone1 to zone2, from west to east, were used for the comparisons. The effective green time for the movement was 28/130s and the number of lanes was 2 for the movement. The GPS data was obtained using GPS plug-in provided.

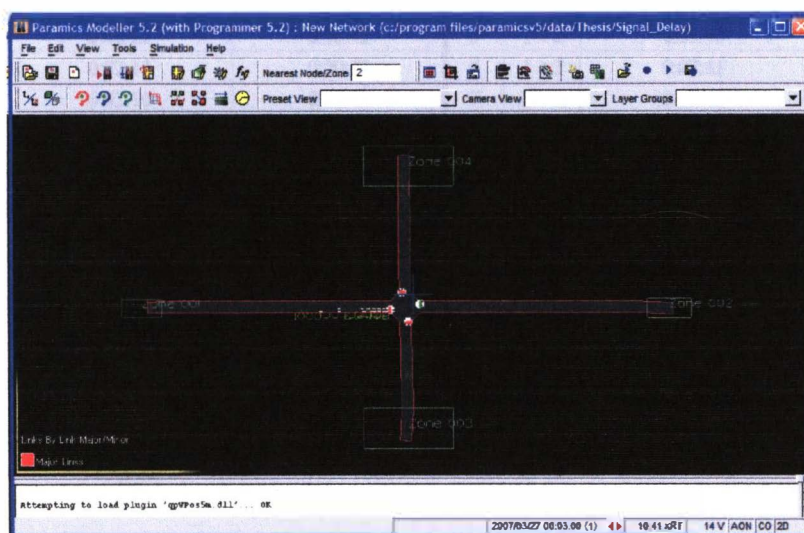


Figure 4 : Simulation in Paramics

For the control delay compared to others from the three methods mentioned above, the definition, the difference between the actual time taken to traverse a road segment, which includes an intersection, and the time to traverse the same road segment at the desired cruising speed, was used. Olszewski in 1993 mentioned that “it is impossible to measure the overall delay directly as we cannot observe how long a particular vehicle would have taken to traverse the road segment if it had not been delayed.” The delay, however, was possibly measured in simulation by running one more time and observing the travel time after simply taking out the signal from the intersection. The control delay was computed simply by averaging the time differences between when there was a signal and when there was not.

(seconds)							
Travel time without signals				Travel time with signals			
##	---	-----	-----	##	---	-----	-----
##	Trip	Arrival Time	Time Taken	##	Trip	Arrival Time	Time Taken
##	---	-----	-----	##	---	-----	-----
1	1->2	0:01:08	0:00:42	1	1->2	0:01:30	0:01:04
2	1->2	0:01:30	0:00:44	2	1->2	0:01:31	0:00:45
3	1->2	0:01:38	0:00:44	3	1->2	0:01:40	0:00:46
4	1->2	0:02:03	0:00:43	4	1->2	0:03:40	0:02:08
5	1->2	0:02:13	0:00:42	5	1->2	0:03:40	0:02:20
6	1->2	0:02:14	0:00:42	6	1->2	0:03:41	0:02:10
7	1->2	0:02:16	0:00:42	7	1->2	0:03:42	0:02:08
8	1->2	0:02:29	0:00:41	8	1->2	0:03:43	0:01:55
9	1->2	0:02:34	0:00:45	9	1->2	0:03:45	0:01:56
10	1->2	0:02:39	0:00:43	10	1->2	0:03:45	0:01:49
11	1->2	0:02:59	0:00:40	11	1->2	0:03:46	0:01:27
12	1->2	0:03:02	0:00:43	12	1->2	0:03:47	0:01:28
13	1->2	0:03:43	0:00:43	13	1->2	0:03:49	0:00:49
			0:09:14				0:20:45
Total			724.0	Total			1245.0
mean			42.6	mean			95.8
				Average Delay			53.2

Table 2: Excel work sheet on travel time difference

After running the simulation for 5 minutes, 13 vehicles passed the

intersection, and GPS data for the vehicles was analyzed. The average delay from the travel time difference was 53.2 seconds. And computations of control delay components by each method were done with the GPS data of 13 vehicles, and the results were as the followings in Table 3.

Vehicle	Control Delay			Stopped Delay			Acc. & Dec. Delay		
	Quiroga	Ko	Thesis	Quiroga	Ko	Thesis	Quiroga	Ko	Thesis
1	19.3	19.6	20.4	9.0	16.0	16.0	10.3	3.6	4.4
2	0.1	0.1	0.7	0.0	0.0	0.0	0.1	0.1	0.7
3	0.0	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.3
4	95.7	95.9	96.3	85.0	91.0	91.0	10.7	4.9	5.3
5	86.1	86.3	87.1	73.0	76.0	76.0	13.1	10.3	11.1
6	83.8	84.2	84.7	73.0	80.0	80.0	10.8	4.2	4.7
7	82.0	81.0	83.0	72.0	67.0	67.0	10.0	14.0	16.0
8	69.8	70.6	71.3	62.0	59.0	59.0	7.8	11.6	12.3
9	69.2	69.4	69.7	60.0	57.0	57.0	9.2	12.4	12.7
10	63.6	63.4	64.6	56.0	49.0	49.0	7.6	14.4	15.6
11	42.6	43.2	44.1	34.0	30.0	30.0	8.6	13.2	14.1
12	40.6	41.1	41.6	32.0	29.0	29.0	8.6	12.1	12.6
13	3.5	0.6	0.6	0.0	0.0	0.0	3.5	0.6	0.6
Sum	656.3	655.7	664.3	556.0	554.0	554.0	100.3	101.7	110.3
Mean	50.5	50.4	51.1	42.8	42.6	42.6	7.7	10.2	11.0
Stdv	35.0	35.3	35.6	31.8	32.2	24.5	4.1	5.6	5.9

Table 3: Delay components by three methods with the GPS data from Paramics

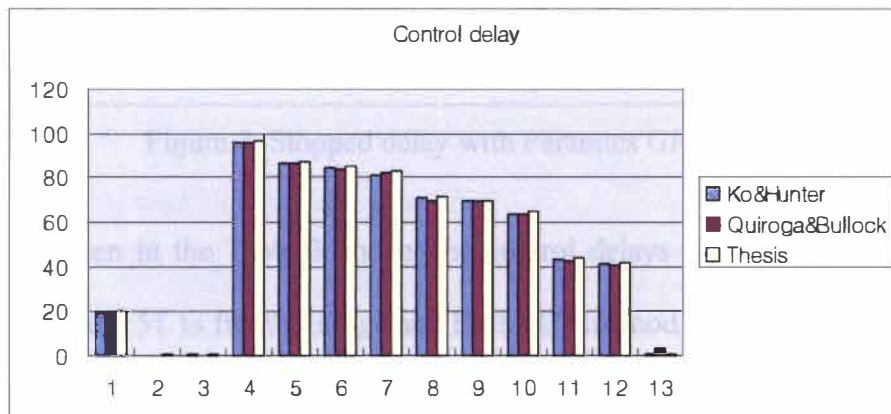


Figure 5: Control delay with Paramics GPS data

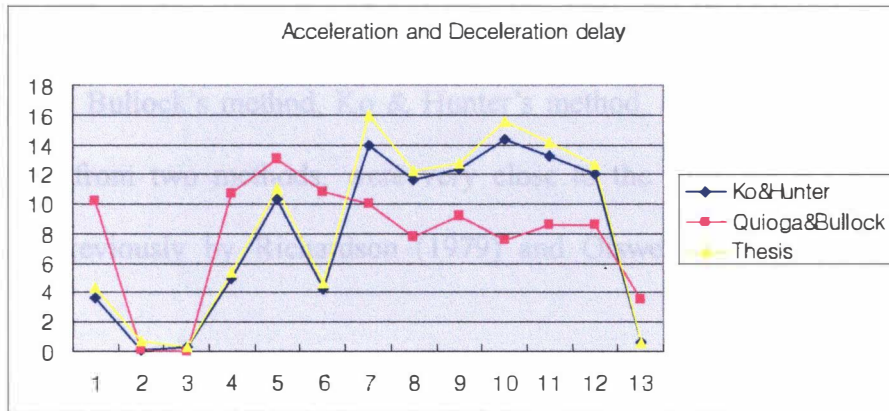


Figure 6: Acceleration and deceleration delay with Paramics GPS data

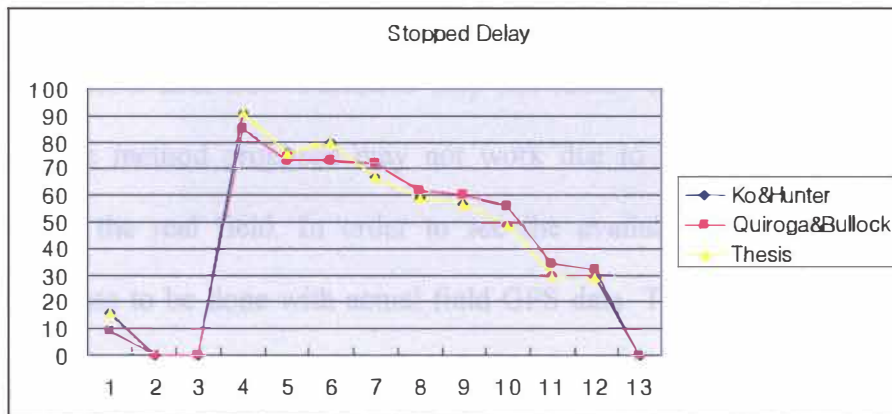


Figure 7: Stopped delay with Paramics GPS data

As seen in the Table 3 above, the control delays from each method were 50.5s, 50.4s, and 51.1s from Quiroga and Bullock's method, Ko & Hunter's method, and the proposed method respectively. The closed value to 53.2s was 51.1s obtained from the method proposed. As pointed out previously, Ko & Hunter's method underestimated acceleration and deceleration delay resulting in underestimating control delay. And Quiroga & Bullock's method had no certain patterns for both control delay, and acceleration and deceleration delay. But it clearly had more error than the method proposed had. It depended on how smooth GPS data was. In

addition, the acceleration and deceleration delay were 7.7s, 10.2s, and 11.0s for Quiroga and Bullock's method, Ko & Hunter's method, and the proposed method. The values from two methods, were very close to the value of 10s, which was estimated previously by Richardson (1979) and Olszewski(1993) based on field observation.

Comparisons with the Field GPS Data

The GPS data from Paramics may not satisfy all the conditions from the field, and the method proposed may not work due to the unexpected conditions occurring in the real field. In order to see the availability in the situation, the comparison has to be done with actual field GPS data. The GPS data was obtained along with the Oakland corridor in Kalamazoo, MI. The data associated with three intersections, @ Wheaton Ave., @ Howard St., and @ Winchell Ave. was analyzed for control delay components by each method.

	@Wheaton Ave.			@Howard St.			@Winchell Ave.		
	Quiroga	Ko	Thesis	Quiroga	Ko	Thesis	Quiroga	Ko	Thesis
Ds	9.0	15.0	15.0	2.0	7.0	7.0	8.0	12.0	12.0
Dacc	7.0	4.3	4.9	5.7	4.5	4.7	5.6	4.1	9.3
Ddec	8.7	4.9	5.1	7.3	2.5	2.7	8.5	4.7	5.0
Dacc_dec	15.7	9.2	10.0	13.0	7.0	7.4	14.1	8.8	14.3
Dc	24.7	24.2	25.0	15.0	14.0	14.4	22.1	20.8	26.3

Table 4: Delay components with real field GPS data

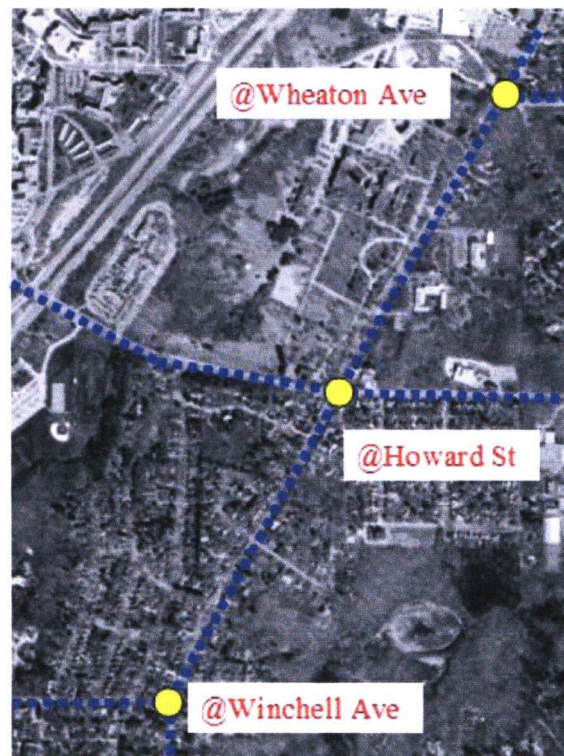


Figure 8: Site map

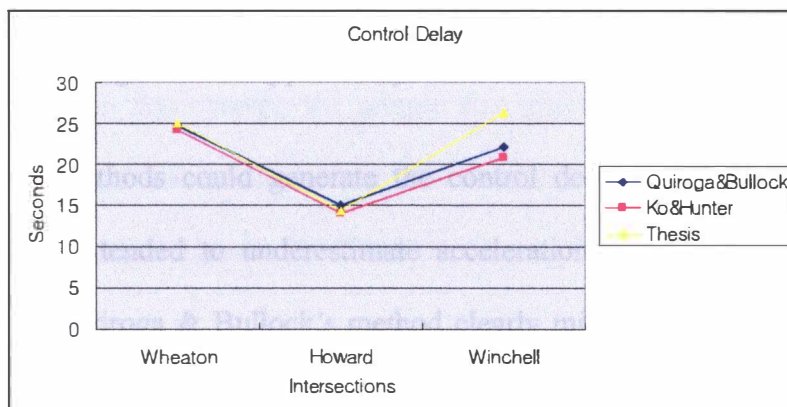


Figure 9: Control delay with real field GPS data

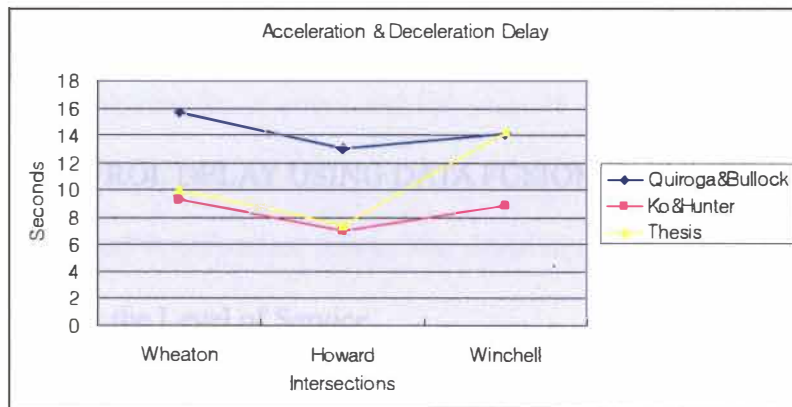


Figure 10: Acceleration and deceleration delay with real field GPS data

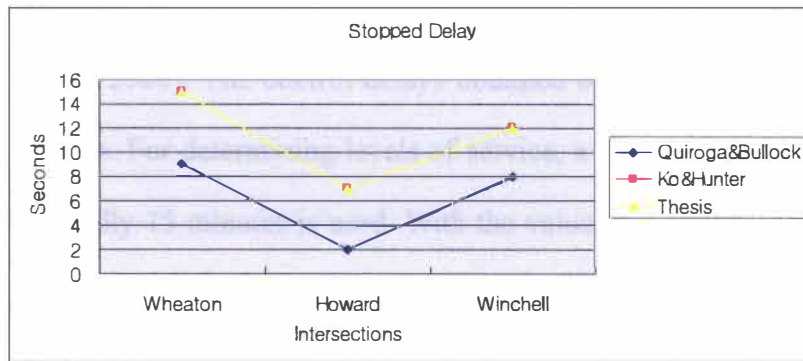


Figure 11: Stopped delay with real field GPS data

Three methods could generate the control delays well. However, Ko & Hunter's method tended to underestimate acceleration and deceleration delay as expected. And Quiroga & Bullock's method clearly misestimated stopped delay as seen in Figure 11 as discussed previously. As a result, the method proposed in this study is more effective and accurate than the other two methods.

CHAPTER IV

CONTROL DELAY USING DATA FUSION TECHNIQUE

Delay Determining the Level of Service

The 2000 Highway Capacity Manual (HCM2000) considers the control delay as a primary measure for determining the level of service at signalized intersection (TRB 2000). The control delays obtained by the methods above are of individual vehicles. For determining levels of service, a total control delay during a study period, usually 15 minutes is used. With the values of individual vehicles, the average control delay of signalized intersection could be computed if the sufficient samples existed. The sample size required, however, is hardly obtained in the real world at present. In this chapter, the sample size problem is addressed using data fusion technique. To test accuracy and effectiveness, comparisons are done with vehicle-in-queue count technique (HCM2000), the data fusion technique proposed.

Vehicle-in-queue Count Technique (HCM2000)

The 2000 Highway Capacity Manual defines a field measurement technique for control delay. The study methodology recommended in the Highway Capacity Manual is most commonly used and based on direct observation of vehicle-in-queue

at frequent intervals and requires a minimum of two observers (Rosses et al 2004). The observers count vehicles in queue and the vehicles passing intersection during a study period. The adjustment factors are applied for the error of sampling techniques and acceleration and deceleration delay. The detailed procedures are described in Appendix A.

Model Validation

As mentioned above, the control delay from vehicle-in-queue count technique is commonly used to determine the level of service at signalized intersections. Previously, the GPS technique for control delay of individual vehicles is proposed. The control delay from GPS data has to be accurate enough to be an alternative of vehicle-in-queue technique.

In order to see how accurate the techniques were, tests were done with simulation data. The travel time difference used in the previous chapter was also used as a ground truth value. At this time, 15 minutes was used as a simulation time. The vehicle-in-queue count technique was conducted following the procedures in HCM2000 by observing the movement of individual vehicles in simulation window. The interval, 15 sec, was used as recommended by HCM2000, 10~20sec. The control delay from GPS data were computed with the data of 85 vehicles that completely passed the intersection during the run. The green to cycle ratio for the movement was 28/130s and the number of lanes was 2 for the movement. And only

through movements were considered. The tables of the results are in Appendix B, C, and D.

As a result, 42.4s, 43.2s, and 41.9s were the control delays from travel time difference, vehicle-in-queue count technique, and the method proposed respectively. The differences from the ground truth value were 0.8s, and 0.5s for vehicle-in-queue count technique and the method proposed respectively. With just one test run and data set, it is inappropriate to say whether the values are statistically the same or not. However, the both techniques produced relatively accurate control delays within the error of 1s that satisfies the requirement of accuracy for level-of-service analysis. Therefore, it is definitely feasible to use the control delay from GPS data to determine the level of service if the sample size required is satisfied.

The Sample Size Requirement

The control delay with GPS data varied considerably, ranging from 0.4 to 104 seconds during the study period. And the standard deviation for the control delays of 85 vehicles was 34.5 seconds that led to the results in very large sample size requirement. Using the equation (5) below, the sample size of 183 is required with 95% confidence level and 5s permitted error and the samples size of 46 and 20 is required with 10s and 15s permitted error respectively.

Assuming that at most 3 to 5 runs are possibly done for a 15-minutes study period, it may take up to 35 days to 60 days that is very costly and time-consuming.

And even if the permitted error drops, it still requires 4 to 10 days. Four days of study period may satisfy the requirements of the cost and time, but the permitted error may not satisfy the requirements of accuracy for determining the level of service at signalized intersections. Li et al in 2002 conducted the related study for sample size requirement of the delay from GPS data and found that the unfeasible sample sizes in reality were required to have the delay with the reasonable permitted error.

$$N \geq \frac{1.96^2 s^2}{e^2} \quad \text{With 95\% confidence,} \quad (5)$$

Where,

N: Sample size requirement

S: Standard deviation

e: Permitted error

Data Fusion Technique

Studies of data fusion have been conducted in transportation field since the end of 1980's. That has been doing a major role in Intelligent Transportation Systems (ITS). In 1991, Linn et al conducted study of data fusion to define levels of data fusion. In early 1990's, ADVACE project in Chicago conducted a full-scale study of data fusion. However, most data fusion applications were to estimate travel time. In this thesis, the application of data fusion for control day is conducted.

Control Delay with GPS Data and Detector Data

As mentioned above, control delay using GPS data only has a sample size problem that is hardly solved at present unless the majority of vehicles traveling in the real world has a GPS device and gives the GPS data to researchers or traffic engineers. Therefore, a new technique is required to execute a function determining the level of service at signalized intersections as an alternative of vehicle-in-technique that is very laborious. The new technique is proposed and evaluated in this study with the data obtained from Paramics.

Methodology

The technique needs three major data: time of vehicle absence from the loop detector, number of vehicles experiencing a queue and not during the study period, and GPS data of samples. In addition, the basic data such as green to cycle ratio, free flow speed of the study area, and the distance from the detector to where queue exists.

Once the time of vehicle absence is obtained, the vehicles can be distinguished either the vehicles experiencing a queue or not at each cycle assuming that vehicles traveling at free flow speed as shown in Figure 12. Note that the study period should start when the signal is red. The vehicles meeting the red signal are considered vehicles experiencing a queue, and the vehicles meeting the green signal

are considered vehicles not experiencing a queue.

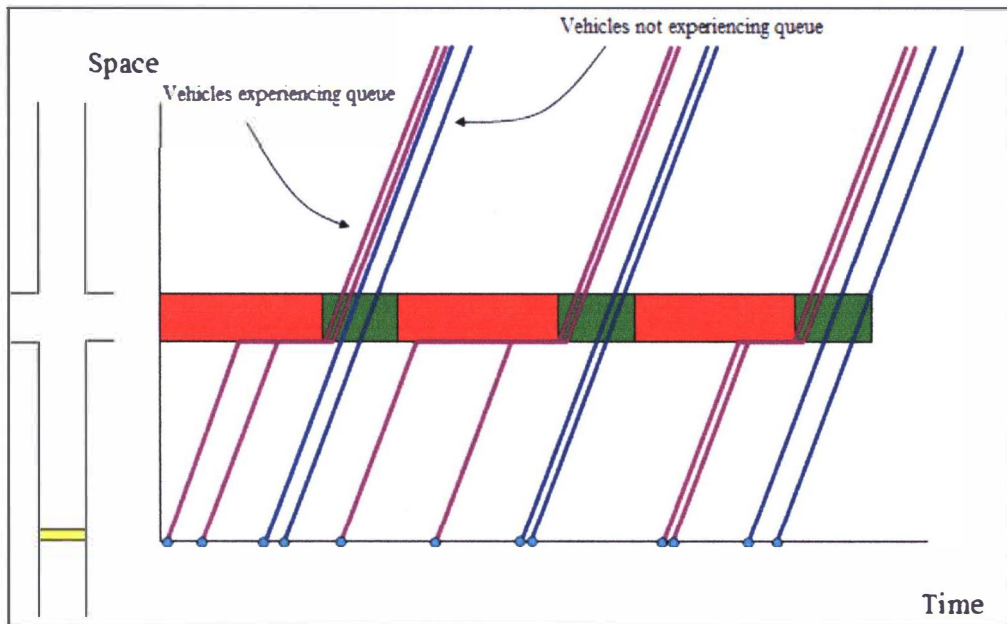


Figure 12: Time-space diagram during the study period

The time that a vehicle passes the detector and the place where the vehicle stands in queue can be known after matching the time absence in detector and the vehicle experiencing a queue and not in order at each cycle. It is assumed that the first vehicle passing the detector is the first vehicle approaching the queue. The travel time of each vehicle can be computed by having the distance correction that the first row in queue has the distance from the detector to the stop line of the intersection, the second row in queue has about a car length less distance, normally 20ft, and others can be obtained in the same manner as shown in Figure 12. However, it depends on the number of lanes. If the number of lanes is two, that means the first two vehicles approaching to the intersection become the first vehicles in queue. After

giving the travel time to each vehicle, the time that a vehicle arrives at queue can be obtained in order by simply adding the travel time to the time absence of the matched vehicles.

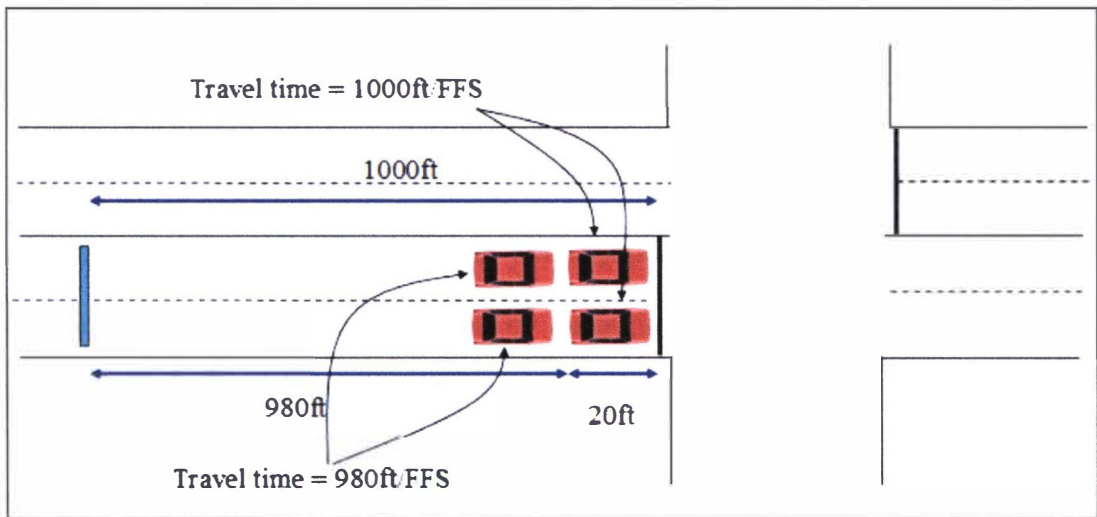


Figure 13: Travel times of vehicles

The next step is to approximate a stopped delay for each vehicle that experiences a queue. The control delay varies because the stopped delay varies at signalized intersection. The stopped delay is a matter of red time left after a vehicle arrives at queue. Therefore, it is important to estimate a stopped delay for each vehicle. With all the information above, the vehicles can be distinguished as either a vehicle experiencing a queue or not at each signal cycle during the study period. The stopped delay of vehicle experiencing a queue can be estimated by subtracting the arrival time from the maximum red time, cycle length – effective green time. The estimated stopped delay is based on the assumption that a vehicle comes at queue with free flow speed (i.e. the delay is estimated without deceleration delay).

In order to give accuracy to the estimated stopped delay above, a conversion factor is applied from the delay of GPS data. Before applying the conversion factor, the probe vehicle can be matched with the data from the detector since GPS has information of time and location. Once the estimated stopped delay of the probe vehicle and the stopped delay from GPS data are matched, the ratio of two delays becomes the conversion factor. The stopped delay of each vehicle is computed after multiplying the conversion factor to each previously estimated stopped delay. Note that the stopped delay of the vehicle not experiencing a queue is zero. The total stopped delay can be now computed by averaging all the stopped delay obtained after applying the conversion factor.

And the final step is to estimate acceleration and deceleration delay. Vehicles tend to behave usually similar with the neighboring vehicles. That means acceleration and deceleration delay may not vary as much as stopped delay does. Therefore, the stopped delay can be estimated by averaging the acceleration and deceleration delay of probe vehicles. Note that a probe vehicle has to experience queue in order to find a relatively accurate conversion factor. All the steps of the methodology are summarized below.

Required input elements

- Data of time absence from loop detector.
- GPS data of probe vehicles
- Green time and cycle length of the signal

Steps

1. Match the data of vehicle experiencing a queue and not at each cycle with the time absence from the detector.
2. Estimate travel time of each vehicle with FFS and the distance from the detector to the queue. Use a length of car, usually 20ft, to have different distance by locations of vehicles in queue
3. Estimate the stopped delays of each vehicle with the cycle length and red time.
4. Match the data of probe vehicles with the time absence data using GPS data.
5. Obtain the control delay and acceleration and deceleration delay of probe vehicles using GPS data.
6. Estimate the conversion factor using the equation below

$$K = \frac{\sum_{i=1}^n Ds_i}{\sum_{i=1}^n Dest_i} \quad (6)$$

Where,

K: Conversion Factor

Dest: Estimated stopped delay from detector

Ds: Estimated stopped delay from GPS data

N: Number of probe vehicles

7. Multiply the conversion factor to each estimated stopped delay from detector
8. Average all the stopped delay after multiplying the conversion factor to the estimated stopped delay of each vehicle experiencing a queue.

9. Average the acceleration and deceleration delay from GPS data of probe vehicles

10. Compute the total control delay with the equation below

$$Dc = \frac{\sum_{i=1}^n Dest_i \cdot k}{n} + \frac{\sum_{i=1}^{n_p} Dacc_dec_i}{n_p} \quad (7)$$

Where,

Dc: total control delay

Dest: estimated stopped delay from detector

K: conversion factor

n: number of vehicles passing the intersection during study period

np: number of GPS samples

Case Study

The case study was done also with the GPS and detector data from Paramics. Other characteristics of the simulation were the same as the previous run. The sample sizes of 1 to 10 was tested with 30 randomly chosen data sets among the control delays of 85 vehicles for each of the occasions when using data fusion technique and GPS data only. The following tables show the results.

#	seconds									
	Sample Size									
	1	2	3	4	5	6	7	8	9	10
1	40.6	41.5	38.8	41.1	41.0	41.3	41.4	41.2	41.4	42.1
2	39.7	37.2	39.8	41.2	41.7	41.3	41.8	42.7	42.7	42.6
3	36.6	39.9	42.5	42.5	42.8	42.5	42.1	42.0	41.8	41.7
4	37.7	41.3	40.4	39.6	42.5	41.9	41.9	42.3	42.1	41.8
5	39.0	40.9	41.7	41.8	40.6	41.3	41.3	40.8	41.3	41.7
6	41.9	40.5	40.9	41.2	42.2	42.4	42.3	42.2	41.9	42.4
7	36.3	40.7	42.0	41.6	41.7	42.1	41.8	41.9	41.9	41.9
8	38.7	39.9	41.7	41.8	42.3	42.1	42.2	42.5	42.3	41.7
9	44.2	42.9	39.2	39.7	42.6	40.5	41.0	41.5	41.5	41.9
10	41.7	42.2	41.5	42.1	42.1	42.4	42.4	42.4	42.4	42.4
11	39.2	41.1	42.5	41.1	39.2	41.2	41.4	40.6	40.6	41.4
12	47.2	42.0	41.7	42.1	41.4	41.3	42.1	42.4	42.2	41.7
13	42.0	42.6	40.7	42.9	42.7	40.8	41.6	43.4	42.7	43.2
14	42.0	38.4	40.3	43.1	41.3	42.7	42.4	41.3	41.5	41.3
15	41.9	44.4	42.3	41.5	42.8	42.5	41.0	42.5	41.4	42.5
16	41.9	39.7	45.2	43.9	41.6	41.3	41.8	41.7	41.6	41.8
17	37.1	42.0	42.7	42.8	41.4	41.4	41.5	41.9	41.1	42.0
18	40.1	44.0	42.0	41.0	40.8	42.7	42.0	41.8	41.7	42.4
19	39.3	42.8	41.7	41.1	41.4	42.8	41.7	41.9	42.2	42.5
20	41.8	41.3	42.9	41.9	41.8	42.1	41.2	41.5	42.1	41.6
21	41.2	41.8	43.0	40.3	42.2	42.6	42.4	42.1	42.3	41.9
22	43.1	39.3	40.3	42.2	41.1	42.5	42.0	41.9	42.6	41.4
23	29.4	41.5	41.7	41.9	41.6	42.3	42.4	42.2	42.7	42.1
24	32.8	40.9	42.5	41.9	41.8	43.3	41.9	41.8	41.4	42.5
25	40.1	37.7	41.5	41.2	42.0	42.9	42.5	42.1	41.1	41.7
26	42.0	42.4	40.6	43.0	43.2	42.8	42.5	42.2	42.3	41.2
27	36.6	41.3	41.1	42.8	41.6	42.3	42.0	42.2	41.4	42.0
28	46.4	43.9	42.8	42.1	40.9	42.1	42.8	41.1	41.4	41.9
29	40.3	42.9	42.1	40.6	40.9	41.6	42.4	41.3	42.5	42.4
30	39.1	41.1	42.5	41.6	41.6	42.0	43.0	41.6	42.1	41.5
Sum	1199.9	1238.2	1248.5	1251.5	1250.6	1261.2	1258.6	1256.8	1256.6	1258.9
Mean	40.0	41.3	41.6	41.7	41.7	42.0	42.0	41.9	41.9	42.0
Stdev	3.6	1.7	1.3	1.0	0.8	0.7	0.5	0.6	0.5	0.5
MAPE	7%	3%	2%	2%	2%	1%	1%	1%	1%	1%

Table 5: Total control delays with sample size 1~10 from data fusion technique

The table shows that all the average values are close to the ground truth value, 42.4s obtained from travel time difference with maximum error of -2.4s. However, the standard deviation of sample size of 1 is large. On the other hand, the sample sizes more than 4 have relatively small standard deviations and seem stabilized. Basically, with all control delay of 85 vehicles, the mean value would be 41.9s. The mean

absolute percentage errors from the value, 41.9s was compared with the same values from 30 randomly chosen data sets with sample sizes of 1 to 10 when using GPS data only. The table 6 shows the results of 30 sets of data from GPS data only.

#	Seconds									
	Sample size									
	1	2	3	4	5	6	7	8	9	10
1	34.8	65.6	74.7	43.7	70.6	52.5	46.5	39.0	48.8	65.3
2	3.3	13.6	32.5	49.8	53.1	49.5	43.6	45.8	34.8	30.6
3	96.7	68.6	48.8	34.3	31.1	49.1	43.0	47.6	35.2	44.8
4	75.9	33.6	27.6	28.3	60.8	54.5	30.0	36.1	36.7	30.6
5	72.9	19.7	16.4	44.3	60.5	21.0	46.7	46.5	50.4	66.4
6	34.6	66.0	29.9	27.9	35.0	61.0	51.9	30.2	58.7	39.5
7	85.4	28.9	19.7	38.9	40.3	11.7	37.3	56.4	42.8	50.5
8	60.9	42.1	25.8	32.8	49.6	53.3	44.2	49.9	51.0	50.5
9	32.0	46.0	29.1	57.3	13.9	42.7	21.0	33.2	45.4	48.2
10	61.5	73.4	58.5	72.9	38.8	25.1	37.2	21.6	58.4	48.6
11	30.9	26.3	48.5	29.4	30.3	50.3	42.0	32.4	35.8	56.3
12	98.1	73.2	56.9	63.3	42.5	45.9	35.0	24.1	46.6	32.4
13	96.7	42.5	44.4	65.0	52.8	49.1	20.4	46.2	28.4	37.7
14	42.8	6.4	46.3	45.9	67.9	57.3	55.8	46.3	48.2	43.0
15	28.8	62.2	33.8	30.5	30.5	34.1	23.3	32.9	16.0	44.3
16	29.9	24.8	75.9	44.1	27.7	41.0	60.5	67.8	40.1	39.1
17	23.7	25.2	47.7	40.3	38.2	25.3	58.3	56.1	28.5	26.5
18	16.2	34.9	17.6	26.0	72.0	37.5	37.1	63.5	39.8	40.8
19	97.3	10.9	13.3	33.3	38.3	11.1	32.4	35.7	25.0	53.1
20	73.2	15.8	52.3	67.0	25.5	52.9	44.2	55.5	48.6	32.8
21	50.7	20.6	37.2	78.2	54.9	23.4	50.7	28.4	19.2	33.1
22	31.5	63.8	41.1	39.5	42.7	50.5	38.2	43.0	33.0	40.6
23	101.8	51.0	79.1	46.9	34.3	18.6	32.7	29.8	38.8	41.4
24	92.5	47.5	42.3	51.6	43.8	42.3	27.1	34.6	47.5	28.5
25	87.4	12.2	44.0	64.9	38.6	29.8	31.9	43.7	55.0	38.4
26	61.6	73.7	39.2	61.3	56.5	39.1	23.3	35.2	46.2	51.3
27	59.4	24.3	37.9	67.3	61.6	28.9	37.2	31.1	26.5	51.3
28	32.7	54.1	32.9	77.7	65.1	60.5	44.4	41.6	39.5	39.2
29	11.0	34.1	23.5	49.8	33.3	28.5	75.0	49.3	44.7	39.8
30	4.3	47.7	37.8	42.5	24.7	44.2	53.8	27.4	21.6	48.4
Sum	1628.5	1208.6	1214.6	1454.8	1335.1	1190.8	1224.5	1231.0	1190.9	1293.1
Mean	54.3	40.3	40.5	48.5	44.5	39.7	40.8	41.0	39.7	43.1
Stdev	31.1	21.2	16.9	15.6	15.2	14.4	12.6	11.6	11.3	10.0
MAPE	66%	43%	31%	32%	30%	28%	24%	23%	22%	19%

Table 6 : Total control delays with sample size 1~10 from GPS data only

And the table 7 represents the comparisons of mean absolute percentage errors

between the control delays from data fusion technique and from GPS data only.

	Sample size									
	1	2	3	4	5	6	7	8	9	10
GPS_Only	66.3%	43.5%	31.2%	31.6%	29.7%	28.4%	23.6%	22.9%	22.0%	18.7%
Data Fusion	6.7%	3.3%	2.3%	1.8%	1.5%	1.4%	1.0%	1.1%	1.1%	0.9%
Difference	59.6%	40.2%	28.9%	29.8%	28.2%	26.9%	22.6%	21.9%	20.9%	17.8%

Table 7 : Mean absolute percentage error

The results indicated that the data fusion technique improved the accuracy by 59.6%, 40.2%, 28.9%, 29.8%, and 28.2% when the number of samples used was 1, 2, 3, 4, and 5 respectively. According to the figure 12 below, the improvement could be seen clearly for all the sample sizes tested even if the difference decreased as the sample size got bigger

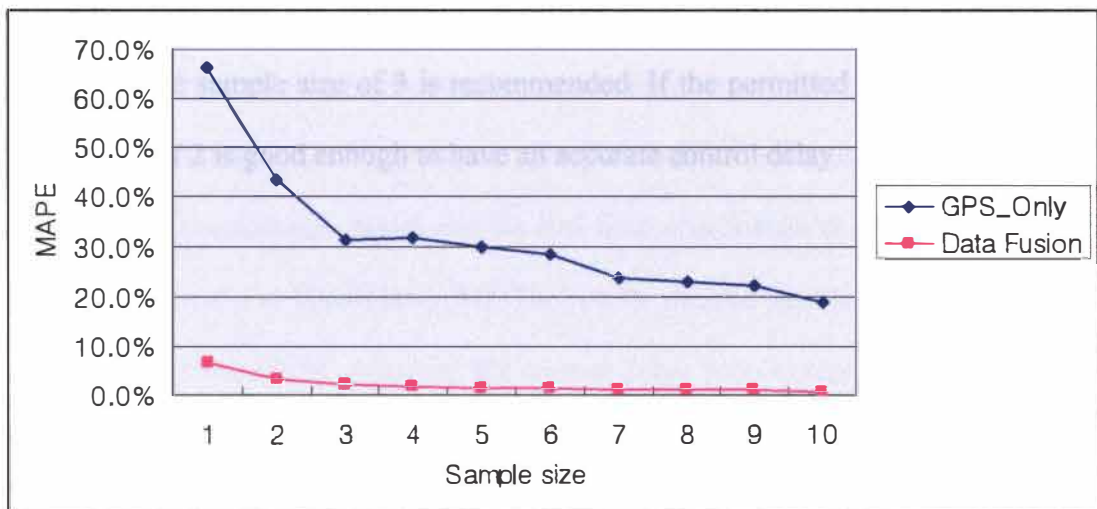


Figure 14 : Comparison of mean absolute percentage error

Statistic tests were done with the Z values assuming that 41.9s is the value that has to be achieved. The table shows the results.

											(%)
		Sample Size									
		1	2	3	4	5	6	7	8	9	10
Mean		40.0	41.3	41.6	41.7	41.7	42.0	42.0	41.9	41.9	42.0
Stdev		3.6	1.7	1.3	1.0	0.8	0.7	0.5	0.6	0.5	0.5
P(40.9<D<42.9)		0.19	0.41	0.55	0.69	0.77	0.85	0.95	0.91	0.93	0.97
P(39.9<D<43.9)		0.37	0.72	0.87	0.96	0.98	1.00	1.00	1.00	1.00	1.00
P(38.9<D<44.9)		0.54	0.90	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
P(38.9<D<44.9)		0.67	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 8 : Probability with permitted error

According to the table above, with the error of ± 1 s, the sample sizes more than or equal to 7 have the percentages more than 90% of possibility having the control delay within the error. With the error of ± 2 s, the sample sizes more than or equal to 4 are required with more than 90% of possibility. The sample size at least 2 or 3 is required to have the control delay within the error of ± 3 s with more than 90% of possibility. To make sure the value falls within the permitted error with higher possibility, the sample size of 3 is recommended. If the permitted error is ± 4 s, the sample size of 2 is good enough to have an accurate control delay.

CHAPTER V

CONCLUSION AND FUTURE TASKS

Conclusion

Collecting traffic data using GPS has been popularly used since GPS data can produce good quality data with low initial cost. The studies, especially by Quiroga et al (1999) and Ko et al (2006), focused on methods generating the control delay at signalized intersections. These studies, however, have some weaknesses and only deal with the control delay of individual vehicles.

To overcome the weaknesses of the previously proposed methods, this study proposed a new method estimating the intersection control delay using GPS data. The performance of the method was compared with other methods based on the data from Paramics simulation model and the real field observation at three intersections in Oakland corridor in Kalamazoo, MI. The results showed that the proposed method in this thesis successfully estimated the control delay and overcame the weaknesses in the previous methods.

Highway Capacity Manual 2000 regards delay typically measured during 15 minutes as a primary measure for determining the level of service at a signalized intersection. Even though the proposed method was able to accurately estimate individual vehicle's delay, it is necessary to have enough vehicles equipped with

GPS in order to provide a representative delay measure. However, currently it is infeasible to have enough GPS samples. Therefore, it is necessary to address the sample size issue.

This study proposes a data fusion technique that uses both GPS data and detector data. The performance was compared with the vehicle-in-queue count technique. The proposed technique was able to successfully estimate the total control delay for 15 minutes. A sample of 4 GPS data or more was recommended with 90% of possibility having the control delay within the error of ± 2 s. A sample size of 2 or 3 at least was required to determine the control delay within the error of ± 3 s with more than 90% of possibility. To make sure the value falls within the permitted error with higher possibility, the sample size of 3 is recommended. If the permitted error is ± 4 s, a sample size of 2 is good enough to have an accurate control delay. More importantly, the data fusion technique improved the accuracy by 59.6% when only one GPS sample is available.

Future Tasks

The study has been successfully done with the fine results. However, only through movements were considered for the control delays. In the future, delays on left turn and right turn have to be further studied. Besides, the data fusion technique was tested only with simulation data due to the cost and time constraints. Testing with actual field data will prove its applicability in practice.

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APPENDIX A

Vehicle-in-queue count technique in HCM2000

The survey should begin at the start of the red phase of the lane group; ideally there is no overflow queue from the previous green phase. There is a need for consistency with the analytic delay equation, which is based on delay to vehicles that arrive during the study period, not before. If the survey does start with an overflow queue, the overflow vehicles need to be excluded from subsequent queue counts. Observer 1 performs the following tasks during the field study.

1. Keeps track of the end of standing queues for each cycle in the survey period by observing the last vehicle in each lane that stops because of the signal. This count includes vehicles arriving when the signal is actually green but stopped because vehicles in front have not yet started moving. For purposes of the survey, a vehicle is considered as having joined the queue when it approaches within one car length of a stopped vehicle and is itself about to stop. This definition is used because of the difficulty of keeping precise track of the moment when a vehicle comes to a stop. All vehicles that join a queue are then included in the vehicle-in-queue counts until they cross the stop line.

2. At regular intervals of between 10 and 20 s, records the number of vehicles in queue (e.g., using the countdown-repeat timer on a digital watch to signal the count time). The regular intervals should not be an integral divisor of the cycle length (e.g., if the cycle length is 120 s, 14-s or 16-s count intervals should be used, not 15-s intervals). Vehicles in queue are those that are included in the queue of stopping vehicles as defined in Step 1 and have not yet exited the intersection. For through vehicles, exiting the intersection can be considered to occur when the rear axle of a vehicle crosses the stop line. For turning vehicles, exiting the intersection occurs the instant a vehicle clears opposing through traffic or pedestrians to which it must yield and begins accelerating back to free-flow speed. Note that the vehicle-in-queue count often includes some vehicles that have regained speed but have not yet exited the intersection.

3. Enters the vehicle-in-queue counts in the appropriate box on the worksheet. Cycles of the survey period are listed in the second column of the sheet, after the column to record clock time every five cycles, and interval count identifiers are listed as column headings. For ease in conducting the study, the survey period is most conveniently defined as an integer number of cycles, though a precisely defined time length for the survey period (e.g., 15 min) can be used. The key point is that the end of the survey period must be clearly defined in advance since the last arriving vehicle or vehicles that stop in the period must be identified and counted until they exit the intersection, per the next step.

4. At the end of the survey period, continues taking vehicle-in-queue counts for all vehicles that arrived during the survey period until all of them have exited the intersection. This step requires mentally noting the last stopping vehicle that arrived during the survey period in each lane of the lane group and continuing the vehicle-in-queue counts until the last stopping vehicle or vehicles, plus all vehicles in front of the last stopping vehicles, exit the intersection. Stopping vehicles that arrive after the end of the survey period are not included in the final vehicle-in-queue counts.

Observer 2 performs the following study task.

1. During the entire survey period, maintains separate volume counts of total vehicles arriving during the survey period and total vehicles arriving during the survey period that stop one or more times. A vehicle stopping multiple times is counted only once as a stopping vehicle. Enters these volumes in the appropriate boxes on the worksheet.

Data reduction is accomplished with the following steps.

1. Sum each column of vehicle-in-queue counts, then sum the column totals for the entire survey period.

2. A vehicle recorded as part of a vehicle-in-queue count is in queue, on average, for the time interval between counts. The average time-in-queue per vehicle arriving during the survey period is estimated using Equation A

$$\text{Time-in-queue per vehicle} = \left(I_s \times \frac{\sum V_{iq}}{\sum V_{tot}} \right) \times 0.9 \quad (A)$$

Where,

I_s = interval between vehicle-in-queue counts (s)

$\sum V_{iq}$ = sum of vehicle-in-queue counts (veh)

V_{tot} = total number of vehicles arriving during the survey period (veh), and

0.9 = empirical adjustment factor

The 0.9 adjustment factor accounts for the errors that may occur when this type of sampling technique is used to derive actual delay values, normally resulting in an overestimate of delay. Research has shown the correction required to be fairly consistent over a variety of conditions.

3. Compute the fraction of vehicles stopping and the average number of vehicles stopping per lane in each signal cycle, as indicated on the worksheet.

4. Using the Table A, look up a correction factor appropriate to the lane group free-flow speed and the average number of vehicles stopping per lane in each cycle. This factor adds an adjustment for deceleration and acceleration delay, which cannot be measured directly with manual techniques.

Free-Flow Speed	≤ 7 Vehicles	8 - 19 Vehicles	20 - 30 Vehicles ^a
≤ 37 mi/h	+ 5	+ 2	- 1
> 37-45 mi/h	+ 7	+ 4	+ 2
> 45 mi/h	+ 9	+ 7	+ 5

Table A: Acceleration-Deceleration Delay Correction Factor, CF(s)

Vehicle-in-queue counts in excess of about 30 vehicles per lane are typically unreliable.

5. Multiply the correction factor by the fraction of vehicles stopping, then add this product to the time-in-queue value of Step 2 to obtain the final estimate of control delay per vehicle.

APPENDIX B

Control delay of 85 vehicles

seconds									
No.	Delay	No.	Delay	No.	Delay	No.	Delay	No.	Delay
1	55.4	21	32.0	41	42.8	61	41.5	81	11.0
2	34.8	22	29.2	42	41.4	62	41.6	82	10.2
3	28.2	23	11.3	43	31.1	63	39.3	83	5.7
4	4.3	24	0.8	44	28.8	64	31.5	84	5.8
5	0.8	25	0.6	45	29.9	65	17.5	85	4.3
6	0.8	26	0.9	46	29.2	66	7.9		
7	0.6	27	0.4	47	27.2	67	1.8		
8	104.0	28	0.6	48	23.7	68	0.6		
9	101.3	29	61.5	49	15.9	69	101.8		
10	96.7	30	61.3	50	16.0	70	94.4		
11	75.9	31	44.8	51	16.2	71	92.5		
12	72.9	32	30.9	52	10.4	72	87.4		
13	34.6	33	8.4	53	4.5	73	85.0		
14	3.7	34	7.0	54	0.9	74	71.5		
15	0.6	35	102.0	55	0.8	75	61.6		
16	92.9	36	101.0	56	97.3	76	55.0		
17	85.4	37	98.1	57	96.4	77	59.4		
18	60.9	38	97.2	58	75.2	78	32.7		
19	41.0	39	96.7	59	53.9	79	21.1		
20	33.4	40	57.3	60	50.7	80	17.2		
								Sum	3521.0
								Mean	41.9
								Stdv	34.5

APPENDIX C

Intersection control delay worksheet for vehicle-in-queue technique

Intersection Control Delay Worksheet

# of lane:	2	Vtot	85
FFS	32	Vstop	64
Is	15	C	130

Clock time	Cycle number	Count Interval									
		1	2	3	4	5	6	7	8	9	10
0:00:00	1	0	0	0	4	5	5	2	0	4	
0:02:10	2	6	8	10	12	12	13	9	0	2	
0:04:20	3	3	6	6	6	7	7	0	0		
0:06:30	4	1	3	4	5	7	9	6	0	0	
0:08:40	5	2	3	5	6	6	9	2	0		
0:10:50	6	3	3	6	6	8	9	0	0		
0:13:00	7	7	0	0	0	2	4	4	1	0	
0:15:10	8										

Vip	248	Nc	7
dvp	39.3882	FVS	0.75294
no.	4.57143	Dad	3.76471
CF	5	Dc	43.2

APPENDIX D

Control delay from travel time difference of 85 vehicles

##-	---	-----	-----	---	-----	-----
##	Trip	Arrival_Time	Time_Taken	Trip	Arrival_Time	Time_Taken
##-	---	-----	-----	---	-----	-----
1	1->2	0:02:05	0:01:39	1->2	0:01:08	0:00:42
2	1->2	0:02:06	0:01:20	1->2	0:01:30	0:00:44
3	1->2	0:02:07	0:01:13	1->2	0:01:38	0:00:44
4	1->2	0:02:08	0:00:48	1->2	0:02:03	0:00:43
5	1->2	0:02:14	0:00:43	1->2	0:02:13	0:00:42
6	1->2	0:02:17	0:00:45	1->2	0:02:14	0:00:42
7	1->2	0:02:18	0:00:44	1->2	0:02:16	0:00:42
8	1->2	0:04:14	0:02:26	1->2	0:02:29	0:00:41
9	1->2	0:04:16	0:02:27	1->2	0:02:34	0:00:45
10	1->2	0:04:17	0:02:21	1->2	0:02:39	0:00:43
11	1->2	0:04:17	0:01:58	1->2	0:02:59	0:00:40
12	1->2	0:04:18	0:01:59	1->2	0:03:02	0:00:43
13	1->2	0:04:19	0:01:19	1->2	0:03:43	0:00:43
14	1->2	0:04:22	0:00:49	1->2	0:04:16	0:00:43
15	1->2	0:04:30	0:00:45	1->2	0:04:28	0:00:43
16	1->2	0:06:25	0:02:09	1->2	0:04:51	0:00:42
17	1->2	0:06:25	0:02:16	1->2	0:04:58	0:00:42
18	1->2	0:06:27	0:01:18	1->2	0:05:25	0:00:43
19	1->2	0:06:27	0:01:45	1->2	0:05:46	0:00:42
20	1->2	0:06:28	0:01:15	1->2	0:05:52	0:00:43
21	1->2	0:06:29	0:01:25	1->2	0:05:54	0:00:41
22	1->2	0:06:32	0:01:15	1->2	0:06:01	0:00:44
23	1->2	0:06:32	0:00:51	1->2	0:06:18	0:00:41
24	1->2	0:06:33	0:00:56	1->2	0:06:24	0:00:43
25	1->2	0:06:40	0:00:44	1->2	0:06:38	0:00:42
26	1->2	0:06:43	0:00:45	1->2	0:06:41	0:00:43
27	1->2	0:06:45	0:00:45	1->2	0:06:43	0:00:43
28	1->2	0:06:45	0:00:44	1->2	0:06:44	0:00:43
29	1->2	0:08:35	0:01:45	1->2	0:07:33	0:00:43
30	1->2	0:08:35	0:01:45	1->2	0:07:33	0:00:43
31	1->2	0:08:37	0:01:16	1->2	0:07:52	0:00:44
32	1->2	0:08:38	0:01:30	1->2	0:08:03	0:00:42
33	1->2	0:08:39	0:00:53	1->2	0:08:29	0:00:43
34	1->2	0:08:42	0:00:52	1->2	0:08:33	0:00:43
35	1->2	0:10:45	0:02:25	1->2	0:09:02	0:00:42
36	1->2	0:10:45	0:02:25	1->2	0:09:03	0:00:43
37	1->2	0:10:46	0:02:21	1->2	0:09:06	0:00:41
38	1->2	0:10:46	0:02:19	1->2	0:09:09	0:00:42
39	1->2	0:10:49	0:01:42	1->2	0:09:11	0:00:43
40	1->2	0:10:49	0:02:21	1->2	0:09:50	0:00:43

##-	---	-----	-----	---	-----	-----	
##	Trip	Arrival_Time	Time_Taken	Trip	Arrival_Time	Time_Taken	
##-	---	-----	-----	---	-----	-----	
41	1->2	0:10:52	0:01:29	1->2	0:10:08	0:00:45	
42	1->2	0:10:53	0:01:29	1->2	0:10:11	0:00:47	
43	1->2	0:10:53	0:01:13	1->2	0:10:22	0:00:45	
44	1->2	0:10:54	0:01:17	1->2	0:10:23	0:00:43	
45	1->2	0:10:55	0:01:12	1->2	0:10:24	0:00:43	
46	1->2	0:10:56	0:01:15	1->2	0:10:25	0:00:42	
47	1->2	0:10:58	0:01:15	1->2	0:10:27	0:00:44	
48	1->2	0:10:58	0:01:02	1->2	0:10:34	0:00:43	
49	1->2	0:10:59	0:01:01	1->2	0:10:38	0:00:40	
50	1->2	0:11:00	0:01:09	1->2	0:10:41	0:00:45	
51	1->2	0:11:01	0:00:50	1->2	0:10:42	0:00:42	
52	1->2	0:11:01	0:01:01	1->2	0:10:53	0:00:45	
53	1->2	0:11:04	0:00:56	1->2	0:10:55	0:00:44	
54	1->2	0:11:10	0:00:45	1->2	0:11:09	0:00:44	
55	1->2	0:11:12	0:00:48	1->2	0:11:10	0:00:46	
56	1->2	0:12:54	0:02:19	1->2	0:11:16	0:00:42	
57	1->2	0:12:55	0:02:21	1->2	0:11:16	0:00:41	
58	1->2	0:12:56	0:01:57	1->2	0:11:41	0:00:42	
59	1->2	0:12:57	0:01:36	1->2	0:12:04	0:00:44	
60	1->2	0:12:58	0:01:25	1->2	0:12:05	0:00:44	
61	1->2	0:13:00	0:01:40	1->2	0:12:15	0:00:42	
62	1->2	0:13:01	0:01:26	1->2	0:12:18	0:00:43	
63	1->2	0:13:02	0:01:24	1->2	0:12:21	0:00:43	
64	1->2	0:13:02	0:01:15	1->2	0:12:28	0:00:41	
65	1->2	0:13:03	0:01:02	1->2	0:12:40	0:00:39	
66	1->2	0:13:06	0:00:55	1->2	0:12:57	0:00:46	
67	1->2	0:13:13	0:00:42	1->2	0:13:11	0:00:40	
68	1->2	0:13:19	0:00:43	1->2	0:13:18	0:00:42	
69	1->2	0:15:05	0:02:18	1->2	0:13:23	0:00:43	
70	1->2	0:15:05	0:02:25	1->2	0:13:29	0:00:42	
71	1->2	0:15:08	0:02:18	1->2	0:13:34	0:00:44	
72	1->2	0:15:08	0:02:11	1->2	0:13:38	0:00:42	
73	1->2	0:15:09	0:02:13	1->2	0:13:43	0:00:46	
74	1->2	0:15:10	0:01:40	1->2	0:13:59	0:00:45	
75	1->2	0:15:11	0:01:18	1->2	0:14:10	0:00:44	
76	1->2	0:15:12	0:01:58	1->2	0:14:14	0:00:44	
77	1->2	0:15:12	0:01:05	1->2	0:14:14	0:00:43	
78	1->2	0:15:14	0:01:48	1->2	0:14:35	0:00:42	
79	1->2	0:15:15	0:01:44	1->2	0:14:48	0:00:41	
80	1->2	0:15:16	0:01:02	1->2	0:14:57	0:00:43	
81	1->2	0:15:16	0:00:55	1->2	0:15:03	0:00:42	
82	1->2	0:15:18	0:00:55	1->2	0:15:07	0:00:44	
83	1->2	0:15:18	0:00:51	1->2	0:15:09	0:00:42	
84	1->2	0:15:19	0:00:49	1->2	0:15:12	0:00:43	
85	1->2	0:15:20	0:00:51	1->2	0:15:12	0:00:42	
		Sum	7246			Sum	3643
		Mean	85.2			Mean	42.9
						Contro Delay	42.4