MEASURING CONTROL DELAY USING SECOND-BY-SECOND GPS SPEED DATA

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ABSTRACT

High-resolution vehicle speed profiles obtained from sophisticated devices such as global positioning system (GPS) receivers provide an opportunity to accurately measure intersection delay, composed of deceleration delay, stopped delay, and acceleration delay. Although the delay components can be measured by manually examining the speed profiles or derived time-space diagrams, identifying when vehicles begin to decelerate or stop accelerating is not always a straightforward task. In addition, a manual identification process may be laborious and time-consuming when handling a large network or numerous runs. More importantly, the results from a manual process may not be consistent between analysts or even for a single analyst over time. This paper proposes a new approach to identifying control delay components based on second-by-second vehicle speed profiles obtained from GPS devices. The proposed approach utilizes both de-noised speed and acceleration profiles for capturing critical points associated with each delay component. Speed profiles are used for the identification of stopped time periods, and acceleration profiles are used for detecting deceleration onset points and acceleration ending points. The authors applied this methodology to sampled runs collected from GPS-equipped instrumented vehicles and concluded that it satisfactorily computed delay components under normal traffic conditions.

INTRODUCTION

As delay is closely linked with driver discomfort, frustration, fuel consumption, and lost travel time, it is a key performance measure for signalized intersections and used as a criterion for evaluating and designing traffic control systems. In fact, the Highway Capacity Manual (HCM) has adopted delay as the prime measure for determining the level of service (LOS) at an intersection. The HCM [1, 2] defines intersection LOS based on control delay, which includes initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay. Thus, the identification of acceleration and deceleration delays as well as stopped delay (which for this effort is taken to include queue move-up time) is critical to the analysis of the performance of signalized intersections or corridors containing traffic signals.

However, deceleration and acceleration delays are not easy to capture without the help of sophisticated devices providing high resolution vehicle speed profiles, such as second-by-second. In contrast, stopped delay is relatively easy to measure in the field, which may explain why stopped delay has long been the primary field measured intersection delay and why control delay has been estimated based on the measured stopped delay. However, stopped delay does not reflect every aspect of intersection performance affected by traffic signals. The relationship between stopped delay and other delay components may not be established in a single all encompassing function, due to site-specific factors affecting the relationship such as signal timing and driver characteristics. Indeed, three different sources reported three significantly different relationships between control delay and stopped delay as follows.

Stopped delay = 0.76 × Control delay	TRB [3]
Stopped delay = 0.959 × Control delay - 19.3	Quiroga and Bullock [4]
Stopped delay = 0.58 × Control delay - 2.31	Mousa [5]

For example, if measured stopped delay is 10 seconds, resulting control delays based on these three different equations are 13, 31, and 21 seconds for TRB [3], Quiroga and Bullock [4], and Mousa [5], respectively. This significant discrepancy implies that each delay component should be measured in the field rather than estimated based on stopped delay.

One tool allowing for sufficient data collection for delay determination is a global positioning system (GPS) device [6]. A GPS device can provide data describing detailed vehicle speed trajectories, enabling researchers to detect when a vehicle begins to decelerate, stops accelerating, stops, or starts moving. However, these critical points are not always easy to identify as speed profiles sometimes have irregular patterns requiring researcher’s subjective judgment, resulting in potential inconsistencies in delays calculated by different analysts and even for a single analysts. In addition, individual review of every vehicle trajectory is laborious and time-consuming work when handling a large network or numerous runs, further requiring the development of efficient automatic processes.

DEFINITION OF CONTROL DELAY COMPONENTS

Control delay at a signalized intersection is generally defined as the delay attributed to the traffic signal operation. Control delay is a portion of the total delay which includes all the delay components, including control delay, geometric delay, volume delay, and incident delay [7].

However, in a practical sense, the distinctions between these delay components are considerably difficult to measure, particularly when using remotely monitored data. For simplicity, this paper defines intersection control delay as the sum of deceleration delay, stopped delay including queue move-up time, and acceleration delay, as illustrated in Figure 1. It is seen in Figure 1 that control delay may be calculated as the difference between the travel time when a vehicle's trajectory is affected by traffic control and the travel time when the vehicle's trajectory is unaffected by the traffic control. The control-affected region ranges from d_1 to d_3, and correspondingly from t_1 to t_4 in Figure 1. The initial part of the control delay is the deceleration delay, which is due to a slow-down from a normal speed. Next, the vehicle is stopped (from t_2 to t_3), and this time period represents the stopped delay. Finally, acceleration delay occurs while the vehicle is returning to a normal speed. Thus, the computation of control delay requires the identification of the critical delay points (i.e., t_1 to t_4) when a vehicle begins to decelerate, stops, or starts moving, and reaches its normal speed.

An examination of speed profiles reveals the two points associated with stopped delay. Even though, strictly speaking, zero speed is the criteria for a vehicle to be considered stopped, a higher speed threshold may be applied to allow for the identification of vehicles crawling forward in a queue as stopped. For example, Mousa [5] used 1 - 1.5m/s (2.237 – 3.356 mph), and Colyar and Rouphail [8] applied 3 mph as the stopped criteria when measuring stopped delay. Also, analyses using GPS data require a threshold greater than zero speed as the values of speed are rarely represented as exactly zero within a GPS data stream [9]. Therefore, in this research effort, stopped delay is computed as the amount of time during which the velocity of a vehicle is below a given threshold.

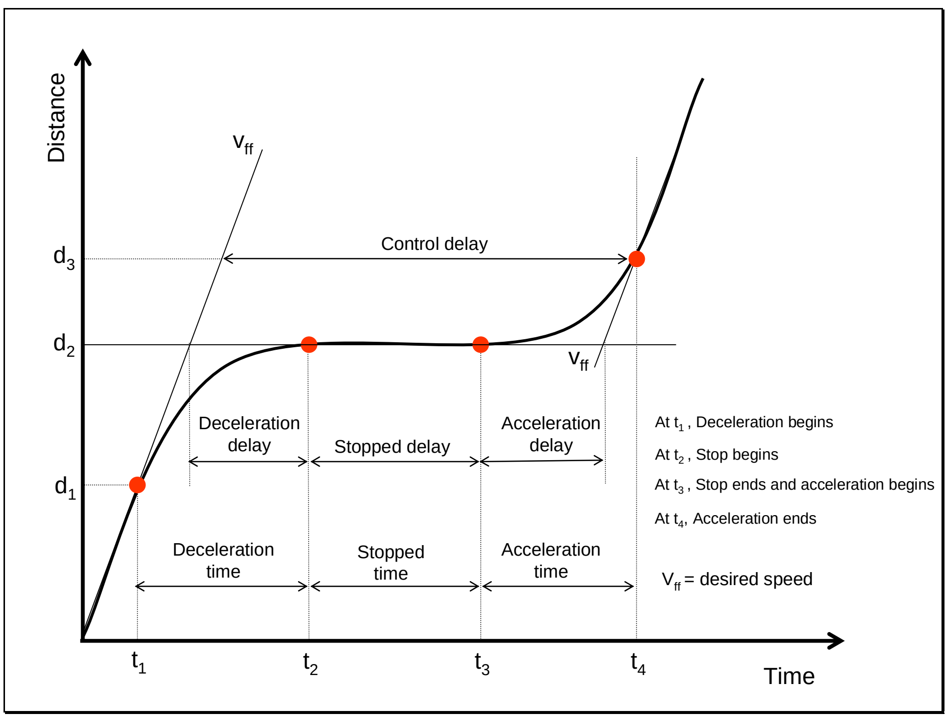


FIGURE 1 Diagram of intersection delay components.

EXISTING APPROACHES TO COMPUTING CONTROL DELAYS

The computation of control delay components requires the speed profiles of individual vehicles. A traditional approach to obtaining speed profiles is known as the "path tracing" method [5]. In this approach, observers trace the trajectories of individual vehicles within pre-specified screen lines, recording the time when the target vehicles pass each screen line. The crossing time, combined with the screen line locations, allows for the construction of vehicle trajectories in a time-space domain. The resolution of the trajectory developed using this approach depends on the number of screen lines. Thus, the higher the data resolution desired, the more personnel resources required. The path tracing method suffers from two primary drawbacks: it is difficult to automate, and the resultant trajectories tend to be quite coarse due to the limited number of screen lines which are typically placed at locations where vehicle operations can be effectively observed.

The path tracing method was applied for the research efforts of Olszewski [10] and Mousa [5]. In the research of Olszewski [10], two screen lines were utilized, and control delay was approximated by subtracting the average travel time of unimpeded vehicles from the observed travel times required for vehicles to traverse the road segment between the two screen lines. Then, deceleration-acceleration delay was found indirectly by deducting the stopped time from the control delay, resulting in a combined value for acceleration-deceleration delay. Similarly, Mousa [5] set up 12 screen lines in an attempt to capture every delay component at an intersection and identified critical delay points using a speed difference threshold of 1-1.5m/s. More specifically, the research effort detected critical points when the difference between speeds at adjacent screen lines was larger than the threshold. As explained before, the approach used in the study might be less efficient in the data collection procedure because it requires at least 12 persons assigned to each screen line. In addition, the paper did not explicitly reveal any automated process for computing control delay.

Benekohal et al. [11] suggested a video image processing system as a tool for measuring approach delay. However, the coverage of the camera view seems to be problematic. In other words, the wide spread use of such a system is limited by the ability of a camera view to capture a sufficient area that encompasses the deceleration and acceleration intervals of a roadway segment of interest. In addition, the system has a disadvantage in handling vehicles with lane changes. Another research effort [12] introduced a methodology for measuring the level of service of urban streets from airborne imagery and claimed that vehicle trajectories could be easily derived from it. However, this approach still requires a methodology that identifies the critical points of the delay components.

Similar to the approach to be introduced in this paper, Quiroga and Bullock [4] suggest a methodology that measures control delay based on GPS data. They identified critical points using accelerations/decelerations computed by forward and backward speed difference approaches in which a forward acceleration algorithm was used to detect when the vehicle starts to accelerate or decelerate, and a backward acceleration algorithm was adopted to detect when the vehicle stops accelerating or decelerating. The algorithms, a filtering scheme, recalculated the filtered accelerations based on a pre-specified acceleration threshold and the original acceleration value a_i, associated with GPS point i. The following equations mathematically express the schemes.

For forward acceleration algorithm,

$$a_{i\_forward} = I \cdot a_i,\ where\ I = 1,\ if\ \frac{1}{n}\left|\sum_{i}^{i+n} a_i\right| > threshold,\ otherwise\ 0\ .$$

For backward acceleration algorithm,

$$a_{i\_backward} = I \cdot a_i,\ where\ I = 1,\ if\ \frac{1}{n}\left|\sum_{i-n}^{i} a_i\right| > threshold,\ otherwise\ 0\ .$$

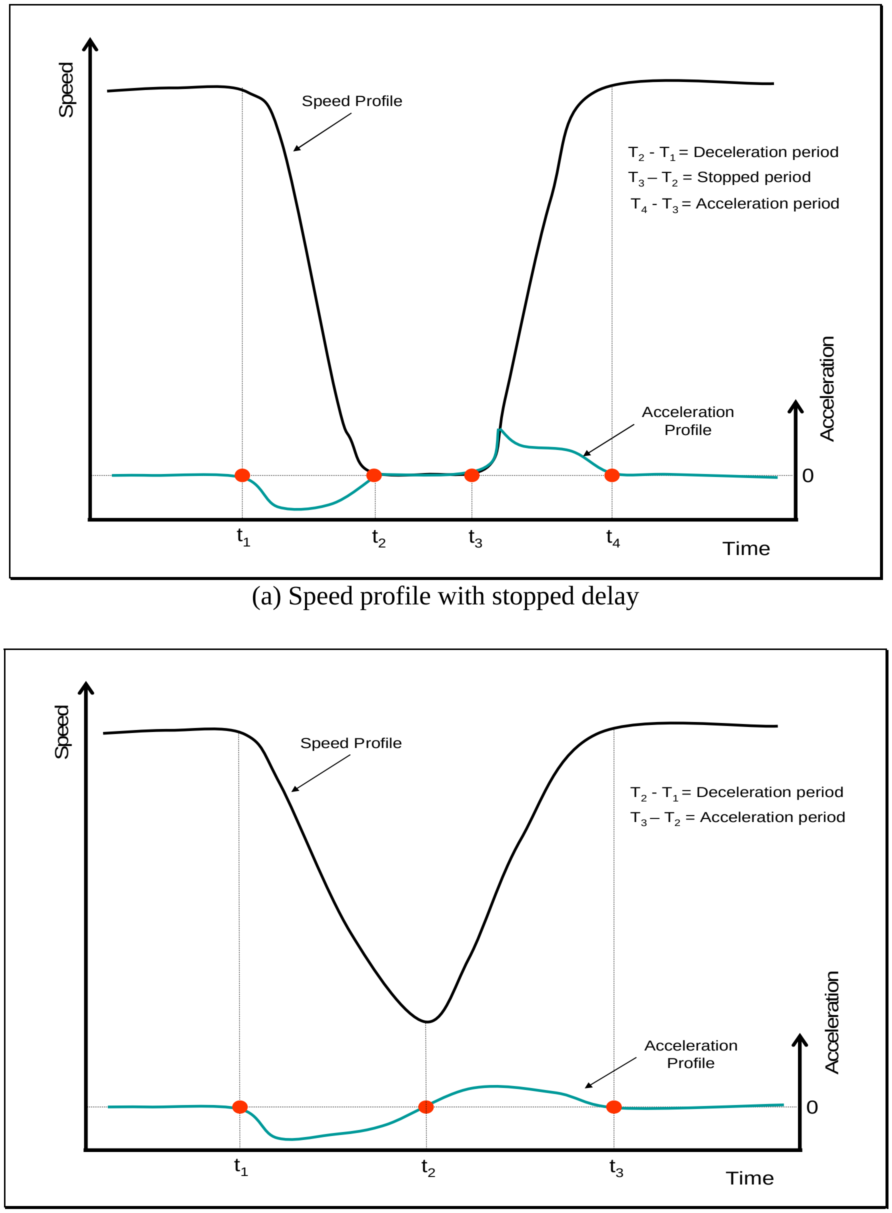
The study demonstrated that the suggested methodology could be successfully applied to GPS probe vehicle data. However, the methodology seems to have three potential weaknesses. For one, the study recommended using an average acceleration of a series of ten data points (thus, n=10 in the equations above) for comparing with threshold values. When this filtering interval is adopted in both the forward and backward acceleration algorithms, the methodology, in fact, requires at least twenty data points to identify whether the current point is a critical point. Thus, the extensive use of data points might render observations near two ends of a speed profile useless. Another potential weakness of this approach is that it assumes all the data points considered for averaging have the same weight. If the purpose of the algorithm is to determine whether the current point is the sharp edge of an acceleration profile, it intuitively seems reasonable that points nearer the potential critical point should more significantly impact this decision than those farther from the potential critical point. The final drawback is that this methodology relies primarily on changes in accelerations to locate critical points, even when detecting stopped time intervals. The direct use of speed profiles may be more desirable since it is more accurate and understandable when capturing stopped time.

More recently, a research effort presented a method for estimating control delay from second-by-second speed profile data obtained from an on-road vehicle data measurement device [8]. This research effort also attempted to identify the critical points associated with delay components by examining speed profiles. However, this research effort adopts a simpler rule for determining whether the vehicle is experiencing delay (if the vehicle has traveled at approximately the same speed (larger than 3mph) over a 5-seconds period, the vehicle is considered not experiencing delay), paying less attention to speed fluctuations often observed in real-world data.

MEASURING CONTROL DELAY

Methodological Approach

Figure 2 (a) and (b) represent two different potential speed and acceleration profiles of a vehicle passing an intersection. The difference between the two diagrams is that one contains stopped time and the other does not. Note that all the critical points associated with the delay components have zero acceleration, indicating that acceleration changes can be good indicators of critical points. Specifically, the sign of acceleration remains negative during deceleration, while it remains positive during acceleration. This observation holds true even when a speed profile does not contain stopped times, under which the number of critical points decreases from four to three. Meanwhile, the stopped time interval is more readily observable in the speed profile than in the acceleration profile.



(a) Speed profile with stopped delay

(b) Speed profile without stopped delay

FIGURE 2 Vehicle speed and acceleration profiles near an intersection.

Consequently, the effective detection of critical points appears to be possible by examining both the speed and acceleration profiles of a vehicle. The speed profile is used for locating critical points associated with stopped delay, and the acceleration profile is used for locating the deceleration beginning point and the acceleration ending point. The advantage of using acceleration profiles in the approach is that only one point is required to identify whether the current point is a critical point. However, if speed profiles are used for the same purpose, at least three points— the before and after points as well as the current point—are required. Thus, one can develop an automated process more efficiently by combining acceleration profiles rather than by depending solely on speed profiles.

Methodology for Determining Critical Points

Based on the concepts noted in the previous section, the authors suggest a new methodology, which requires several input elements as follows:

1) the speed profile,
2) the x and y coordinates of each data point,
3) the location of the intersection (x and y coordinates of the intersection location), and
4) the desired speed.

The first two elements can be obtained directly from GPS data stream, and the next two items may be externally determined. For the speed profile, the removal of noise should be considered, as a minor speed change may affect the determination of the critical points. Therefore, the proposed methodology includes a smoothing process in an attempt to prevent such errors. The location of the intersection, in particular represented by x and y coordinates, can be easily identified using electronic maps built on Geographic Information System (GIS). The desired speed is used for computing the reference travel time which represents a trip in which no delay is experienced.

The proposed methodology follows six steps below:

1) Smooth the speed profile creating a de-noised speed profile.
2) Compute the acceleration profile.
3) Find the critical points for the stopped time interval (t_2 and t_3 in Figure 2 (a)) using the de-noised speed profile.
4) Search backward from t_2 (in Figure 2 (a)) to detect the critical point (t_1 in Figure 2 (a)) when the acceleration is non-negative.
5) Search forward from t_3 (in Figure 2 (a)) to detect the critical point (t_4 in Figure 2 (a)) when the acceleration is non-positive.
6) Compute delay components based on the desired speed and the critical points identified in the previous steps.

In the case of no stopped times, the starting points of the search in steps 4 and 5 are replaced by the point at which the sign of acceleration changes, as represented by t_2 in Figure 2 (b).

Smoothing Method

A critical element of the proposed approach is to smooth the speed profile. The objective of the smoothing is to develop a smoothed profile that preserves actual critical point locations while eliminating minor fluctuations in speed that may result in inaccurate detection of critical points. The authors judged that a local polynomial regression technique could satisfy this objective as it can de-noise speed profiles while minimizing the distortion of the original series. The technique considers data points mostly within a specified range, the center of which is on a query point x_0 and estimates a new value by fitting a model. The technique generally adopts a kernel, which is used as a weighting function. The function assigns smaller weights to data points as their distance from x_0 increases, helping satisfy the aforementioned conditions (i.e., de-noising while preserving the critical points).

The authors decided that a quadratic model would be appropriate for the polynomial regression. Although a linear model would require fewer computation resources, it may fail to represent curvatures that exist in the true function, resulting in a decreased accuracy in the determined critical point locations. On the other hand, higher degree polynomials may produce better outputs than a quadratic polynomial, but the marginal improvements were found to be too small to justify the increased complexity.

In the next step, a kernel type and the aforementioned range, called a bandwidth, should be determined. The authors judged that the Gaussian kernel and a two-second bandwidth should be adequate. In the Gaussian kernel, all the data points are considered to estimate a smoothed value for a query point. However, the impact of the data points outside the bandwidth is negligible since their weights are small. For example, the data points within the bandwidth occupy 68.3% of the total weights, and the sum of the weights in the twofold bandwidth amounts to 95.5%. (The size of the bandwidth is interpreted as the standard deviation of a normal distribution with a zero mean. Thus, a two-second bandwidth results in assigning 68.3% of the total weights to the five points: the center point and two points to each side of the center point.) The bandwidth is a crucial parameter affecting the detection results of the critical points. As a bandwidth becomes narrower, the estimated value approaches its individual data points. In contrast, the wider bandwidth incurs smoother profiles. The effects of bandwidth size on delay computation results will be discussed later in detail.

The objective function of local polynomial fits for any degree d with solution $\hat{f}(x_0) = \hat{\alpha}(x_0) + \sum_{j=1}^{d} \hat{\beta}_i(x_0) x_0^j$ can be mathematically represented as follows [13]:

$$\min_{\alpha(x_0),\beta_j(x_0),j=1,\ldots,d} \sum_{i=1}^{N} K_\lambda(x_0, x_i) \left[y_i - \alpha(x_0) - \sum_{j=1}^{d} \beta_j(x_0) x_i^j \right],$$

where α and β are parameters to be estimated, and K_λ is the kernel with a parameter λ, which is the bandwidth. In addition, x_0 is the data point at which the equation is evaluated, and N is the data size. When a Gaussian kernel is adopted, K_λ is expressed as follows:

$$K_\lambda(x_0, x_i) = \frac{1}{\sqrt{2\pi}\lambda} e^{-\frac{(x_i - x_0)^2}{2\lambda^2}}.$$

Computation of Delay

Control delay can be readily calculated from the time difference between desired travel time which is directly associated with the desired speed on a given section and actual travel time over critical points. For the desired speed, most existing research efforts have used the posted speed limit or the approaching speed observed at the moment when control-incurred deceleration begins. However, the determination of actual desired speed may not be readily apparent as drivers are likely to have their own desired speed. In a later section, the authors will list the assumptions used in this effort to determine desired speed. Once the desired speed is determined, delay components can be easily calculated using the following equations, for which the definitions of symbols can be found in Figure 1.

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

$$\text{Stopped delay} = t_3 - t_2$$

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

APPLICATION

Data

The authors tested the developed methodology using real-world GPS data collected from a signalized intersection in Atlanta, Georgia. The data were collected for the Commute Atlanta project, an instrumented vehicle research program being carried out by the researchers of the Georgia Institute of Technology [14]. The project team instrumented approximately 485 vehicles with event data recorders, including GPS devices, for monitoring the speed and locations of the vehicles. The second-by-second vehicle operation data (more than 1.5 million vehicle trips, as of May 2006) provide an opportunity to measure the performance of intersections on a regional basis once effective automation processes for the computation of control delay are developed.

As test cases, the authors randomly selected 14 runs (through-movements only observed during November – December 2003) made by eight real-world drivers over a 0.95-mile one-lane roadway segment in the same direction. The segment includes one signalized intersection with posted speed limits of 40 and 30mph before and after the intersection, respectively. This intersection is located approximately 0.45 mile from the beginning point of the segment. Figure 3 shows the time-space diagram developed from the 14 sampled runs. Each line in the diagram represents the trajectory of each run over the selected 0.95-mile roadway segment, illustrating that some runs include stopped time and that total travel time over the segment varies from 93 to 228 seconds.

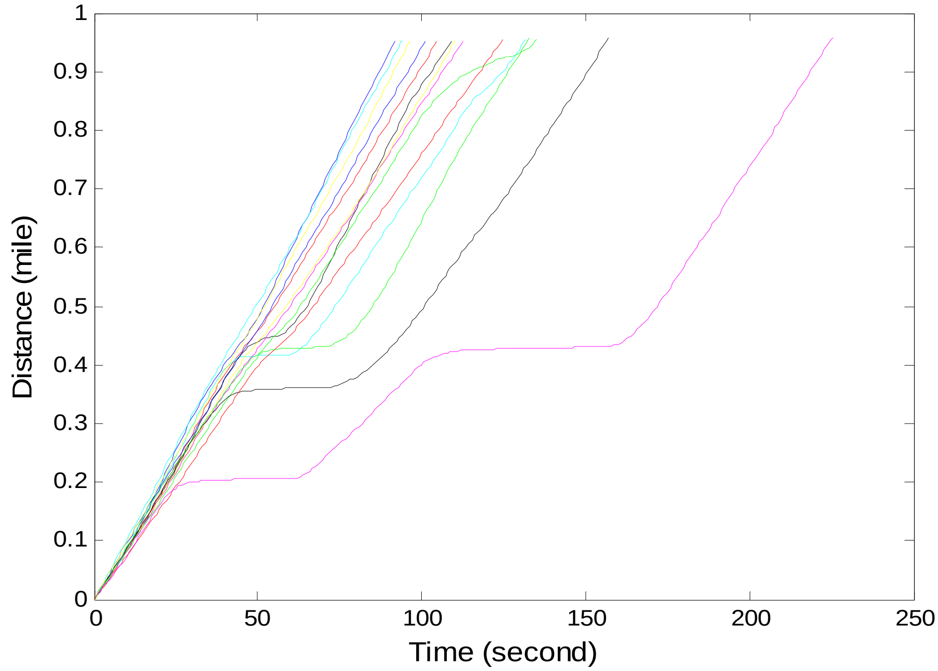


FIGURE 3 Time-space diagram of sampled runs.

Parameters/Assumptions

In this application, the authors used a threshold of 2.5mph to detect stopped time periods (i.e., the vehicle is considered stopped if its speed is less than 2.5mph). The desired speed was set to the greater of 30mph or the normal speed of each run, which is the speed at the moment when a vehicle begins to decelerate or stop accelerating. The pre-specified speed of 30mph was set as it was observed that several drivers seemed to select this speed as their desired speed, even though it is lower than the posted speed limit of the approaching segment. By allowing for some variability in the desired speed of each vehicle, this rule intuitively seems to more closely reflect the variability in driver's desired speeds than selecting a single speed that is assigned as the desired speed of all drivers.

The acceleration computation method in this study follows the central difference scheme commonly used in other research efforts such as Quiroga and Bullock [4] and Mousa [5]. The central difference scheme is known to be simple to use and provides accuracy levels that are at least one order of magnitude better than those obtained with either a forward difference scheme (difference from the front data point and the current data point) or a backward difference scheme (difference from the current data point and the previous data point) [15]. The authors used a two-second bandwidth for the quadratic local regression smoothing. A latter part of this paper will discuss the effects of bandwidth sizes on delay computation results in detail.

Results

The developed process generates several useful plots, facilitating the interpretation of outputs and visual examinations, as well as computed delay values. Figure 4 gives the speed profiles, the time-space diagrams, and the acceleration profiles for four runs. The plots contain the critical points and the intersection location marked as * and + (or Δ), respectively. Note that the profiles are from the original data, not from the smoothed speed profiles. The first two runs have only three critical points since they do not include complete stops while the last two runs have four critical points. As suggested by the principles adopted in the methodology, critical points are located on the points at which the signs of acceleration change. A small shift from the exact points when the changes occur is due to the use of the de-noised speed profiles, instead of the raw speed profiles, for the detection of critical points. As a whole, the proposed methodology appears to reasonably identify the critical points for the test data set.

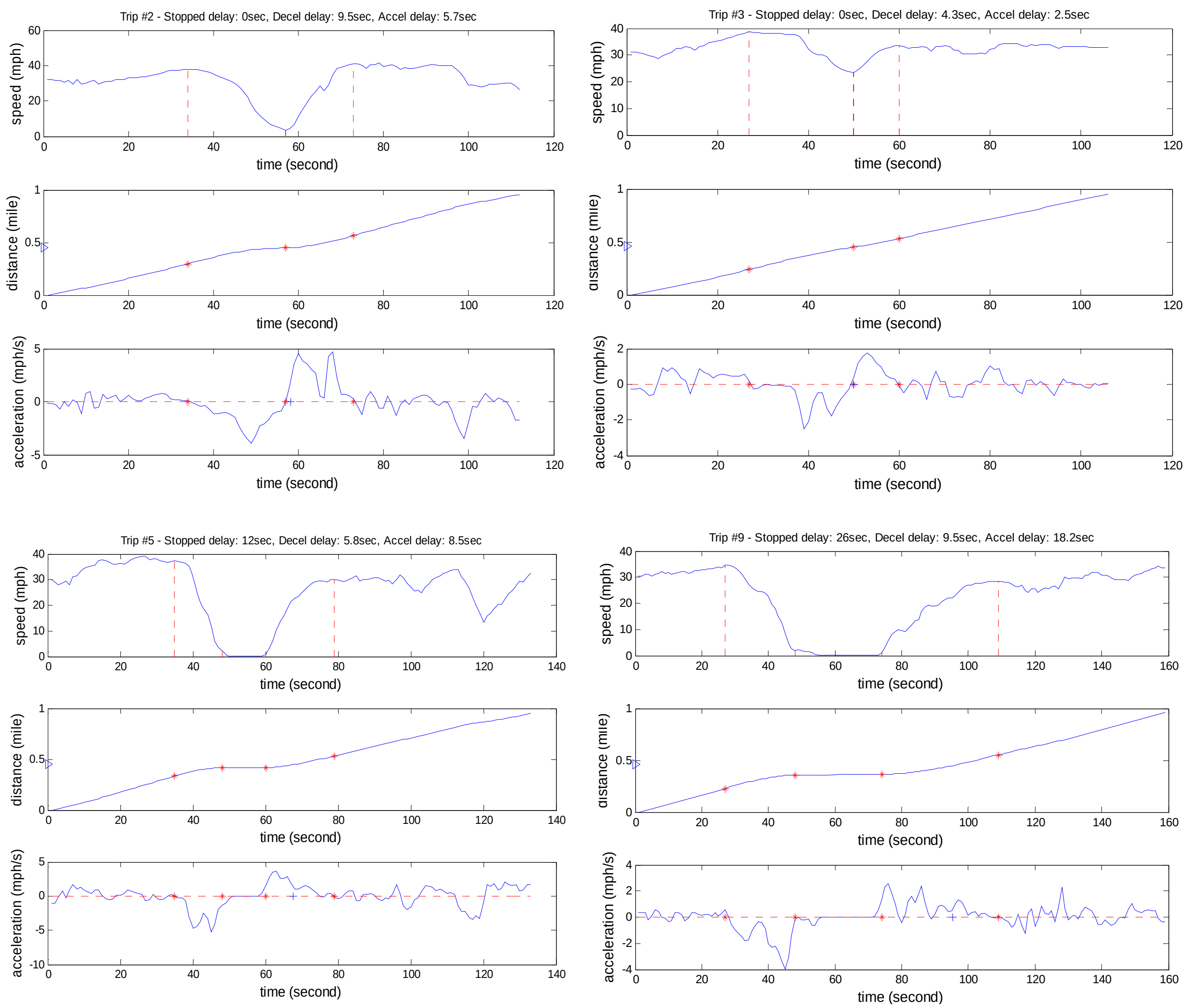


FIGURE 4 Examples of speed profile, time-space diagram, and acceleration profile with identified critical points.

The delay computation results are summarized in Table 2, in which control delay is the sum of the three delay components. Of the 14 runs, four runs contain stopped time, resulting in much larger control delays than the other trips. Total stopped delay for the sampled runs are 98 seconds, which is about 50% of the total control delay. The stopped delay ranges from 12 to 46 seconds, and the minimum and maximum control delays are 1.1 and 63.9 seconds, respectively.

TABLE 1 Delay Computation Results for Sampled Runs

Sample #	Deceleration delay (sec)	Stopped delay (sec)	Acceleration delay (sec)	Control delay (sec)
1	3.9	0	1.8	5.7
2	8.7	0	5.7	14.4
3	3.7	0	1	4.7
4	2.7	0	1.7	4.4
5	5.3	12	5.1	22.4
6	3.4	0	1.5	4.9
7	1.9	0	1.6	3.5
8	1.4	0	0.7	2.1
9	7.6	26	12.6	46.2
10	2.7	0	3.2	5.9
11	7.7	14	9.6	31.3
12	1.7	0	0.1	1.8
13	10.6	46	7.3	63.9
14	0.2	0	0.9	1.1
Total	61.5	98.0	52.8	212.3

* Bandwidth for local quadratic regression smoothing = 2 seconds
* Control delay = deceleration delay + stopped delay + acceleration delay

Figure 5, which illustrates the compositions of delay components for the 14 sampled runs, shows that deceleration delays tend to be larger than acceleration delays for non-stopped runs, possibly due to cautious drivers slowing down before entering the intersection. In contrast, for four stopped vehicles, their average acceleration and deceleration delays are 8.7 and 7.8 seconds, respectively, indicating a slightly higher acceleration delay. Similarly, Mousa [5] reports that the average acceleration delay (11.4 seconds) is higher than the average deceleration delay (7.2 seconds) for the sampled 100 stopped vehicles. However, these observations, based on only four runs, may not truly reflect the characteristics of delay components, and thus, more detailed analyses are required using a sufficient number of samples.

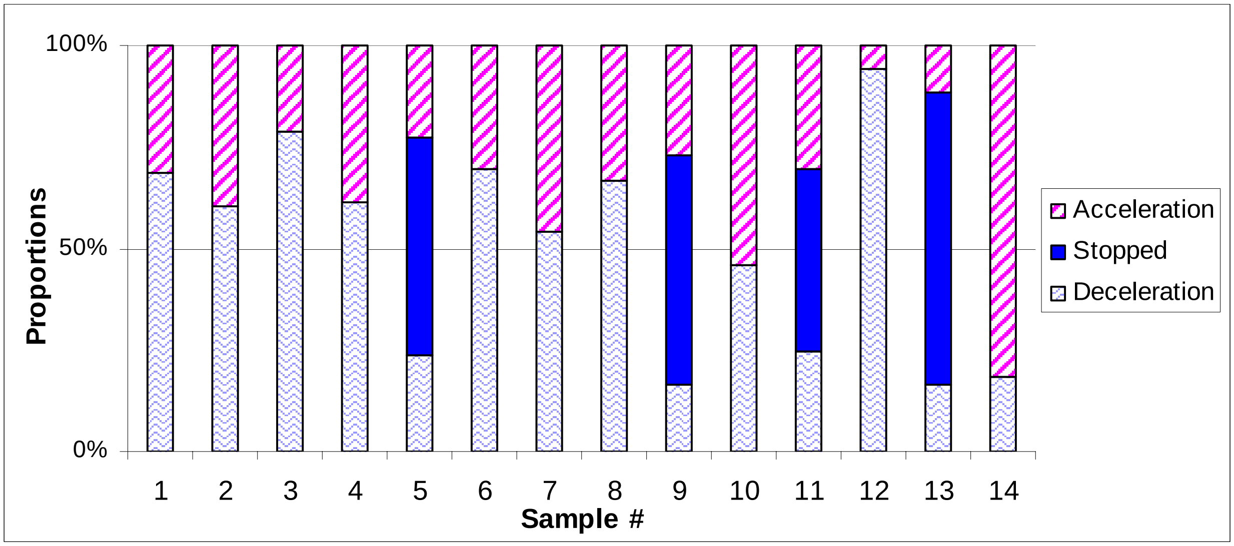


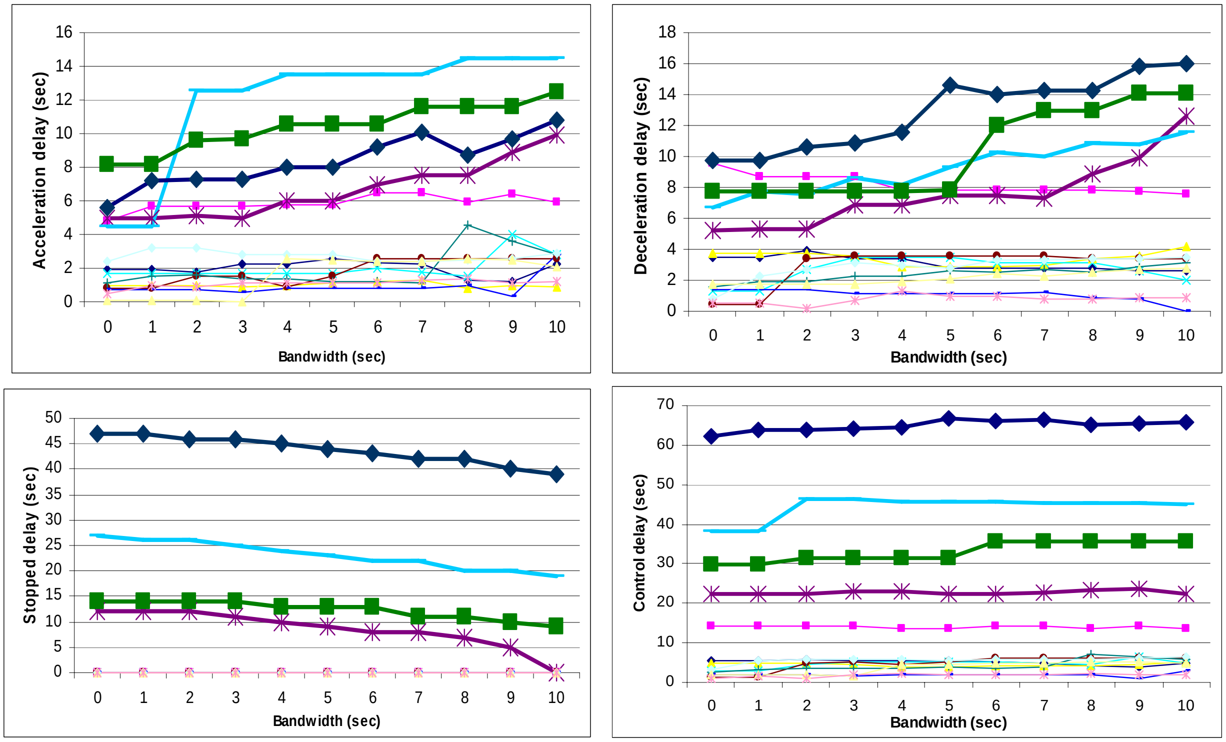
FIGURE 5 Composition of Deceleration Delay, Stopped Delay, and Acceleration Delay.

Effect of Smoothing Bandwidth Sizes on Delay Computation Results

The delay computation approach adopted in this paper includes a smoothing process for speed profiles. As mentioned before, the smoothing process should employ an appropriate bandwidth to reasonably locate the critical points associated with delay components. Unfortunately, no single rule guides the bandwidth selection, and thus, one should decide the bandwidth rather empirically. However, a narrower bandwidth, if possible, would be desirable since it minimizes the distortion of the original data by assigning more weights to the current data point and its neighboring data points.

The authors implemented a sensitivity analysis by changing the bandwidth from 0 to 10 seconds (zero bandwidth indicates no smoothing). Figure 6 shows how delay computation results change as the size of bandwidth increases or decreases for the 14 sampled runs. In general, acceleration and deceleration delays increase while stopped delay decreases with the size of bandwidth. This result is expected since a smoothed speed profile based on the wider bandwidth tends to increasingly smooth sharp edges, resulting in the detection of deceleration beginning points earlier and acceleration ending points later. In addition, the stopped time interval shrinks toward the middle point of the stopped time period. This phenomenon implies that the selection of a large bandwidth may produce unreasonable results. In fact, run #5 (marked by an *) actually had 12 seconds of stopped time, but the stopped time disappeared when the bandwidth reaches 10 seconds. Meanwhile, the changes in control delay are relatively insensitive to the size of the bandwidth due to the trade-off between stopped delay and deceleration/acceleration delay, as explained above.

From the perspective that the smaller bandwidth is desirable, a two-second bandwidth may be appropriate since the amount of delay tends to be stable after two seconds, as illustrated in Figure 6. The two-second bandwidth seems to be small enough not to distort the original profile while at the same time large enough to eliminate any minor speed changes. Note that since this tendency was observed only for 14 sampled runs on a specific roadway, further research efforts should be performed to generalize it.



* The zero bandwidth means that no smoothing process is applied to the speed profile.

FIGURE 6 Sensitivity of delay computation results to the size of bandwidth.

LIMITATION TO THE METHODOLOGY

Although the developed methodology was successfully applied to the test cases observed under normal traffic conditions, its application may falsely detect the critical points under congested conditions which incur complex vehicle activities near intersections. One such example is illustrated in Figure 7, in which the speed profile indicates that the vehicle stopped twice in the upstream of the intersection and experienced a speed drop after passing the intersection. However, the developed methodology captures only the stop which occurred nearest to the intersection and detects early the ending point of acceleration due to the speed drop, resulting in the measured control delay significantly less than the actual one. In fact, the developed methodology identifies that the starting point of the control-affected time period occurred at 76 seconds, but it should be at approximately 20 seconds, when the vehicle first started to decelerate. In addition to the congested conditions, closely spaced intersections, for which desired speed is rarely observed, may induce inaccurate computation results for control delay, requiring cautions in applying and interpreting the resulting outputs. Future research efforts will enhance the proposed methodology by considering the vehicle activities observed under congested conditions and at closely spaced intersections.

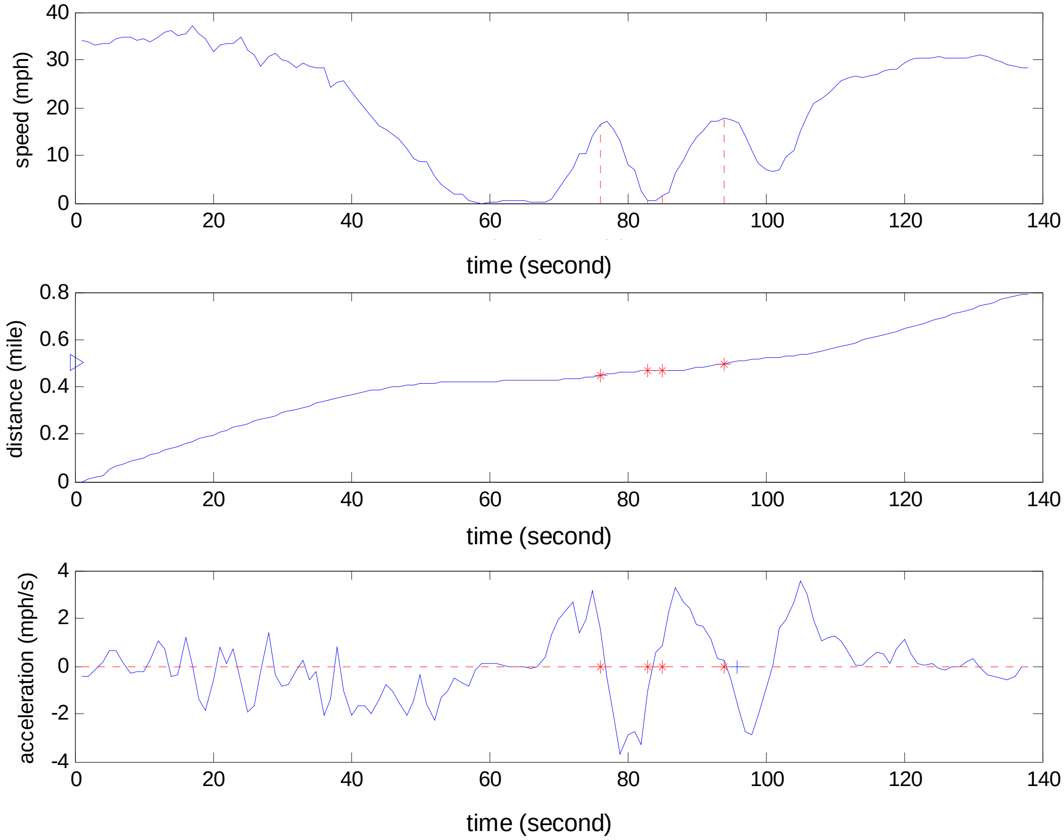


FIGURE 7 Application to over-capacity conditions.

CONCLUSIONS

The authors proposed a new methodology for measuring control delay, including deceleration delay, stopped delay, and acceleration delay, using speed profiles obtained from GPS devices. The proposed methodology is based on the observations of speed changes of vehicles passing through intersections and implemented by developing an acceleration-based algorithm that detects deceleration onset points and acceleration ending points. In addition, stopped time periods were directly identified from de-noised speed profiles, not from acceleration profiles. For de-noising speed profiles, the quadratic local regression approach using a two-second bandwidth was applied.

The proposed approach was successfully applied to real-world GPS-derived speed profiles, reasonably computing each delay component, as suggested by the plots displaying the locations of the critical points. In addition, the relative magnitudes of delay components were compared, and it was noted that deceleration delay tends to be larger than acceleration delay for vehicles with zero stopped delay. Finally, the sensitivity analysis of the bandwidth indicated that the size of bandwidth may affect the magnitude of each delay component. However, control delay, the sum of the three delay components, appeared to be less sensitive to the size of bandwidth due to the trade-off between the delay components.

The benefit of the proposed approach is that it can provide an automation process for the analysis of large-scale instrumented vehicle data. Without an adequate automation process, data analyses on large data sets would be impractical in both time and cost. More importantly, the automation process provides consistent results, which are unlikely obtained from a manual process. However, the proposed approach still needs to be fine-tuned to handle over-capacity conditions and closely spaced intersections, for which the detection of critical points is likely to be considerably difficult. Once this fine-tuning is completed, the proposed approach will be capable of playing an important role in identifying the characteristics of control delay components under various traffic and roadway conditions.

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