

Estimating Traffic Speed with Single Inductive Loop Event Data

Xiao-Yun Lu, Pravin Varaiya, Roberto Horowitz, Zhaomiao Guo, and Joe Palen

The estimation of traffic speed based on loop detector occupancy is a long-standing problem that is critical to traffic management and control. Single-loop detector stations are still popular in highway traffic systems in practice. Although dual loop stations could generate more accurate speed estimation with event data, updating single loops to dual loops is costly. Most previous work, such as the g -factor method on speed estimation with a single-loop system, used aggregated data and assumed a known effective vehicle length. However, those methods did not always produce good results, particularly in traffic transition phases. This paper proposes a new approach using event data and mode occupancy within a moving window of variable length to estimate the effective vehicle length, or g -factor. Berkeley Highway Laboratory dual loop data with a 1-Hz update rate and 60-Hz information were used for algorithm validation and reliability tests. The speed estimated from the corrected dual loop data was used as the ground truth for comparison. Root mean square error was used to quantify the discrepancy. Results showed that the proposed approach generates very satisfactory speed estimations compared with estimations from dual loop stations. This algorithm can be run at the control-cabinet level, in which event data of an individual loop from a 170 or 2070 controller are available without the need of any hardware modification. These controllers have the processor capabilities to handle data in real time.

Traffic speed estimation is critical to active traffic management and advanced traveler information systems (1). Traffic speed, flow, and density are the fundamental traffic state parameters for most applications. Active traffic management needs accurate and reliable speed estimation with the shortest possible time delay to determine control strategies. Advanced traveler information systems need link speed to estimate factors such as travel time. Traffic speed estimation using healthy dual loop detectors can be accurate if event data are used for this purpose, as individual vehicle speeds can be obtained from the on and off times of the upstream and downstream loops (2). However, most loop stations in traffic operation in California are still single loops. Because updating single loops to dual loops is a costly

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process, improving single-loop traffic speed estimation is necessary to meet the needs of active traffic management and advanced traveler information systems operating on limited budgets. Although several algorithms have been developed for this purpose and reported in the literature, single-loop speed estimation, including the g -factor method used in the PeMS system, is still not good enough in practice (3, 4). Improving this situation is the motivation for this work.

Vehicle lengths on the highways have particular distributions; most vehicles are passenger cars with an average length of 14 to 17 ft. Mode occupancy (or duration) is generated statistically on a fixed loop of all passing vehicles. An obvious idea is to use this mode occupancy characteristic to give a better estimation of effective vehicle length for traffic speed estimation. The critical issue is how to properly extract the mode occupancy (or equivalently, the mode vehicle length plus the loop length) in a moving window.

The main characteristics and contributions of this paper include

- Assuming that the mode vehicle length for each tolling period is known or can be calibrated for a specific road section (in California, this length is 15 ft),
- Using variable-length time windows for mode vehicle data selection to capture traffic transition dynamics and to reduce induced time delay,
- Using mode vehicle length (occupancy) for accurate speed estimation and for capturing traffic transitions,
- Using speeds estimated from the corresponding dual loop station of the Berkeley Highway Laboratory (BHL) for algorithm validation, and
- Using root mean square error (RMSE) to quantify discrepancies.

Quantitatively, RMSE is approximately 2 to 3 mph for a healthy station. This value indicates that the performance of the proposed method is very close to the speed estimation from dual loop stations, and that the method could be applied directly to all the single-loop detector stations on a highway as long as real-time event data were available, which is the case for both 170 and 2070 controllers. These controllers also have the processor capabilities to handle data in real time.

The paper is organized as follows: the next section reviews some relevant literature on this topic; the third section details the proposed algorithm; the fourth section considers algorithm validation and error analysis using field data; and the final section concludes the paper.

LITERATURE REVIEW

This section reviews only a small portion of the most relevant research on traffic speed estimation based on loop detectors.

An introduction to the physical principles of inductive loop detectors, which are very useful to understanding the sensitivity

setting of a loop, is available (5). Physical characteristics have been discussed in detail for several loop shapes (6). The main factors that affect the inductance of the loop include loop shape and size, vehicle shape and size, distance to the ground, number of turns of the circuits, and location with respect to the loop. These factors are important to understand the loop data characteristics and to analyze both single and dual loop data for traffic state parameter estimation.

Preliminary time mean speed estimation was proposed by Dailey (7). A continuous flow model is used to predict the auto and cross-correlation function that is used to estimate delay time between loops half a mile apart. This model could be considered as distance mean speed estimation. Coifman used dual loop event data for speed estimation, which has an obvious advantage because the on-off time instants of each loop are available. The method also implies the advantages of using event data for speed estimation (2). Dailey proposed a statistical analysis method by explicitly introducing the variance of the measurement while deducing the distance mean speed from flow and occupancy (8). With such a formulation, a Kalman filter is used to further smooth the speeds over time. Coifman intended to improve the effective length for improving the distance mean speed estimation (9). He observed that for the same section of road, different times of day result in different estimations of length. Chen et al. used aggregated single-loop detector data for traffic time mean speed estimation (10).

Hellinga indicated that the former approaches for traffic speed estimation over single-loop methods had an RMSE of about 23%, which was significant (11). This work intended to improve time mean speed estimation accuracy using real-time estimated effective vehicle length during each polling interval. The work proposed an approach for speed estimation in a situation in which single loops and dual loops are mixed. The work used the effective vehicle length estimated from dual loop stations for single-loop speed estimation. The results indicated significant improvement on speed estimation accuracy by 41% after applying exponential smoothing to the flow. It is clear that this study implicitly assumed that upstream and downstream stations have the same effective vehicle length estimation. This assumption is true unless the vehicle types are evenly distributed along the link. Otherwise, even with a first in, first out assumption, a time delay is implicitly introduced because the platoon of vehicles passing the upstream loop will take some time (depending on traffic speed) to reach the downstream loop.

Wang and Nihan used single-loop measurements to provide speed and vehicle classification estimates (12). Vehicles were divided into two types (short and long) according to the vehicle length, with 11.89 m as the threshold. The algorithm consisted of three steps: finding the intervals (dwell time of vehicles over a loop in 20 s) of long vehicles; using measurements of short-vehicle time intervals for speed estimation with constant vehicle length; and identifying the volumes for the time intervals of the long vehicles using the estimated speed.

Coifman et al. examined new aggregation methods to reduce estimation errors (13). The work computed the speed from the median occupancy to improve speed estimation to reduce the variance of measurement caused by a wide range of vehicle lengths in actual traffic. The work showed that using 5-min aggregated data would produce satisfactory results. Hazelton estimated traffic speed by using single-loop detector aggregated vehicle counts and occupancy with a statistical method (14).

Rakha and Zhang clarified time mean speed at fixed loop locations and space mean speed and provided the relationship between

the two (15). Those differences are important for the type of sensors used in traffic state estimation and for applications in modeling, simulation, and traffic management and control. This paper also reviewed several other approaches for speed estimation.

All the work discussed above indicated or implied that vehicle effective length is critical in speed estimation from single-loop detector data if occupancy and vehicle count in the polling time interval measurement are reasonably accurate. Therefore, to improve the estimation of the effective vehicle length would improve the speed estimation. Clearly it cannot be assumed that over a given time interval traffic is free flow and most vehicles have the same length, since different vehicle types are mixed in practice, particularly in heavy-traffic corridors such as I-80 in the San Francisco Bay Area in California. Extracting effective vehicle lengths for more accurate estimation still needs consideration.

SPEED ESTIMATION ALGORITHM

To address the difficulties that all vehicle types may appear at any time, that traffic flow changes significantly around peak hours, and that an incident or accident may occur, this paper proposes a new approach with three distinctive characteristics for speed estimation based on single-loop data: (a) using the event data (basically the on-off times) of a loop, which distinguish individual vehicles; (b) extracting mode occupancy (or duration) in the polling interval, as the mode occupancy in California is known to be 15 ft; and (c) using extracted mode duration for speed estimation. Clearly, only event data could provide mode occupancy.

Basic Concepts

The following basic concepts are used throughout the paper:

- Dwell time (or duration, i.e., on time minus off time). Dwell time of individual vehicles over a loop is available if the data have 60-Hz information.
- Moving window. Traffic changes are analyzed within a moving window up to the current time interval. The window length is directly related to the time delay induced in the analysis, so that a longer window length will induce more time delay.
- Mode dwell time. The following procedure is used to determine mode dwell time:
 - Deposit all dwell times of individual vehicles obtained in the moving window into N_b evenly distributed bins;
 - Choose the bin with the largest deposits, which corresponds to the mode duration; and
 - Average the dwell times of all the deposits in the bin to produce the mode duration.
- Mode occupancy. Mode occupancy is defined as the ratio of the mode dwell time to the sample time interval. For most BHL data, the sample time interval is 1 s.

Algorithm Development

The algorithm development process includes several steps: preliminary data selection; extraction of vehicle mode dwell time (or mode occupancy) within an appropriate moving window; filtering of the mode occupancy to reduce noise; estimation of speed based on

the g -factor method; and capturing transition phase dynamics of traffic for better estimation.

Speed Estimation Algorithm

The g -factor algorithm (shown below) used in this paper essentially calculates the space mean speed (v). The g -factor is an average of vehicle length; its method is calculated as follows:

$$v(t) = g(t) \times \frac{c(t)}{o(t) \times T} \quad (1)$$

where

T = polling time interval;

$v(t)$ = space mean speed;

$g(t)$ = effective vehicle length plus loop length;

$c(t)$ = vehicle count during time interval T , which is flow at loop detector; and

$o(t)$ = the fraction of time during this period that detector senses occupancy.

For event data (for individual vehicles) the parameters in Equation 1 are replaced with its mode value, and $c(t) = 1$. Equation 1 becomes

$$v(t) = \frac{g_m(t)}{o_m(t) \times T} \quad (2)$$

where $g_m(t)$ is the mode vehicle length plus loop length (21 ft), and $o_m(t)$ is occupancy, the percentage of time within the detection period when a vehicle is over the loop.

Mode occupancy $o(t)$ and mode dwell time (duration) have the following relationship:

$$o_m(t) = \frac{\text{dur}(t)}{T}$$

where $\text{dur}(t)$ is mode dwell time in time interval T .

An equivalent formula to calculate speed from Equation 1 by mode dwell time can be obtained as follows:

$$v(t) = \frac{g_m(t)}{\text{dur}(t)} \quad (3)$$

The formula for point mean speed estimation based on mode occupancy (Equation 1) and mode dwell time (Equation 2) are summarized as the following:

$$v(t) = \eta \frac{g_m(t)}{o_m(t) \times T}$$

$$v(t) = \eta \frac{g_m(t)}{\text{dur}(t)} \quad (4)$$

where η is a sensitivity parameter. Using Equation 1 to estimate speed would require counting the number of vehicles during (moving window) time interval T . Equation 4 would not have such a requirement, but the equation also needs data; that is, the sampling rate of the loop detector should be fast enough to capture individual vehicle activation. Introducing η as a parameter is based on the consideration that dwell time (or equivalently, occupancy)

depends on the sensitivity selection of the loop detector card and also the installation of the loop. Data analysis showed that η varied between 0.9 and 1.0.

Preliminary Data Selection

Maximum and minimum dwell times (durations) will change according to the traffic and the vehicle type. Because of sensor measurement noise and errors, it is necessary to select data preliminarily with a bound checking. The following upper and lower bounds for vehicle dwell times over a loop are estimated:

$$T_{\text{on}}^{\text{min}} = \frac{(L_{\text{loop}} + L_{\text{veh}}^{\text{min}})}{V_{\text{max}}} = \frac{(3 + 1.83)}{31.29} = 0.15 \text{ s}$$

$$T_{\text{on}}^{\text{max}} = \frac{(L_{\text{loop}} + L_{\text{veh}}^{\text{max}})}{V_{\text{min}}} = \frac{(18.5 + 1.83)}{2.24} = 9.1 \text{ s}$$

The estimation is based on the following considerations: loop length (L_{loop}) is fixed at 1.83 m (2 ft); minimum vehicle length is assumed to be $L_{\text{veh}}^{\text{min}} = 3.0$ m; maximum speed is assumed to be 31.29 m/s (70 mph); and minimum speed is assumed to be 2.24 m/s (5 mph). Maximum vehicle length is 18.5 m, which corresponds to Class A trucks with trailers. By using these estimations, the dwell time is set to the upper (lower) bound value if it is over (below) it.

Mode Occupancy

To extract mode occupancy or model dwell time (duration) from data within a moving window, it is necessary to determine the following factors:

- Definition of the moving window,
- Size of the bin for mode occupancy selection, and
- Range of the bin for efficient location and data selection.

Variable-Length Moving Window A variable-length moving window with a fixed number of samples is used in all traffic situations. Most moving window approaches use fixed-time window lengths. However, for traffic data at a fixed location, vehicle arrival is stochastic, and on average vehicle arrivals are at higher frequencies for heavier traffic. If a fixed-time window is used, it will end up with too few samples for off peak hours and too many samples for peak hours. Having too few samples is not good for mode selection. To avoid having too few samples, the authors propose selecting the window on the basis of a fixed number of samples with a flexible time length; for example, a moving window could be defined as having 100 to 200 vehicles passing the loop detector. One could adjust the number in practice.

Another less obvious advantage of using a variable-length moving window is that higher flow will lead to shorter time windows for a fixed number of passing vehicles. A moving window with a shorter time length would lead to less time delay in speed estimation, which would reduce the estimation error caused by the delay when speed changes. Accordingly, using a variable-length moving window makes the algorithm more sensitive to high-flow traffic, which often happens occurs before traffic breakdown.

However, for heavily congested (stop-and-go) static state traffic, which can be identified as very high occupancy and very low flow, the time needed for a fixed number of vehicles to pass a loop would

be lengthened. In this situation, a fixed-time-length moving window could be used until traffic begins to recover, which is characterized by occupancy decreasing and flow increasing.

Range of Bins It is obvious that the range should be between the lower and upper bounds identified in each time interval. A dynamic range identification is necessary because the range varies according with the traffic situation. Within this range, evenly distributed bins are set up to select the mode occupancy.

Size of Bins The moving window needs to be divided into bins for mode occupancy selection. How many bins should be used? Since the moving window is determined with a fixed number of samples, the size of the bins should be stretched or reduced accordingly. This adaptation can be achieved by evenly dividing the moving window along the time horizon. If the decision is made to have 10 bins, for example, then the mode bin should have at least 10 samples. Some bins may be empty. Clearly, too few bins would lead to a more coarse selection, but too many bins may not allot a significant portion of the samples into each mode bin. In practice, bin size could be considered as a tuning number. Data processing showed that 20 to 50 bins are adequate.

With this setup, the mode occupancy (duration) can be generated as shown in Figure 1.

Traffic Transition Phase Dynamics

In traffic transition phases with significant speed changes, such as congestion onset with shockwave, mode occupancy may be needed to provide information quickly enough to determine speed changes, which is necessary for traffic congestion detection. If mode occupancy cannot be determined fairly quickly, it might not be possible

to extract this value at all from the time sequence from traffic with significant speed changes.

To capture transient traffic dynamics, the following three values are monitored from the time sequence data:

- Mean occupancy for all samples within the moving window,
- Mean occupancy for all samples within the first half of the moving window, and
- Mean occupancy for all samples within the second half of the moving window.

Selecting g_m

It is clear that the selection of g_m is very important to the accuracy of the speed estimation. Coifman found that approximately 85% of the individual vehicle lengths observed at one detector station were between 15 and 22 ft, but some vehicles were as long as 85 ft, or roughly four times the median length (9). For example, on the I-80 BHL section, which leads to the Port of Oakland, California, many heavy-duty trucks travel on Lanes 3 and 4. For this study, however, the California mode vehicle length of 15 ft is used in speed estimation.

ALGORITHM VALIDATION USING BHL EVENT DATA

This section presents and discusses the algorithm validation and error analysis with BHL-achieved data.

Field Data

Multiple days of BHL-achieved 24-h data were used for the algorithm validation. The daily traffic in the test section is extremely

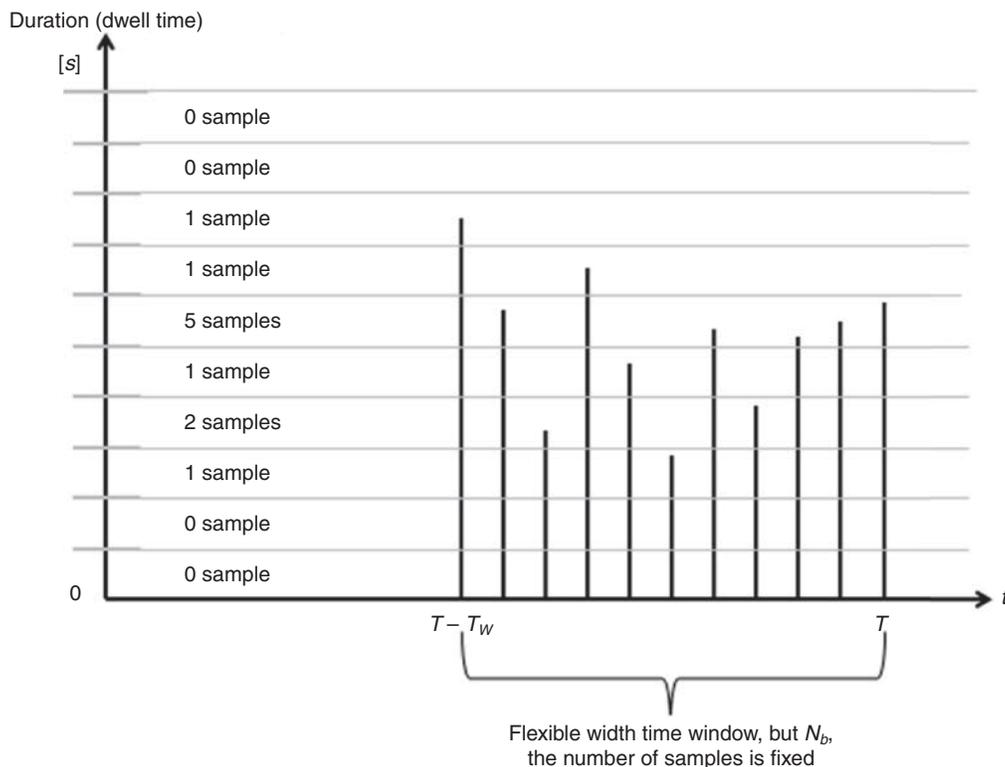


FIGURE 1 Mode dwell time is generated with N_b evenly distributed bins (between horizontal lines) and averaging dwell times (durations) in bin with largest number of samples.

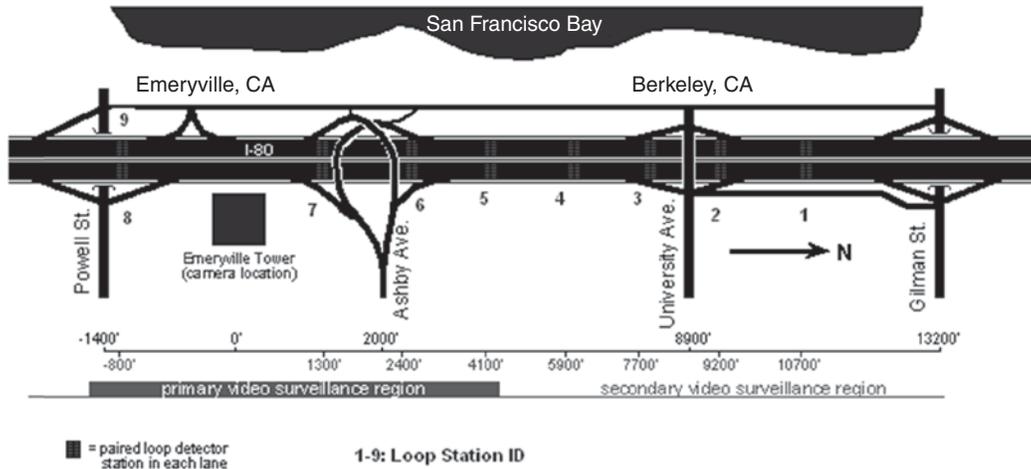


FIGURE 2 BHL with dual loop detector stations and five lanes in each direction.

high in peak hours. After validation, 2 months of data were used for reliability testing of the algorithm. Data from Wednesday, April 13, 2005, obtained from several stations (1, 4, 6, and 7, as shown in Figure 2) were used for error analysis. Each station has five lanes. Lane 1 is an HOV lane. These stations were selected because the data quality was mostly good except for Station 1, Lane 2. The selection also considers the traffic volume and the recurrent bottleneck westbound near the MacArthur Maze. Station 7 is close to it.

The fixed number of data samples and the number of bins in the moving window are $N_s = 200$ and $N_b = 25$, respectively. The selection of number of bins depends on the duration range in consideration. If the preliminary data selection range is tight, the number of bins could be reduced.

Dual Loop Speed Estimation

Dual loop speed trap characteristics were used as reference. To obtain accurate speed estimation from the achieved dual loop data using the on-off times of the upstream and downstream loop, it is

necessary to first clean up the data, fill in gaps with interpolation over time or distance (or both) if either upstream or downstream data are missing, and then match upstream and downstream data in pairs (2). Note that speed estimation with dual loop data is independent from the sensitivity level as long as the data are the same for the upstream loop and the downstream loop. This relationship is based on the following equations:

$$T_{1,on}^d - T_{1,on}^u = T_{2,on}^d - T_{2,on}^u$$

$$T_{1,off}^d - T_{1,off}^u = T_{2,off}^d - T_{2,off}^u$$

This relationship can be easily observed from Figure 3 (also with the notation definition): although the duration or occupancy will differ for different levels of sensitivity, the difference of on (or off) times of the upstream loop and downstream loop are the same. In practice, the dual loops are usually connected with a single-loop detector card in the field. Therefore, they have the same sensitivity level setting.

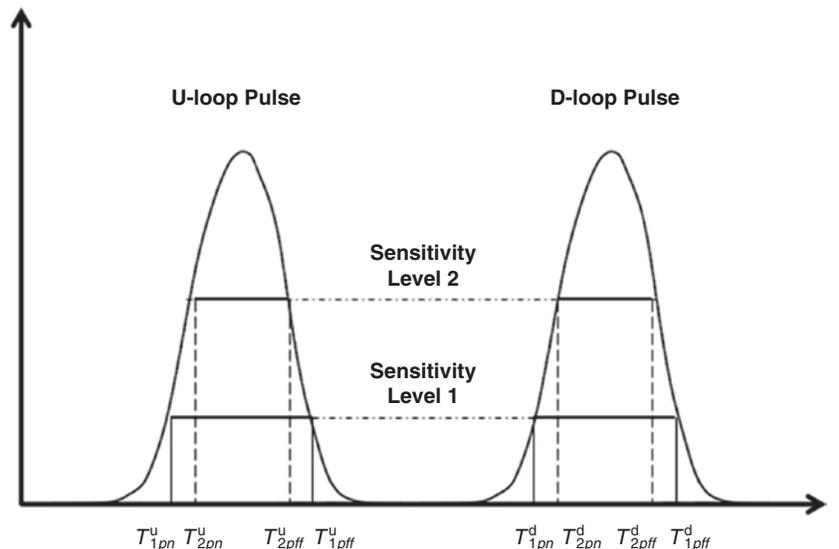


FIGURE 3 Loop signal pulse and sensitivity threshold level settings and their effects on loop on-off time instants and durations.

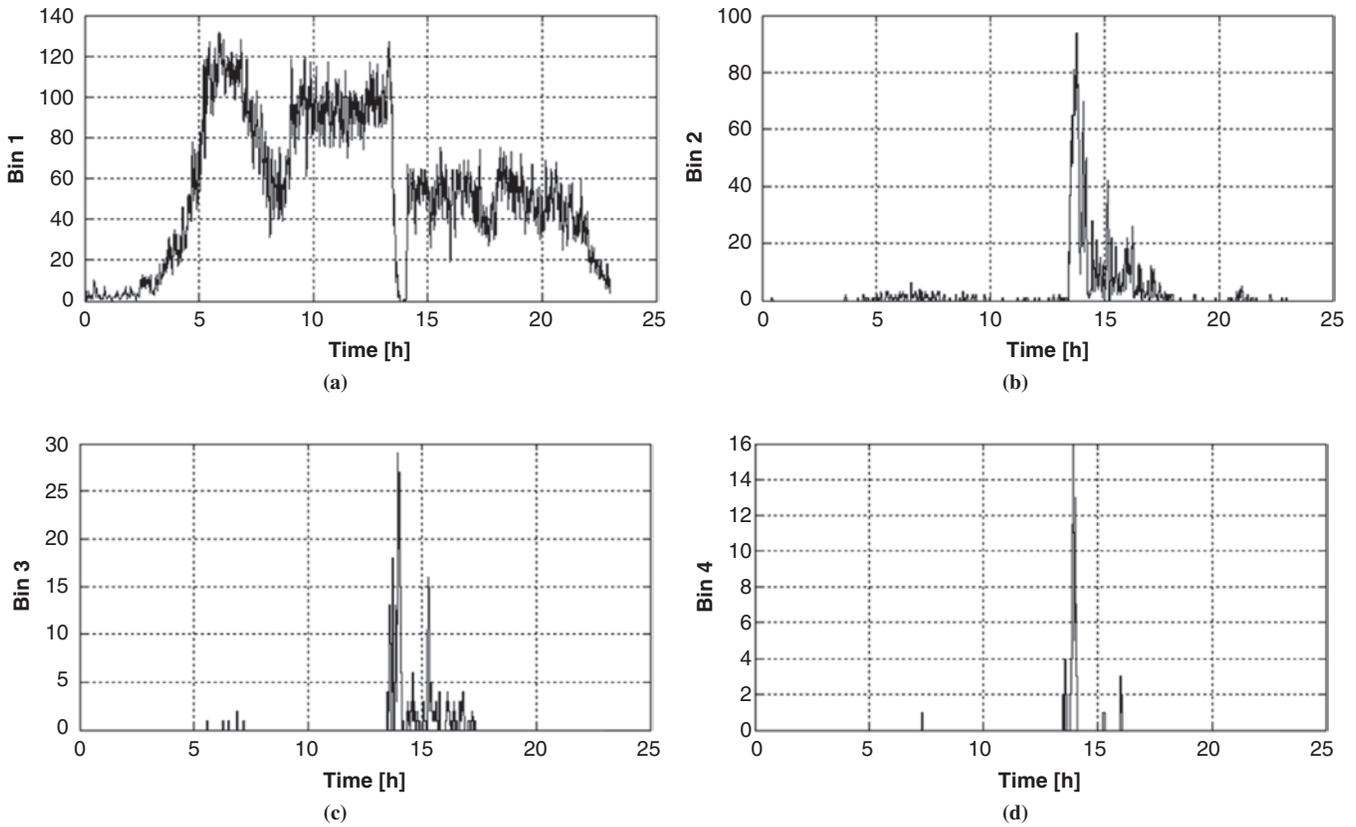


FIGURE 4 Number of samples from BHL data for April 13, 2005, for Station 7, westbound Lane 1, downstream loop for Bins (a) 1, (b) 2, (c) 3, and (d) 4.

Discussion

It is interesting to investigate the shift of mode bins for different lanes at the same station. Using Station 7 westbound as an example, for Lane 1 (an HOV lane), Bin 1 always corresponds to the mode duration for low to high traffic volume, but not for congested conditions; Bin 2 is the mode bin for congested traffic, which may indicate vehicle type changes in the afternoon peak hours (Figure 4). This situation is similar for Lane 3 for noncongested traffic. For afternoon peak congested traffic, most mode durations fall into Bin 2, but some fall into Bin 3, as well (Figure 5).

Figure 6 and Figure 7 show the mode durations extracted for Lanes 1 and 3, respectively, with respect to time. It can be observed that the durations have little fluctuation except in the afternoon peak congested hours. This lack of fluctuation implies the filtering effect of the process of selecting the model duration.

The corresponding speed estimations are shown in Figure 8 and Figure 9. It can be observed that the speeds estimated for both the upstream and downstream single loops are well matched with those obtained from the dual loop. This situation holds even for traffic transition phases and congested situations in peak hours. The speed estimated is not aggregated over time. The same time

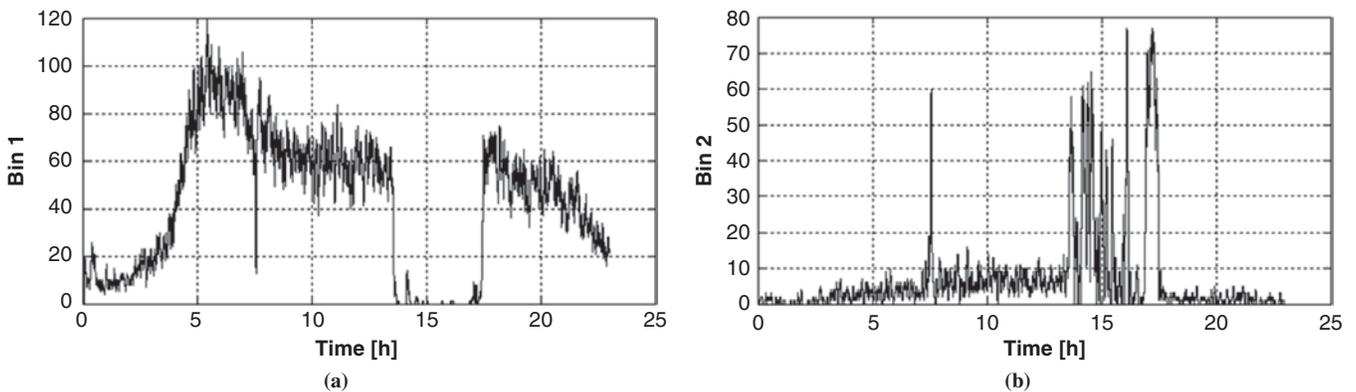


FIGURE 5 Number of samples from BHL data for April 13, 2005, for Station 7, westbound Lane 3, downstream loop for Bins (a) 1 and (b) 2. (continued)

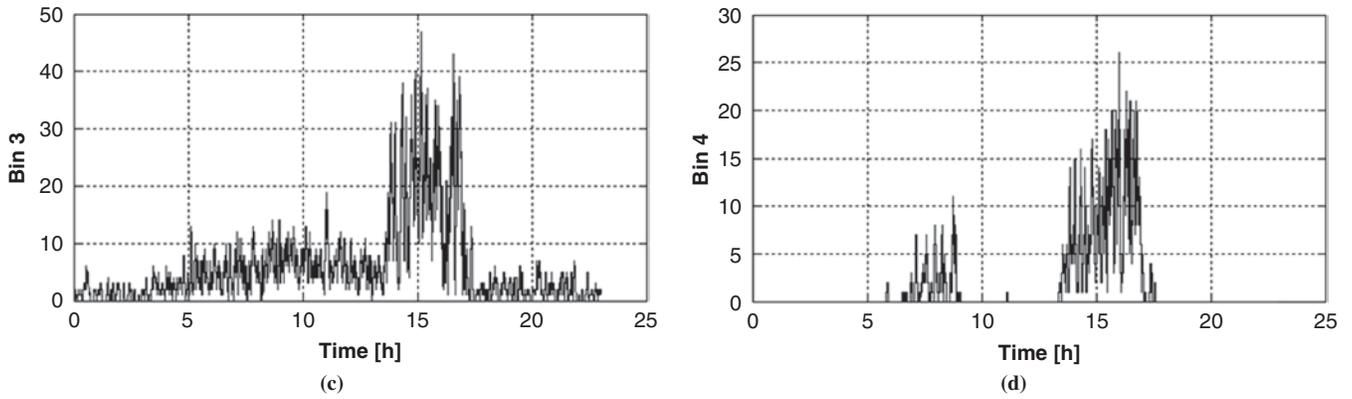


FIGURE 5 (continued) Number of samples from BHL data for April 13, 2005, for Station 7, westbound Lane 3, downstream loop for Bins (c) 3 and (d) 4.

interval as the event data remains in the corresponding speed estimated.

Estimation Error Analysis

RMSE in Table 1 is used to quantify the discrepancy between speeds estimated from upstream and downstream single-loop data and speeds from the dual loop data. Data analysis was conducted for four stations both eastbound and westbound over 24 h. It can be observed from the table that RMSE ranged between 1.73 and 5.39 mph. However, for most stations and lanes, RMSE was about 2 to 4 mph. The sensitivity parameter η ranged between 0.95 and 1.0. For consistency, the parameter was not adjusted with respect

to each lane at a station, but the results seem to be reasonably good. The results probably reflect the loop circuit setup: the loop circuit installation for all the lanes at a station are very similar, and all the detector cards of all the lanes at the same station are likely to be set at the same sensitivity level.

CONCLUSION

This paper uses single inductive loop event data with a 1-Hz update rate and 60-Hz information for speed estimation with the g -factor algorithm. The key points are to properly select the g -factor as the mode vehicle length (fixed for a specified road) and to extract the mode occupancy (or dwell time). To capture traffic transition

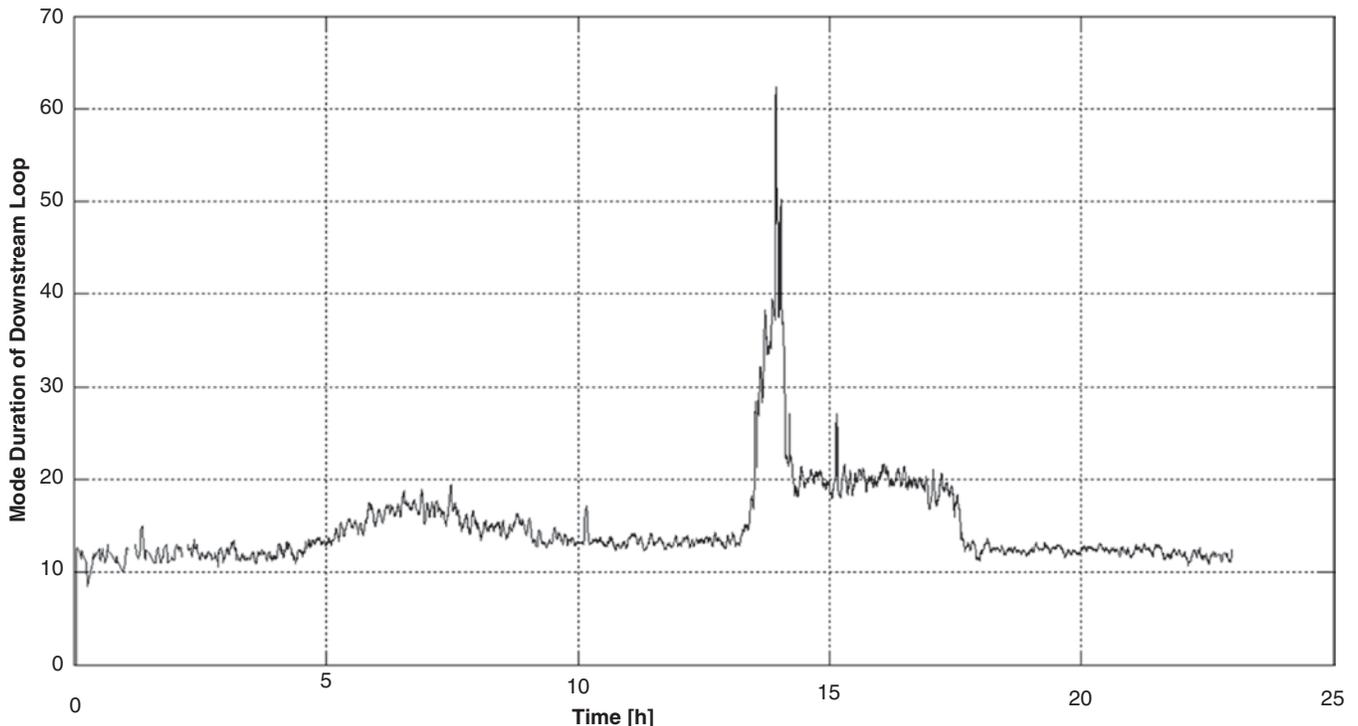


FIGURE 6 BHL data for April 13, 2005, for Station 7, westbound Lane 1, downstream loop: mode duration 1/60 s extracted.

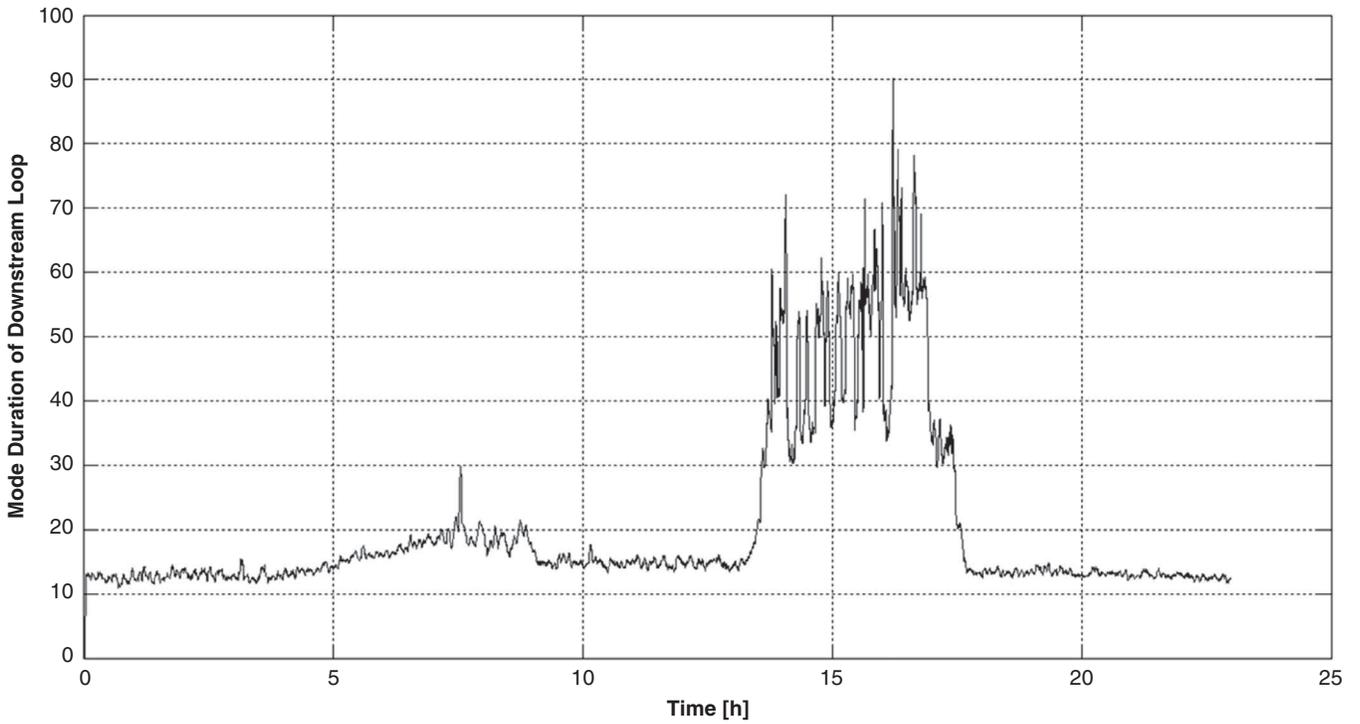


FIGURE 7 BHL data for April 13, 2005, for Station 7, westbound Lane 3, downstream loop: mode duration 1/60 s extracted.

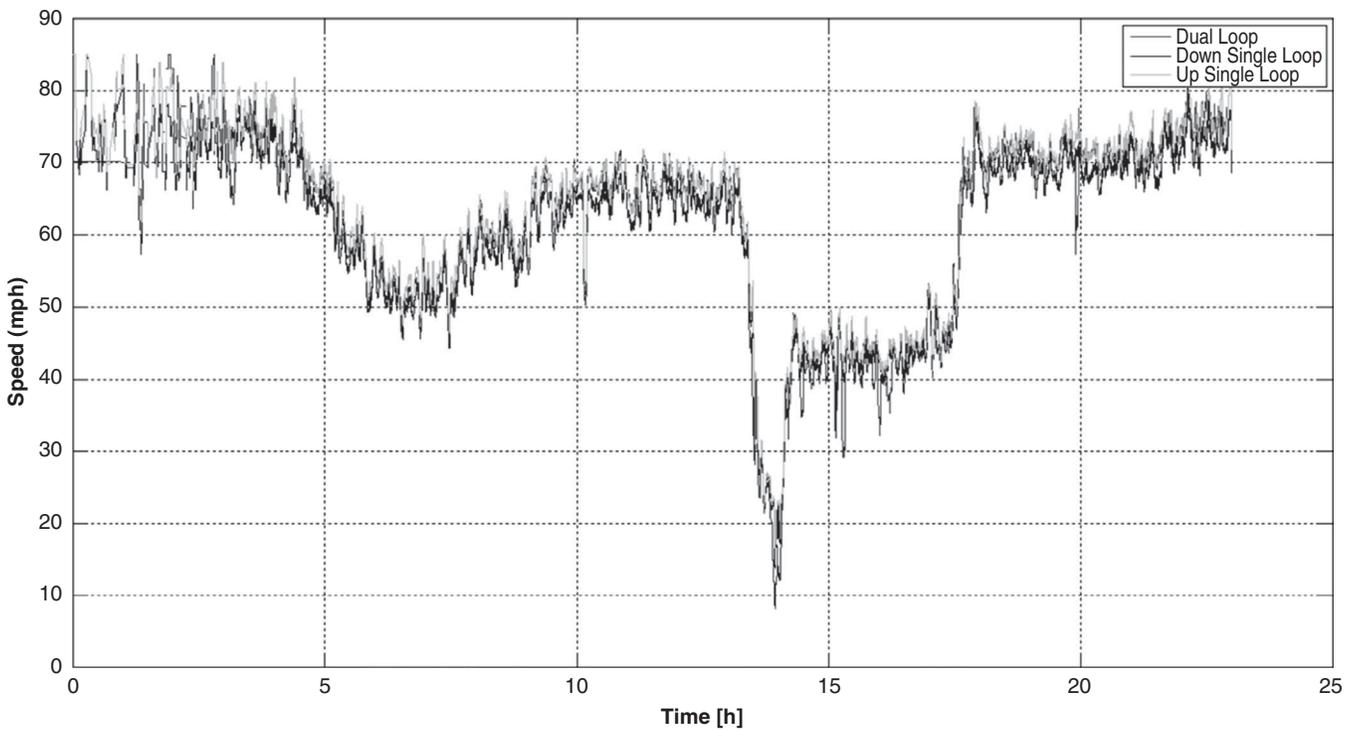


FIGURE 8 BHL data for April 13, 2005, for Station 7, westbound Lane 1: estimated speed comparison of dual loop and single loop (downstream and upstream).

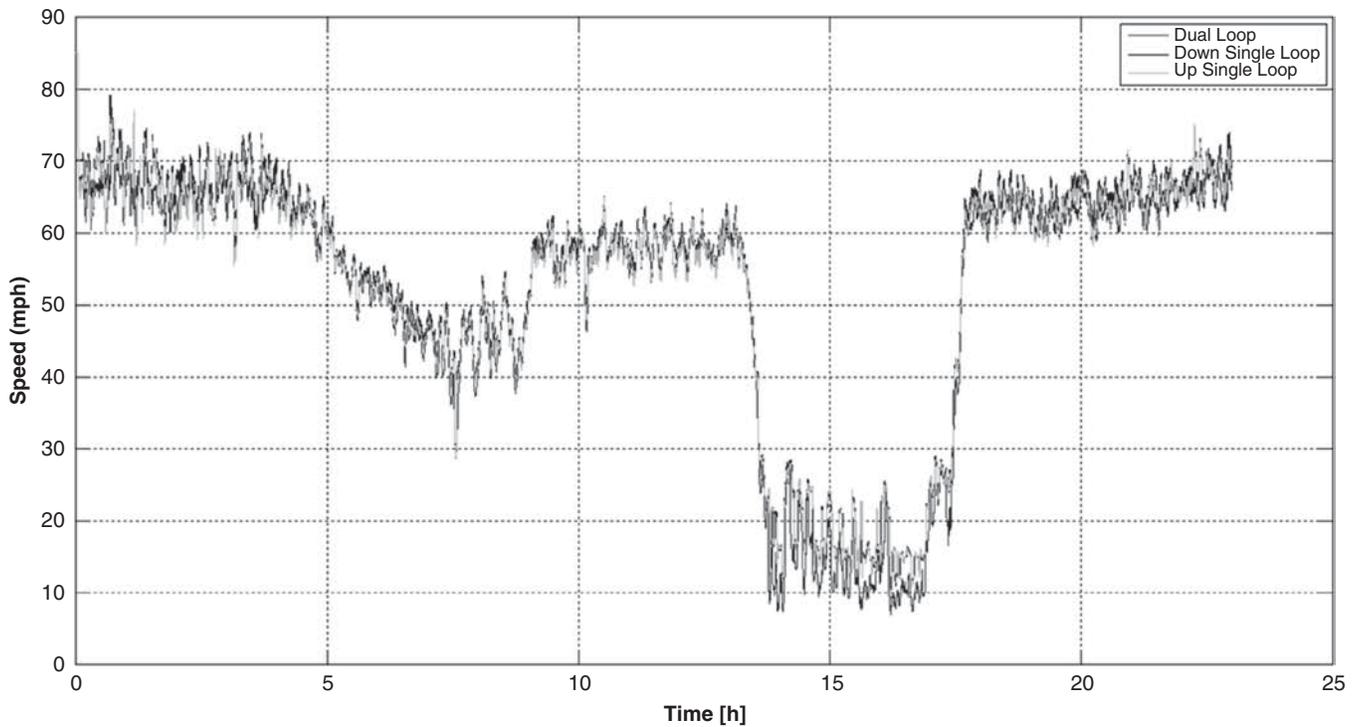


FIGURE 9 BHL data for April 13, 2005, for Station 7, westbound Lane 3: estimated speed comparison of dual loop and single loop (downstream and upstream).

dynamics (other than static state), a moving window with variable time length but a fixed number of samples is used to determine mode occupancy.

A comparison of the speed estimations from single-loop and dual loop data showed that RMSE were on the level of 2 to 4 mph in most cases. After analyzing multiple-day data, the results seemed consistent and reliable. This consistency may be partially the result of another benefit of using mode occupancy: the variation and noise of the data have been effectively reduced or filtered out. The dual loop data were cleaned up and matched the upstream and downstream on-off times used for speed estimation. None of the speed estimations used aggregation, because aggregation is believed to artificially introduce time delay and therefore estimation error. RMSE analysis showed that the estimation from single loop data is

very close to that from dual loop estimation. This algorithm can be run at the control-cabinet level, in which event data from an individual loop from a 170 or 2070 controller is available without need of any hardware modification. These controllers have the processor capabilities to handle data in real time.

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TABLE 1 RMSE of Upstream and Downstream Single- and Dual-Loop Speeds for Each Lane

| Station | Direction | η | Lane 1 | | Lane 2 | | Lane 3 | | Lane 4 | | Lane 5 | |
|---------|-----------|--------|--------|------|--------|------|--------|------|--------|------|--------|------|
| | | | D | U | D | U | D | U | D | U | D | U |
| 1 | E | 0.95 | 2.52 | 2.51 | 2.70 | 2.49 | 2.73 | 2.56 | 2.91 | 3.56 | 3.49 | 2.41 |
| | W | 0.95 | 4.14 | 3.77 | NA | NA | 3.15 | 2.81 | 2.37 | 2.40 | 2.74 | 2.41 |
| 4 | E | 1.0 | 3.05 | 2.94 | 3.44 | 3.12 | 3.96 | 2.77 | 2.56 | 3.85 | 2.70 | 2.44 |
| | W | 0.95 | 2.19 | 2.12 | 3.69 | 3.48 | 2.22 | 2.22 | 2.13 | 1.73 | 1.79 | 1.71 |
| 6 | E | 0.95 | 4.66 | 2.71 | 5.39 | 3.01 | 2.88 | 2.67 | 3.57 | 2.72 | 3.70 | 3.03 |
| | W | 0.95 | 2.65 | 1.80 | 3.25 | 3.49 | 3.43 | 2.93 | 3.97 | 2.39 | 3.94 | 2.71 |
| 7 | E | 0.95 | 3.10 | 2.96 | 6.71 | 3.32 | 3.54 | 2.80 | 2.66 | 2.64 | 3.08 | 2.72 |
| | W | 1.0 | 2.64 | 2.45 | 4.27 | 3.70 | 2.87 | 2.57 | 2.95 | 2.61 | 2.28 | 2.50 |

NOTE: E = eastbound; W = westbound; D = downstream; U = upstream; NA = not available. Data are from Wednesday, April 13, 2005.

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