Detector Placement Strategies for Freeway Travel Time Estimation

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***Abstract*—One popular class of approaches to estimate freeway corridor travel time is based on measured or estimated speed data from roadside detectors. In most estimation practices, using either simulated or actual data, detectors are assumed to evenly distribute with a close spacing of around half mile. Unfortunately, this detector location scheme will be too costly for most freeway corridors under limited budget. To contend with this issue, this paper examines some widely used estimation algorithms under various traffic conditions with different detector spacing, and then proposes a set of strategies for locating detectors. Numerical results, based on traffic conditions on I-70 corridor of Maryland, have demonstrated the promising properties of our proposed strategies under recurrent congestion pattern.**

I. Problem Nature

As a direct indicator of network congestion level, travel time information plays an important role in the Advanced Travelers Information System. To set up such a system for I-70, a major commuting corridor in Baltimore region, this research project aims to estimate travel time for a freeway segment of more than 20 miles, especially during morning peak hours. The study area, as illustrated in Figure 1, extends from the interchange with MD27 to the interchange with I-695, the Baltimore Beltway.

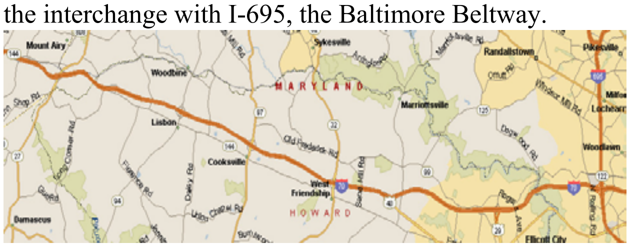

Figure 1. Illustration of the Study Area

Freeway travel time estimation has been a widely studied issue in the literature. All existing methods can be classified into four classes. The first class of methods measures travel time directly with probe vehicles or other advanced technologies, such as license plate matching or automatic vehicle identification [1]. The second class of approaches uses point speed, either measured or estimated from detector data, to generate section wide speed and thus to computes travel time [2-4]. The third class tries to reconstruct the relations between travel time and detected flow, speed, occupancy data with regression models or neural network or macroscopic flow equations [5, 10]. The last class of methods tries to estimate travel time by comparing other measurements from up/downstream locations, such as recognizing platoons, employing flow conservation law, checking flow correlation, or building models between up/downstream flows [6-9].

Due to the budget constraint in the current phase, the data source available for this study can only come from a maximum of 10 roadside detectors. Also by taking into consideration the heavy congestion during morning peak hours, the second class of approaches based on detected data appears to be the most viable option among all aforementioned methodologies. However, most related studies in this category were developed on an even detector spacing of around half mile [11] or less (500m) [12], which is apparently not the case here. Thus, selection of detector locations and estimation algorithms so as to best estimate travel time has emerged as the priority research issue in this study.

This paper is organized as follows. Next section gives a review on some widely used travel time estimation algorithms based on speed data. Then, a research scheme is defined in section 3 to test these algorithms under various traffic conditions with different detector spacing. Section 4 presents the experimental results and proposes a set of strategies for locating detectors. Applications of these strategies for the I-70 corridor of Maryland under recurrent congestion are reported in the last section.

II. Literature Review

As the base case, the estimation of travel time between two detectors, denoted as section level travel time estimation [12,13], is first discussed. This is followed by studies for multiple detectors, or corridor travel time estimation. To facilitate the presentation, Figure 2 illustrates a typical freeway corridor, showing only one direction for simplicity.

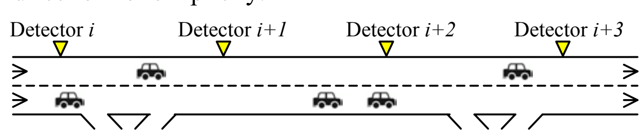

Figure 2. An illustration of a typical freeway corridor

Some important notations used hereafter are given below. d_i is the location of detector *i*. $v_i(t)$ and $q_i(t)$ are

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speed and flow measured by detector i at time t. $x(t)$ and $v(t)$ are vehicle location and speed at time t. T^i is vehicle departure time from detector i. $tt_{i,j}(t)$ is the travel time between detector i and j, if departing from i at time t.

A. Section level travel time estimation

The first type of methods is called Constant Speed Based (CSB) algorithms, where one computes the travel time from the section length and the assumed constant speed between two detectors, estimated with either of the following ways:

--The detected speed from the upstream detector at vehicle's departure time:

$$v(t) = v_i(T^i) : x(t) \in (d_i, d_{i+1}) \quad 1)$$

--The average or minimum of the speed from two end detectors at a vehicle's departure time [11,14,15]:

$$v(t) = [v_i(T^i) + v_{i+1}(T^i)]/2 : x(t) \in (d_i, d_{i+1}) \quad 2)$$

$$v(t) = \min\{v_i(T^i), v_{i+1}(T^i)\} : x(t) \in (d_i, d_{i+1}) \quad 3)$$

$$v(t) = 2/[1/v_i(T^i) + 1/v_{i+1}(T^i)] : x(t) \in (d_i, d_{i+1}) \quad 4)$$

--The linear combination of the speed from the upstream detector at the vehicle's departure time and the speed from the downstream detector at the vehicle's arrival time [16].

$$v(t) = \alpha v_i(T^i) + (1-\alpha) v_{i+1}(T^i + tt_{i,i+1}) : x(t) \in (d_i, d_{i+1}) \quad 5)$$

The second type is called Piecewise Constant Speed Based (PCSB) algorithms, which assume that a vehicle discretely updates its speed at certain update intervals that are determined in two ways:

--The detector aggregation interval Δt, i.e., speed is updated every time the detectors get new data [12,13];

--The time computed from detector aggregation interval Δt, previous vehicle speed v and backward shockwave speed during congestion u_c [17]

$$update \quad interval = \Delta t \times u_c / [u_c + v] \quad 6)$$

When the update interval is reached, the speed gets updated using revised Equation 1-4 with the departure time T^i substituted with the update time. The segment travel time can be obtained by comparing the updated vehicle location with downstream detector location.

The third type is called Piecewise Linear Speed Based (PLSB) algorithms, which assume a vehicle continuously updates its speed based on its current distance to the upstream detector as in Equation 7. The travel time can then be obtained by solving this differential equation [4,12].

$$v(t) = v_i(t) + \frac{x(t) - d_i}{d_{i+1} - d_i}[v_{i+1}(t) - v_i(t)] : x(t) \in (d_i, d_{i+1}) \quad 7)$$

B. Corridor travel time estimation

Corridor travel time can be calculated from estimated travel time on each segment. Generally, there are two kinds of estimated corridor travel time, namely, instantaneous or actual travel time.

The instantaneous corridor travel time is obtained by adding the (weighted) section travel time, estimated at a vehicle's departure time from the first detector [4,18]:

$$tt_{i,j}(T^i) = \sum_{k=i}^{j-1} tt_{k,k+1}(T^i) \quad 8)$$

$$tt_{i,j}(T^i) = (d_j - d_i) \times \frac{\sum_{k=i}^{j-1}[tt_{k,k+1}(T^i) * q_k(T^i)]}{\sum_{k=i}^{j-1}[(d_{k+1} - d_k) * q_k(T^i)]} \quad 9)$$

The instantaneous corridor travel time assumes traffic conditions on the corridor remain unchanged during the entire travel period, which may introduce large errors if the corridor is long and the traffic condition varies significantly. To avoid this problem, the corridor travel time can be computed with the iterative equation [19]:

$$tt_{i,j+1}(T^i) = tt_{i,j}(T^i) + tt_{j,j+1}(T^i + tt_{i,j}(T^i)) \quad 10)$$

C. Other critical issues affecting estimation accuracy

The successful applications of the above algorithms all have to take into account two important issues, namely the relation between space mean speed and time mean speed as well as the concept of Representative Lane.

Most studies in the literature of speed-based travel time estimation have identified the need of using space mean speed v_{sms}, which is the total travel distance divided by the total travel time of all vehicles passing a time-space unit $\{(x,t) : x \in [x_1, x_2], t \in [t_1, t_2]\}$. Yet the speed measured from detectors is time mean speed v_{tms}, which is the averaged vehicle speed over the detector aggregation interval Δt. Although these two speed measurements are similar under stationary and homogeneity conditions (such as free flow) [12], time mean speed may greatly exceeds space mean speed under heavy congestions, especially under stop-and-go conditions. This will result in underestimated travel time. Assuming the availability of local speed variances σ_{tms}^2, some studies use the following equation to correct the bias from speed measurements [20]:

$$v_{sms} = (v_{tms} + \sqrt{v_{tms}^2 - 4\sigma_{tms}^2})/2 \qquad : \sigma_{tms}^2 < v_{tms}^2/4$$

Since the above relation is applicable within limited range, and the detector may not be sufficiently accurate at low speeds or under stop-and-go traffic conditions, some researchers suggest that one may use speed data estimated from the observed speed flow relation [19].

Another issue occurred in travel time estimation is the computation of speeds for a freeway segment of multiple lanes, where speed at a specific location is generally computed as the average or flow weighted average speed from all detectors at the location. However, flows passing a location may have different destinations, which may cause apparently different traffic patterns in different lanes. This means when we estimate travel time between certain origin destination pairs, information from some lanes should be disregarded. In such studies, those lanes that are selected to compute the average speed of a target OD trip are called Representative Lanes.

Figure 3 presents an example for the Representative Lane application. In this case, since there are a large number of vehicles leaving the off ramp with limited capacity, a queue will form at the upstream segments. In the farther upstream end, two lanes tend to show similar pattern because vehicles with different destinations will use both lanes. But in the immediate upstream region, the left lane will have a much higher speed because almost all vehicles leaving via the off ramp have already changed to the right lane. Thus, to compute the travel time for vehicles continuing travel on mainline links, the left lane at detector $i+2$ will be taken as the Representative Lane.

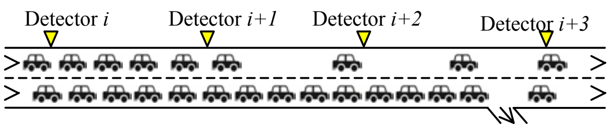

Figure 3. Illustration of the Representative Lane

III. RESEARCH METHODOLOGY

Due to the cost associated with detector relocation in practice, it is unrealistic to test the effects of different detector locations on travel time estimation with a real-world system. Thus, this study will analyze some widely used estimation algorithms under various traffic conditions and different detector spacing with a simulated system, which is built up with the widely applied microscopic simulation software, CORSIM.

A. *Experimental Design*

The simulation experiments include the following three different types of freeway segments.

--Freeway segments under free flow conditions

--Freeway segments evolving from the free flow condition to segment wide queue

--Freeway segments evolving from the free flow condition to partial queue.

Under each segment type, the study will investigate two categories of scenarios.

--Detectors are evenly distributed in scenarios under Category 1, but with different spacing.

--Two end detectors are fixed in scenarios under Category 2, with a third detector moving in the segment from upstream to downstream in different scenarios.

Thus, the definition of a scenario will have two distinctive features, namely a segment type related to congestion level and a detector location scheme. To improve the robustness of the experimental results, three random runs will be performed under a specific scenario. Detector data are obtained from simulation output. True travel time data are calculated by tracing every vehicle.

Note that for both the operational and cost concerns, the most dense detector location scheme on a road segment will be even distributed spacing of 1000ft. Based on the logic of point-speed algorithms, this extremely short detector spacing should provide sufficiently reliable travel time estimate.

B. *Algorithm and MOE Selection*

In this paper, four widely used algorithms for section travel time estimation will be tested.

--CSB1 algorithm based on Equation 4;

--CSB2 algorithm based on Equation 2;

--PCSB algorithm with fixed update interval; and

--PLSB algorithm.

The estimation of corridor travel time is based on the iterative procedure in Equation 10. For performance evaluation, the study applies the following two indicators:

$$AveErr = \sum\nolimits_{departure\ \ interval\ \ t\in T} \left|\overline{tt}(t) - tt(t)\right| / \left|T\right|$$

$$AveReErr = \sum\nolimits_{departure\ \ interval\ \ t\in T} \left|\overline{tt}(t) / tt(t) - 1\right| / \left|T\right|$$

Here $\overline{tt}$ is the estimated travel time while tt is the true travel time. T refers to the set of departure intervals.

IV. SIMULATION RESULTS ANALYSIS

A. *Free flow segments*

The first case simulated a 48,000ft freeway segment under free flow traffic conditions. Figure 4 illustrates the change of the two performance indicators with increasing detector spacing, given an even distribution of detectors.

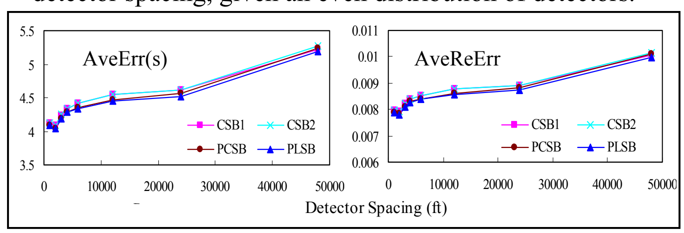

Figure 4. Algorithm Performance on Free Flow Segments

In general, both performance indicators tend to deteriorate as the detector spacing increases, regardless of the differences in algorithms, but all at a negligible rate. As the detector spacing increases from 1000ft (49 detectors) to 48000ft (2 detectors), the maximal error has changed less than 6 seconds. These results indicate that it is sufficient for both monitoring and travel time estimation as long as a reliable detector station is placed at both ends of a free-flow roadway segment.

B. *Segments fully covered with queue*

When detectors are evenly distributed on a simulated freeway segment of 12,000ft, the change of the two performance indicators with respect to detector spacing is shown in Figure 5.

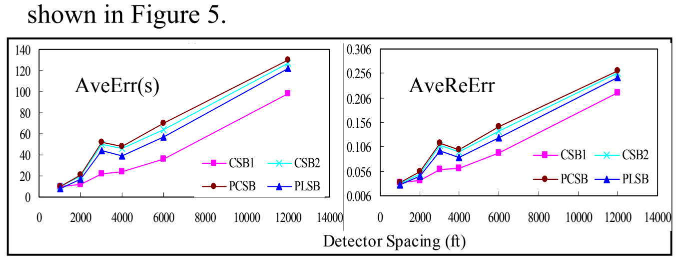

Figure 5. Algorithm Performance on Congested Segments – Detectors Evenly Distributed

As expected, both performance indicators tend to deteriorate as the detector spacing increases. The deterioration rate is much faster than that for the free flow segment. As the detector spacing increases from 1000ft (13 detectors) to 12000ft (2 detectors), the maximal error changes from 40-60 seconds to around 450 seconds, while *AveErr* changes from 10 seconds to more than 100 seconds. These results clearly indicate that for a congested segment, more detectors are sure to provide a better estimate of travel time variation.

Next, the paper tests if two end detectors are set, where is the best location for the third detector within the segment. Figure 6 illustrates the change of the two performance indicators with the distance between the third and the upstream detector on the 12000ft segment.

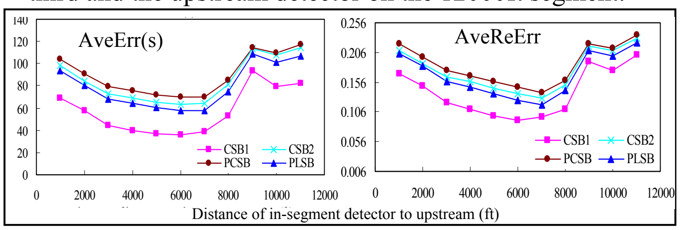

Figure 6. Algorithm Performance on Congested Segments –Detectors Unevenly Distributed

As shown above, when the third detector approaches the mid-point of the segment, both performance indicators tend to improve, although locations near the downstream detector suffer from longer period of congestion.

C. Segments partially covered with queue

This section simulates a 12,000ft freeway segment. Three different cases are tested with the maximal queue varied from 3000ft to 9000ft. Figure 7 illustrated the change of the two performance indicators with respect to detector spacing when detectors are evenly distributed.

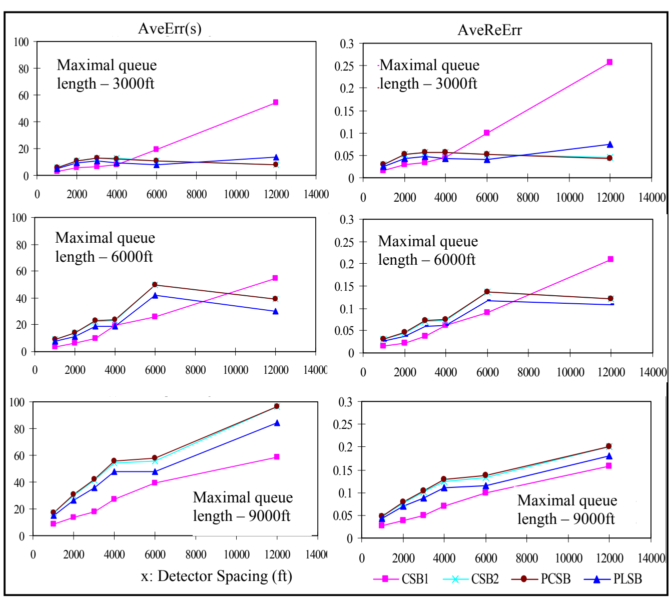

Figure 7. Algorithm Performance on Segments with Partial Queue – Detectors Evenly Distributed

As in Figure 7, CSB1 algorithm shows a performance pattern different from the other three algorithms under various detector spacing and maximal queue length. To further compare these algorithms, Figure 8 illustrates the change of *AveErr* and *AveReErr* with detector spacing and maximal queue length for CSB1 and PLSB algorithm.

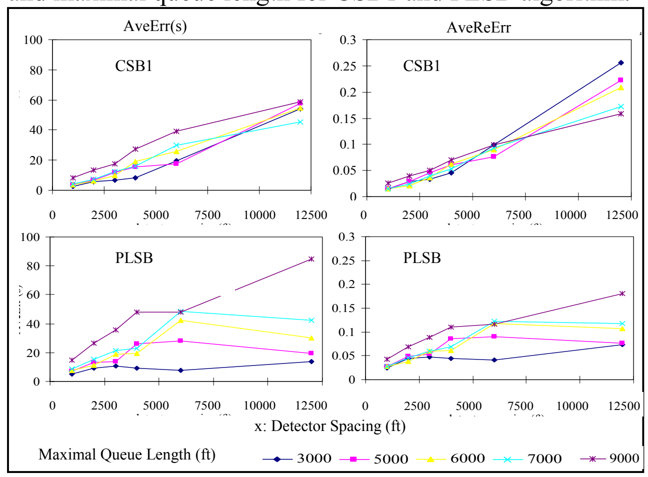

Figure 8. Comparison of CSB1 and PLSB algorithm

As for CSB1 algorithm, one can find

--The performance of CSB1 algorithm indicates a clear deterioration pattern as the detector spacing increases, regardless of the maximal queue length.

--Based on the same detector spacing, the indices *AveErr* and *AveReErr* are relatively stable as the maximal queue increases.

As for other three algorithms, it is observed that

--The change in algorithm performance with respect to increased detector spacing is somewhat different under different maximal queue lengths. When the maximal queue is short, the influence of detector spacing is not apparent. As the maximal queue grows, the performance clearly deteriorates with increased detector spacing.

--Based on the same detector spacing, both performance indices will go up as the maximal queue increases, especially under large detector spacing.

From Figure 5-8, it can be found that CSB1 algorithm is a more robust choice among the four algorithms tested. It almost always works better under detector spacing of no more than one mile. If detector spacing is larger, CSB1 algorithm is not preferred unless the maximal queue occupies a large portion of the segment.

Next we want to test if two end detectors are set, where is the best location for the third detector within the segment. Figure 9 presents the change of the two performance indicators with respect to the distance between the in-segment and the upstream detector.

As indicated, the location of the third detector has different effects under different maximal queue length.

--As to the CSB1 algorithm, a location of the third detector to divide free flow segment and segment with queue works when the maximal queue is short. But the advantage brought by this will be exceeded by the large error due to longer congested segment as the maximal queue length increases. Thus, the preferred location for third detector will approach the mid-point of the maximal queue instead of the end of the maximal queue.

--For the three algorithms except CSB1 algorithm, the mid-point of the maximal queue length is always a good position for the third detector. Yet the influence of the third detector's location is insignificant when the maximal queue is short.

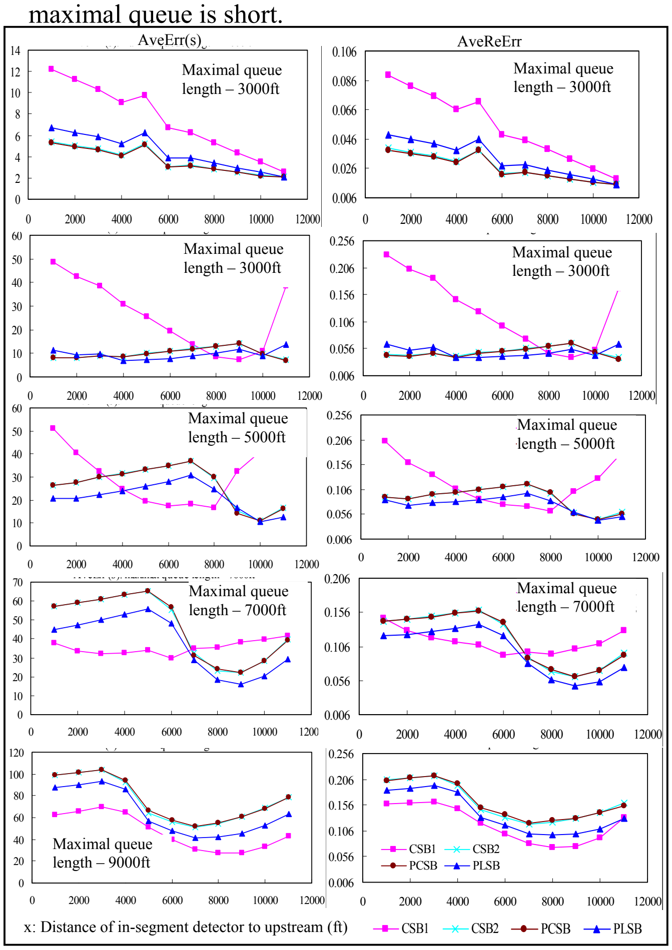

Figure 9. Algorithm Performance on Segments with Partial Queue – Detectors Unevenly Distributed

Finally Figure 6 and 9 also indicate the estimation performance for segments of different maximal queue length, similarly with 3 properly located detectors. For the same segment, estimation accuracy generally deteriorates as the maximal queue increases. Yet for CSB1 algorithm, the estimation error keeps around a level similar to that under full queue conditions if the maximal queue is over 50% of the segment length. Because of its robustness, only CSB1 algorithm will be discussed in later sections.

V. DETECTOR LOCATING STRATEGIES

Based on the experiment results from last section, this study summarizes some rules for locating limited number of detectors as below:

--Rule 1-1 for segments partially covered with queue: it is preferred to divide free flow part and congested part if the maximal queue is only a small part of the segment length (less than 50%)

--Rule 1-2 for segments partially covered with queue: the mid-point of the maximal queue is a preferred detector location if the maximal queue takes a large percent of the segment length (more than 50%).

--Rule 2 for free flow segment: two end detectors will be enough to control estimation accuracy.

--Rule 3 for segments that would be fully covered with queue: an even detector spacing is preferable

Based on these aforementioned rules, this study comes out an iterative procedure for locating detectors, via applying Rule 1-3 for every three consecutive detectors.

--Step 1: Divide a real-world freeway corridor into several segments partially covered with queue;

--Step 2: Locate all other detectors evenly onto those segments based on segment length;

--Step 3: Check if there are detectors within two detectors that locate on the same free flow segments;

○ If yes, remove these detectors based on Rule 2. Then re-define segments partially covered with queue with un-removed detectors, and go to Step 2.

○ Otherwise go to step 4;

--Step 4: Compare the length of each free flow segment with the detector spacing on its immediate downstream segment covered with queue.

○ If the free flow segment is longer, move the detector at the downstream end of the free flow segment to the end point of maximal queue; Go to step 2

○ Otherwise, keep the detector as it is; Go to step 5

--Step 5: Stop and return current detector locations

VI. TESTING OF THE LOCATION STRATEGIES ON I-70

Our study network, as described in the introduction, is a 20 miles long segment on the major commuting corridor I-70 in Baltimore region. The daily recurrent congestion pattern during the morning peak hour is as follows.

--Segment between MD 27 to MD40 (0- about 74000ft): free flow segment

--Segment between MD40 to MD29 (around 74000ft-94000ft): partially covered with queue. The start of queue is between 93000ft and 94000ft, while the end of the maximal queue is between 78000ft and 79000ft

--Segment between MD29 to I695 (around 94000ft-11700ft): partially covered with queue. The end of the maximal queue is between 107000ft and 108000ft.

Using the procedure in last section, Figure 10 gives the preferred locations for the 10 detectors.

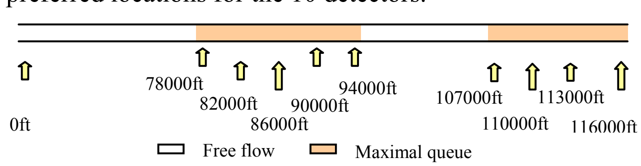

Figure 10. Unequal Spacing Detector Locating Plan

Since both free flow segments are long compared to their immediate downstream segments containing congestion, the detector location plan ends up as intuition:

--Divide free flow segments with congested segments

--Put other detectors evenly on congested segments

To test the effectiveness of this unequal-spacing detector locating plan, this study denotes this plan as Plan 0 and compares it with two other detector locating plans.

--Plan 1: even distribution with 10 detectors

--Plan 2: even distribution with 3000ft spacing

The comparison uses data collected in a simulation environment built in the microscopic simulation software CORSIM. Both the network and the model input are based on actual traffic data of the I-70 corridor. Table 1 presents the two performance indicators, while Figure 11 indicates the distribution of the estimation error.

Table 1. Comparison of *AveErr* and *AveReErr*

Detector Plan	0	1	2
AveErr (s)	67.77	138.64	73.46
Max Error (s)	321.80	481.34	250.10
AveReErr	3.72%	7.53%	3.70%
Max Relative Error	18.41%	33.18%	11.24%

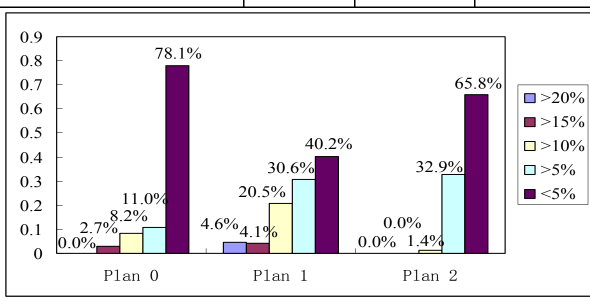

Figure 12. Distribution of estimation error

As illustrated, CSB1 algorithm with the unequal detector spacing plan can yield a fairly good estimate for the freeway corridor compared with the traditional detector location plan, Plan 2. Besides, Plan 0 only uses 10 detectors instead of 40 detectors in Plan 2.

VII. CONCLUSIONS

This paper reviews some widely used travel time estimation algorithms based on point speed data. To identify the best detector locations under a limited number of detectors, these algorithms are examined under various traffic conditions and detector location schemes. Research findings mainly focus on three types of comparisons.

--Comparison of travel time estimation performance using different algorithms;

--Comparison of travel time estimation performance under different traffic conditions, including both free flow and various sizes of maximal queue;

--Comparison of travel time estimation performance under various detector location plans.

Based on the experimental results, this study proposes three rules and an iterative procedure for locating limited number of detectors. The numerical experiment on the I-70 corridor of Maryland has shown the potential of the detector placement strategies under recurrent congestion.

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