A Heuristic Data Enhancement Method for Probe-based Traffic Monitoring System

Jie Fang
Graduate Researcher
Department of Civil and Environmental Engineering
Jfang3@ wisc.edu

Steven T. Parker, Ph.D.
IT Program Manager
sparker@engr.wisc.edu

Bin Ran, Ph.D.
Professor
bran@wisc.edu

David Noyce, Ph.D., P.E.
Associate Professor and Director
noyce@engr.wisc.edu

Dean Beekman, P.E.
Wisconsin Department of Transportation
Statewide Traffic Operations Center
dean.beekman@dot.state.wi.us

Traffic Operations and Safety (TOPS) Laboratory
Department of Civil and Environmental Engineering
University of Wisconsin – Madison
1415 Engineering Drive
Madison, WI 53706

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Abstract

Probe-based real-time traffic monitoring systems, such as Wireless Location Technology and probe car GPS-based systems, have become increasingly attractive as a cost-effective alternative to traditional loop-detector and other fixed detection technologies. In order to enhance traffic operations control room monitoring capabilities, however, probe-based systems must be capable of providing reliable link speed information during short-term non-free flow conditions such as traffic incidents and severe weather events. This paper describes a heuristic data enhancement algorithm that takes probe-based system measurements as input and generates a real-time output stream that provides a more accurate trace of ongoing event conditions.

The data enhancement algorithm detects an unplanned event by seeking traffic speed measurements beyond the pre-defined speed threshold from a calculated reference speed. A variable event clearance window is then established by checking the number of low-speed event data points over the last two hours and the length of time from the start of the current event. Within the variable length event clearance window, the last trusted non-free flow traffic speed will be reported instead of un-trusted free flow system measurements. The enhanced measurements provide a more faithful representation of the continuous impact of the event when compared to ground truth data.

Key words: Probe-based real-time traffic monitoring system; WLT technology; evaluation and system improvement

Introduction

Background

In 2007 the Wisconsin Department of Transportation (WisDOT) initiated a federally sponsored study to evaluate the effectiveness of probe based traffic information systems to enhance real-time traffic monitoring along state trunk highways. Two different systems were selected for comparison, one based primarily on cell-phone location technology and the other based on in-vehicle GPS technology. The evaluation study was conducted by the University of Wisconsin-Madison Traffic Operations and Safety (TOPS) Laboratory in collaboration with the WisDOT Statewide Traffic Operations Center. The cell-phone based system covered three corridors between Madison and Milwaukee including IH 94, STH 18, and STH 19. The GPS system, which is this main focus of this paper, covered a freeway segment of 250 miles on US 41 and US 43 between Milwaukee and Green Bay. The GPS system reports real-time traffic flow speed at 5 minute intervals with respect to fixed, predefined segments. Although each system relies on a particular technology for speed data collection, it should be noted that both systems also collect and architecture real time traffic information data from a hybrid of existing data sources including GPS probe data, road sensor data, state DOT public traffic information, and others.

A critical objective of the WisDOT study was to evaluate how well these systems can be used for traffic operations in a control room setting. That objective relates, in particular, to the effectiveness in capturing non-free flow traffic conditions during planned and unplanned events such as traffic incidents, weather events such as snow and flooding, and work zones. Such non-free flow conditions will be here after referred as "events."

Traffic monitoring at the WisDOT Statewide Traffic Operations Center (STOC) is based primarily on traditional loop detector technologies and supplemented by ongoing traffic camera deployments. Due to an array of factors, including cost and physical maintenance, operations detection is currently limited to major urban areas around Milwaukee, Madison, and Wausau. Probe-based technologies offer a cost-efficient alternative to supplement fixed detection in other parts of the state and along corridors that connect urban areas.

In order to provide useful monitoring in a control room setting, the probe-based traffic information collecting system should be able to:

- Report traffic speed data on short segments (one to three miles)
- Report traffic speed information in real time
- Provide a reliable detection mechanism for non-free flow events

Although the ability to report reliable traveler information such as route travel times is also important, the WisDOT study has focused on the systems' performance to detect and continuously report on the impact of non-free flow traffic events. To evaluate whether the system can fulfill these requirements, three categories of events were chosen: traffic incidents, weather events (snow and flooding), and high-impact work zones. A total of 25 events (4 work zones, 8 weather impact events, and 13 incidents) were studied to evaluate the performance of the studied traffic monitor system from January to December 2008. Traffic incidents provided an opportunity to evaluate the system's ability to detect sudden, short-term unplanned event impacts. Incident detection and coordination with first-responders is an increasingly important function of the STOC. Work zones and major weather events provided an opportunity to evaluate the system performance under longer-term non-free flow conditions. Several significant snow and flood events in the last two years have demonstrated the need to expand traffic monitoring capabilities beyond the major urban areas.

Overall, the system was able to detect the event impact (i.e., report low speed data during roughly 70% of the incident duration) from 12 of all the studied events, which is 48% of the total. Although the system was able to detect the event impact, the system's ability to report event data accurately and over the whole event duration is much less reliable. A typical example of this issue is illustrated in Figure 1 below:

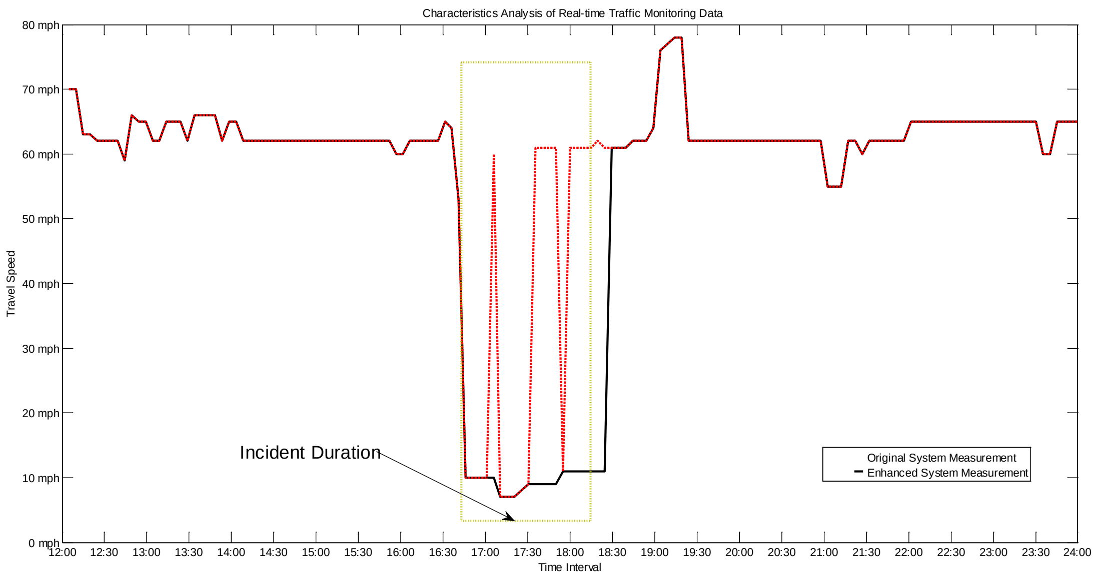

Figure 1 A Typical Example of Original Data Output.

The actual incident duration, which took place from 4:45 PM to 6:20 PM, is given by the boxed area. The process in which "ground truth" traffic incident information is collected is described below. The original probe-based traffic monitoring system output, which will be referred to as "original system measurement," is shown by the red dotted line. Note that the probe system was able to detect the event impact right after the incident occurred and reported a significant drop in traffic speed on the given segment. However, as a possible result of low penetration rate, the probe system did not detect the whole incident continuously but reported intermittent default speed values instead. This case is typical among the incidents detected by the two probe based traffic monitoring systems in the evaluation study.

The enhanced measurement, which was generated by the algorithm proposed in this paper, is shown by the black solid line. The enhanced output continuously reports lower speeds over the duration of the incident. Whereas the probe system data reverts to free flow conditions about 20 minutes before the incident was reportedly cleared, the enhanced output overcompensates by continuing to show low speeds for about 5 minutes past the incident duration. We believe this is a better alternative for traffic control centers. Specific tuning parameters to improve the lag time are described further in the paper. The output enhanced by the algorithm proposed in this paper will be referred as “enhanced measurements.”

Based on the GPS probe system output characteristics, a heuristic data enhancement method was developed to improve the system performance under non-free flow event impacts. Compared to the original system measurements, the enhanced measurements improves real-time traffic control room capabilities to detect and continuously monitor traffic conditions during event without disrupting normal free-flow traffic data reporting.

Study of Previous Traffic Monitoring System Deployments WisDOT has deployed a large network of loop detectors and other fixed detection devices over the past decade as part of its freeway operations monitoring program. These detectors are used to collect traffic flow (volume, speed, and occupancy) and travel time data for real-time control room operations and traveler information. By using a dense detector network, short (under three miles in length) link flow conditions can be monitored and are further aggregated to obtain longer route-based travel times. Many detectors on the network are often in need of maintenance or repair at any given time. In-vehicle probe-based technologies provide a potential cost-efficient alternative to increase coverage and overcome maintenance pitfalls.

As described, the WisDOT evaluation focused on two different probe-based monitoring systems. To implement a probe-based traffic monitoring system, there are generally two approaches. The first approach is the use of wireless location technology (WLT) to locate wireless devices. The second approach is to locate floating vehicles equipped with GPS devices. Many traffic data firms are combining probe data from GPS-equipped fleets and WLT to generate traffic data *[1]*.

Several landmark studies over the past decade have evaluated the effectiveness of probe-based traffic monitoring systems for reporting travel time information. Those include Cayford, R., Yim, Y.B. *[2, 3]*, Fontaine, M.D., Smith, B.L., *[4]* and Ben Gurion University (2005) *[5]*. More recently, the I-95 Coalition has sponsored a study through the University of Maryland CATT Lab to evaluate the effectiveness of fleet-based GPS traffic monitoring along the multi-state I-95 corridor *[6]*. And server commercial firm effects of developing their own probe-based traffic monitoring systems around the states, such as INRIX *[7]* and Airsage *[8] were evaluated*.

As noted in the summary report of state-of-practice WLT-based traffic monitoring systems *[1]*, the current deployments have a common problem: probe-based traffic monitoring systems tend to have relatively low sampling rates, especially during event impacts. One approach for estimating roadway travel times using automatic vehicle identification (AVI) data for low sampling rates has been studied by Dion and Rakha (2005) *[9]*. Their study describes a low-pass adaptive filtering algorithm to predict average roadway travel times.

In the context of control room operations, however, an increasingly critical requirement is to assist first responders by providing real-time link speeds for purposes of detecting traffic incidents and other non-free flow conditions. Compared to travel time, traffic speed is more sensitive to speed variations (flow speed could change for more than 40 mph within 10 minutes). Therefore, in this paper, we propose a heuristic data enhancement algorithm to address the need of improving the traffic monitoring system performance based on low sampling rate probe data, especially under the event impact.

Data Enhancement Algorithm Methodology

A heuristic data enhancement algorithm is introduced in this paper to improve real-time monitoring of traffic conditions by post-processing the probe-based system output. The algorithm will enhance the probe-system data according to the following principles:

- The data enhancement algorithm should be able to trace the full duration of the event;
- The data enhancement algorithm should replace erroneous default free-flow speed values with better estimates of ground truth speeds during the event window;
- The data enhancement algorithm should be applied in real time – it can only use historical data to predict current conditions.

An event window will be established once proposed algorithm detects an event impact and cover through the event duration. Within the event window, any free flow system measurement will be considered to be an un-trusted system default measurement and will be replaced by the last trusted non-free flow system measurement value.

The algorithm consists of a filtering and imputation process that can be divided into two procedures: historical measurement inspection and current measurement calibration. For each original system measurement, the heuristic data enhancement filtering algorithm will go through these two procedures to determine whether the traffic is under an event impact and whether there is a need to replace the current probe system output with the last trusted system output speed measurement.

Then proposed algorithm will look for system measurement that is lower than the calculated reference speed minus the pre-defined speed threshold. Once an event is detected, a variable event clearance window is established by checking the number of low-speed event data points over the last 2 hours and the length of time from the start of the current event. Within the variable duration clearance window, the un-trusted free flow original system measurement will be replaced with the last trusted non-free flow system measurement value.

Four “windows” will be used in the proposed algorithm through its processing:

- *Event Window*. The period of time during which the data enhancement algorithm traces an event.
- *Reference Speed Calculation Wi*ndow. The time interval covering the last six trusted free flow system measurements. During an event, this window corresponds to the six speed values leading up to the event window.
- *Event Persistence Test Window*. Period of time leading up to the current system measurement that defines the interval over which the number of non-free flow system measurements are counted (event persistence test).
- *Variable Event Clearance Window*. A variable length window that defines the expected end-point of an event, determined by the current event duration and the event persistence test. The expected end-point is updated with each system measurement.

Table 1 lists the key variables that are used in the algorithm with their symbols and applications.

Table 1 Variables Used In the Enhancement Algorithm

Symbols	Variables Names	Applications
u_r	Reference Speed	To determine whether system measurements was under event impact
L_{RSCW}	Length of the reference speed calculation window	Period of time to calculated reference speed
u_τ	Pre-defined speed threshold	Pre-defined threshold to determine whether system measurements was under event impact
L_{EPW}	The length of the event persistence window	Period of time to determine event persistence
L_{CLR}	Length of the event clearance window	defines the expected end-point of an event
N_{miss}	Real time measurements missing timer	Period of time that missing real time system measurements

Historical Measurement Inspection

Each system measurement will initiate an historical measurement inspection. This inspection includes reference speed calculation and the event persistence window test.

Reference Speed Calculation

The calculated reference speed refers to the expected free flow speed at a given time and location. It is used by the event persistence test and the current measurement calibration to determine whether a measurement should fall within an event window.

In proposed algorithm, we set the length of the reference speed calculation window L_{RSCW} to 30 minutes (optimum empirical value set up after analyzing the 25 traffic impact events on the system). Moreover, the reference speed is always calculated from trusted free-flow system measurements, i.e., outside of an event window. Assuming the system reports the traffic speed at an interval of *t* minutes, for each measurement at the current spot of time I $u(I)$, the reference speed u_r is calculated by Equation (1):

$$N = \frac{\mathrm{L_{RSCW}}}{System\_measurement\_\mathrm{int}erval}$$
$$u_r(I) = \frac{\sum_{n=1}^{N} u(I-n)}{N} \quad (1)$$

where, $\mathrm{L_{RSCW}}$ is the length of reference speed calculation window. Inside an event window, the reference speed is taken as the last calculated reference speed before the event started.

For this particular system, knowing that the probe system reports the traffic speed at an interval of 5 minutes, assuming all system measurements are free flow measurements, the reference speed u_r will be calculated as the mean of these last 6 trusted free flow system measurements:

$$u_r(I) = Mean\_of\_[u(I-6), u(I-5)..., u(I-1)].$$

After calculating the reference speed, we can use it to determine whether a system measurement is under an event impact. According to the analysis of traffic characters on the studied area, we define that if a measurement was more than 20 mph (pre-defined speed threshold u_τ) lower than the calculated reference speed, it will be considered as under an event impact. This threshold value is an empirical value based on prevailing system characteristics and can be adjusted to adapt to other traffic monitoring systems or roadway areas.

Event Persistence Test Window

The length of the event persistence window L_{EPW} was set to be 2 hours (an optimum empirical value based on our analysis of the 25 events) in the proposed filtering algorithm. The proposed algorithm will check the number of measurements under an event impact within the past 2 hours using the calculated reference speed and pre-defined speed threshold mentioned above. The number of measurements that are under the event impact, N_{imp}, will be used in the current measurement calibration procedure to determine the length of event clearance window L_{CLR}.

Current Measurement Calibration

The measurement calibration procedure consists of two sub-procedures to determine whether the current probe system measurement is under event impact. If there is an ongoing traffic impact event, the algorithm exams the current system measurement to prevent the system from reporting an un-trusted free-flow speed measurement. Un-trusted speed measurements are replaced with a last trusted non-free flow measurement value u_{last}. The sub-procedures are illustrated by flow chart in Figure 2.

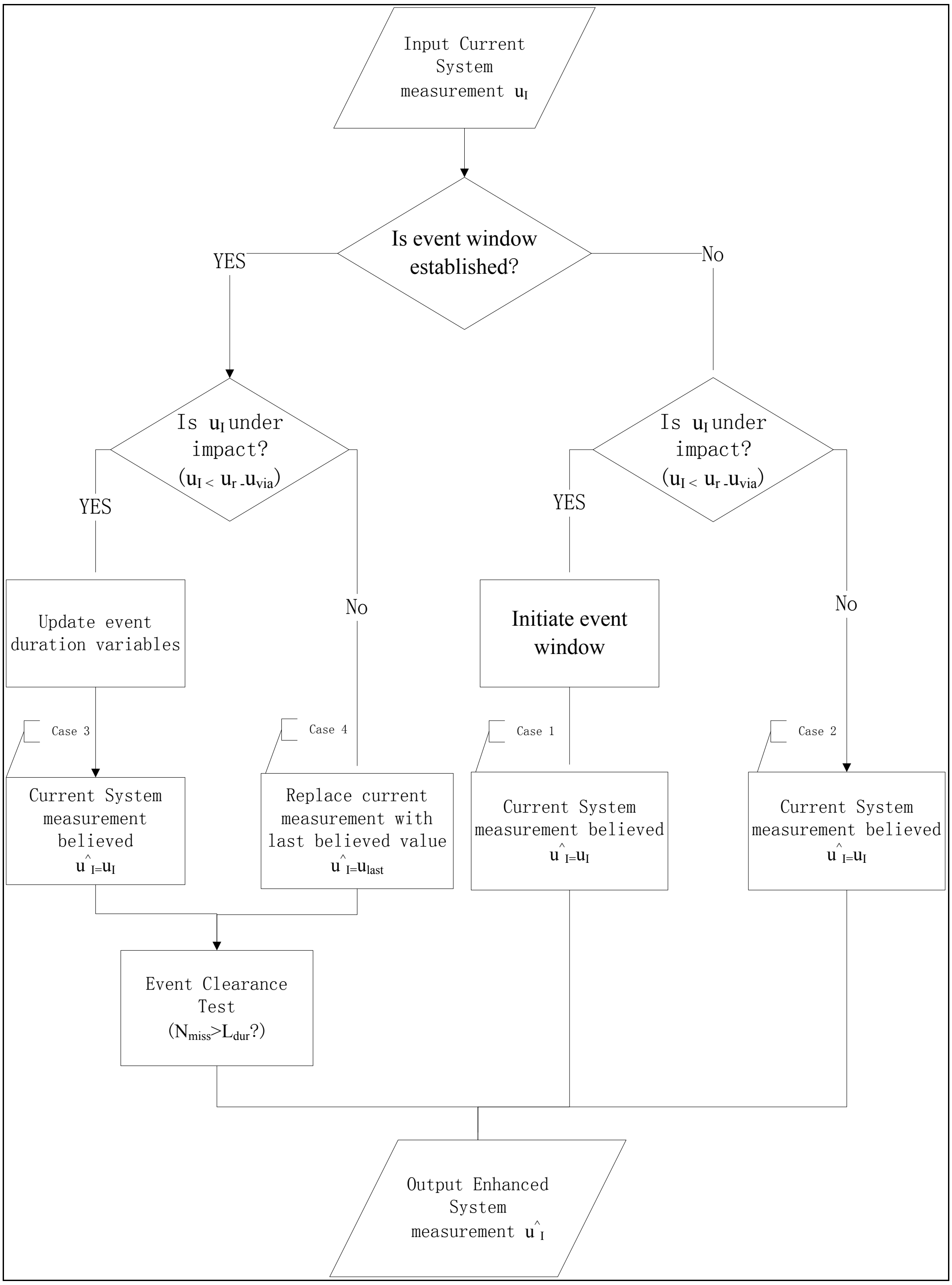

Figure 2 Sub-procedures of Current Measurement Calibration

For each original system measurement, the calibration procedure checks whether the event window has been established. Four possible cases exist:

Case 1: If the event window has not been initiated by the algorithm and the current system measurement is under an event impact (determined by using the calculated reference speed u_r and pre-defined speed threshold u_τ that we discussed above in the historical measurement inspection section), an event window will be initialized. This initialization starts an event duration timer N_{dur} and a new variable event clearance test window with a real-time measurement's missing timer N_{miss}. Both of these timers will be set at zero that indicates a new traffic flow impact event was just detected and a real-time trusted system measurement was reported at zero system measure intervals ago. Furthermore, the last trusted speed measurement u_{last} will be set to the value of current system measurement. This last trusted speed measurement u_{last} could be used to replace any un-trusted non-real time system measurement in the following procedures.

Case 2: if an event window has not been initiated by the algorithm and the current probe system measurement does not appear to be impacted by an event, the current original system measurement is trusted and remains unchanged.

Case 3: if the event window has already been initiated by the algorithm and the current probe system measurement appears to be under an event impact, the algorithm will accept that the current system measurement as a reliable real time system measurement indicating a continued impact to the traffic flow. Therefore the procedure will execute the following sub-procedures:

- The event duration timer N_{dur} will increase by 1 to indicate that the current event has lasted one more system measure interval.
- Since a new reliable real time system measurement was found, the algorithm will re-establish a variable event clearance window with real time data absence timer set to zero.
- The last trusted speed measurement u_{last} will be replaced with the value of current system measurement.

Notice that the event duration timer N_{dur} will not be reset to zero because the sustained impact from the current traffic impact event was detected. After executing these three sub-procedures, the algorithm will implement the variable event clearance test, which will be presented in the following section.

Case 4: if the event window have already been initiated by the algorithm, but the current probe system measurement does not appears to be affected by that traffic impact event, the current system measurement would be considered as a non-real time default system output and the following sub-procedures will be executed to calibrate the system measurement:

- The current system measurement will be replaced by the current last trusted speed value u_{last}.
- The real time measurements missing timer N_{miss} will increased by 1 to indicate that the system has reported un-trusted free flow speed for 1 system measure interval.
- The event duration timer N_{dur} will increase to keep a record of the current traffic impact event duration.

After executing these sub-procedures, the algorithm will perform the variable event clearance test to check whether the impact from the event should be cleared.

Event Clearance Test Window

The event clearance test window is a variable length window that will be used by the algorithm to determine whether the traffic flow is still under the event impact. This test will use its varying window length to prevent the system measurement from reporting un-trusted free flow system measurement during the event duration as well as reporting low speed measurements after the event impact was cleared.

The length of event clearance window L_{CLR} is one of the critical "tuning" parameters used by the enhancement algorithm to optimize the algorithm's performance on events with different characteristics. It is determined by two key factors:

- The number of probe system measurements under an event impact in the last 2 hours N_{imp} (Discussed in section 2.1 historical measurement inspection);
- The number on the current event duration timer N_{dur}.

The length of the event clearance window L_{CLR} is be calculated by Equation 2 below:

$$L_{CLR} = \begin{cases} Min(N_{imp} + 2, 8) & (0 \le N_{dur} \le 24) \\ Min(N_{imp} + 2, 8) - (N_{dur} - 24) & (N_{dur} > 24) \end{cases} \quad (2)$$

This variable will determine how quickly the algorithm will trust the event impact was cleared and stop replacing the non-free flow system measurement with last trusted non-free flow system measurement value. If the number of the real time data missing timer N_{miss} have not gone beyond the length of variant event clearance window, the algorithm will consider the traffic was still under the impact of current traced event and any free flow system measurement could be considered as un-trusted non-real time system measurement. If N_{miss} has already reach the length of the event duration timer, the event impact to the traffic would considered to be cleared and the event window will be terminated. Therefore the trace of the traffic impact event will be terminated and the event duration timer will be disabled.

Equation 2 is based on an analysis of the impact from traffic incidents. By using this equation to calculate L_{CLR}, the length of variable event clearance window will be optimized to improve the probe based traffic monitoring system for traffic incidents that are generally characterized by sustained short term decreases in traffic speed.

However, a long term traffic impact event, such as a snow storm or work zone, generally exhibits different characteristics compared to a traffic incident. These events generally have much longer impact duration (more than 8 hours) with fewer real time system measurements. Since the existence of these type of events are often known, adjustments could be made to the algorithm to ensure the enhanced measurement has an optimum performance under the impact of these long term traffic impact events.

In particular, if we extend the variables threshold values and remove the event duration restriction, the system could reported more steady non-free flow traffic speed and better reflect the ongoing traffic condition. The equation to calculate length of event clearance window L_{CLR} could be adjusted to the following:

$$L_{CLR} = Max(N_{imp} + 5, N_{dur}) \quad (3)$$

The trade-off is that Equation 3 results in a more pronounced time lag when the traffic flow actually recovers. In general, a fully optimized algorithm would allow for variation in the event duration window based on the prevailing non-free flow event characteristics. This could be accomplished through external controls (e.g., based on work zone schedule or weather reports) or, as a topic of future research, through adaptive feature detection techniques.

Several cases are presented in the following section to illustrate the enhancement result of the proposed algorithm.

Model Validation

To evaluate the ability of the proposed heuristic data enhancement algorithm to correctly reflect the event impact on traffic flow, the model validation will use event impact case study to simulate the enhanced system measurement performance in Wisconsin. A total of 25 traffic impact events were studied and all the system measurements during those events were processed by the proposed heuristic data enhancement algorithm.

As part of the Wisconsin statewide Traffic Emergency Management Enhancements (TIME) program, traffic incidents and other high impact unplanned events occurring on the state trunk highway system are called into the STOC control room by police and other first responders. Information about the start time, severity, and traffic impact is recorded and distributed through an email alert system. Incident updates and clearance times are also recorded and included with subsequent notifications.

Information from the STOC incident notification system was used in this study to provide "ground truth" information about incidents and other events occurring on the probe-system coverage area where traditional ITS detection such as cameras and fixed detection is otherwise unavailable. Like other forms of ground truth, the incident reports themselves are subject to error. However they do provide a reasonable snapshot of the event for this analysis.

Data Enhancement Case 1

A crash was reported on US highway 41 southbound near Winnebago County, WI. All travel lanes were closed from 8/7/2008 7:15:00 AM to 8/7/2008 9:28:57 AM and the traffic was detoured onto nearby roadways. The probe system speed measurement output on the corresponding location segment during the day and the enhanced measurement result are compared in the figure 3 below (L_{CLR} was defined by Equation 2):

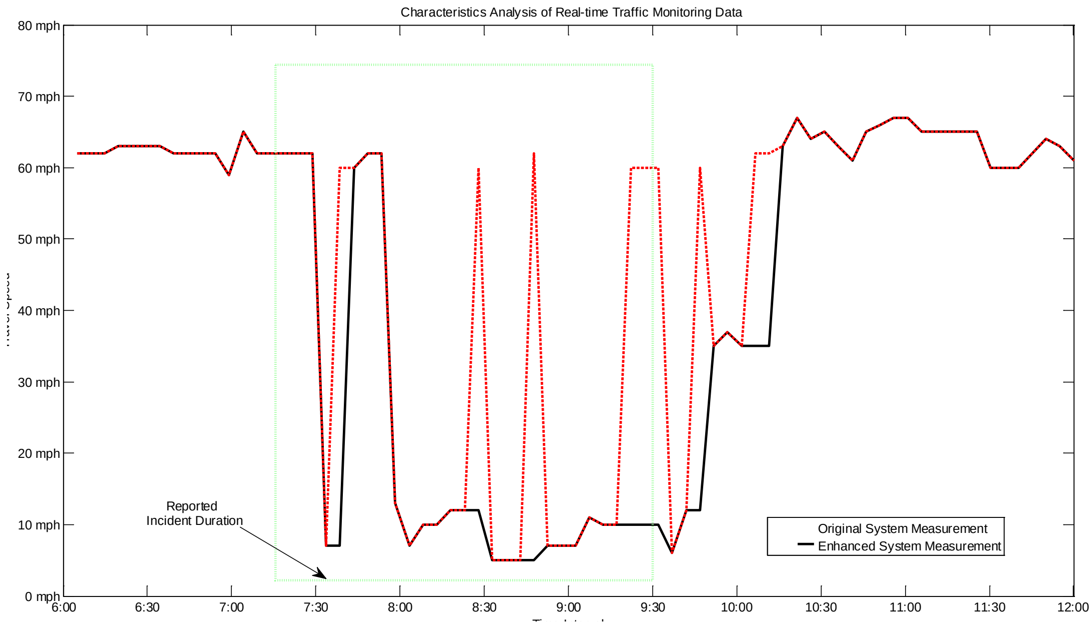

Figure 3 Data Enhancement Case 1

From the figure we can see that the un-trusted default speed measurements during the event duration were replaced by the last trusted measurement values. However at the start of the event, the enhanced measurement briefly reports free flow conditions based on un-trusted probe system default values. The data enhancement algorithm is a heuristic real time method that improves as more information is provided. At the start of the incident, there was insufficient real time system measurement to determine that the traffic flow was under the impact of a longer term event. As such, the enhancement algorithm accepted the false probe-system free flow speeds a reliable measurement. However, once the speed dropped again, the algorithm was more conservative and thereafter replace false measurements by extending the last reliable non-free flow speed. . Note also that at the end of the event, the enhanced measurements did not extend the incident impact because the duration of this has exceeded the pre-defined experiential regular incident duration (2 hours). Therefore the enhanced measurements match reported incident duration closely.

Data Enhancement Case 2

A second crash was reported on US highway 41 southbound in Winnebago County, WI. All travel lanes were reported to be closed from 8/7/2008 4:45:00 PM to 6:20:00 PM and the traffic was detoured onto nearby roadways. The comparison result is shown in Figure 4 (L_{CLR} was defined by Equation 2):

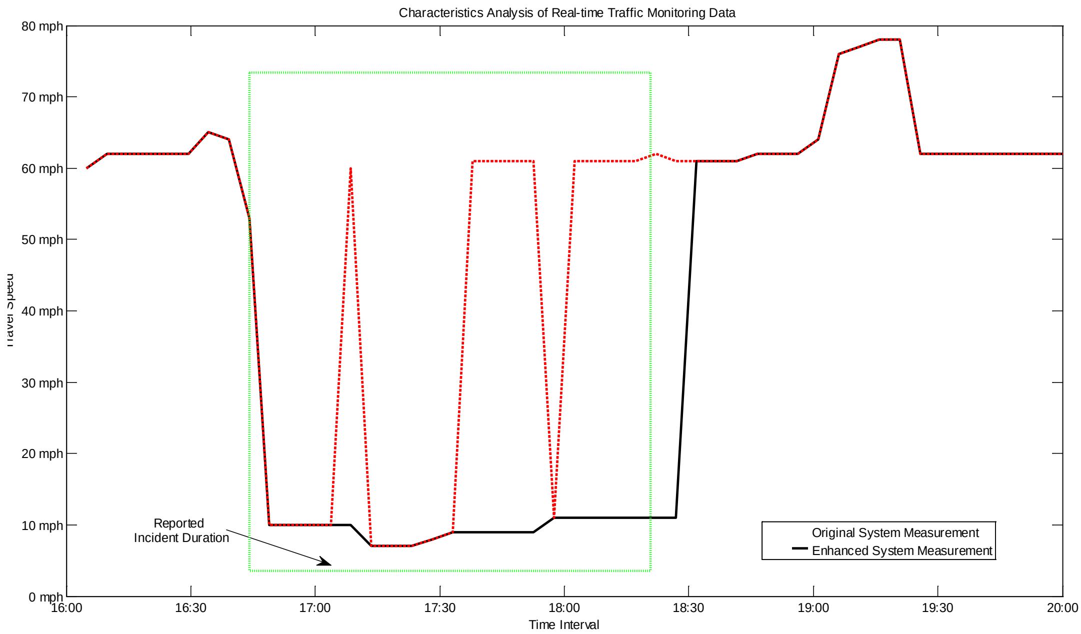

Figure 4 Data Enhancement Case 2

This incident case has a relatively shorter reported duration compare to the first case. We can find from the figure that the algorithm shows perfectly continuously non-free flow system measurements during the reported incident duration even in the early part of the incident. This is because the heuristic data enhancement algorithm has already detected enough non-free flow system measurements to cause the algorithm to disregard the first occurrences of free flow system measurements. As a trade-off, the algorithm appears to have overestimated the incident duration (enhanced system measurement returns to free flow about 15 minutes later then the reported end of incident duration). The major cause of this time lag is that the incident duration is less than the pre-defined experiential regular incident duration (2 hours), the algorithm prefers to trust that the traffic was still under the impact of the traffic impact event.

Data Enhancement Case 3

In this case, the proposed heuristic data enhancement algorithm is evaluated against a long term snow event. Both the original probe system measurement and enhanced measurement are compared to traffic speed data collected by WisDOT loop detectors in the same event impacted area.

From February 5-7, 2008, a major snow event impacted most parts of Wisconsin. A segment of highway on US 43 northbound near Port Washington, Wisconsin was selected to compare the speed values from the original system and enhanced measurements with loop detector data. Figure 5 compares the probe system measurement and enhanced measurement (L_{CLR} was defined by Equation 3):

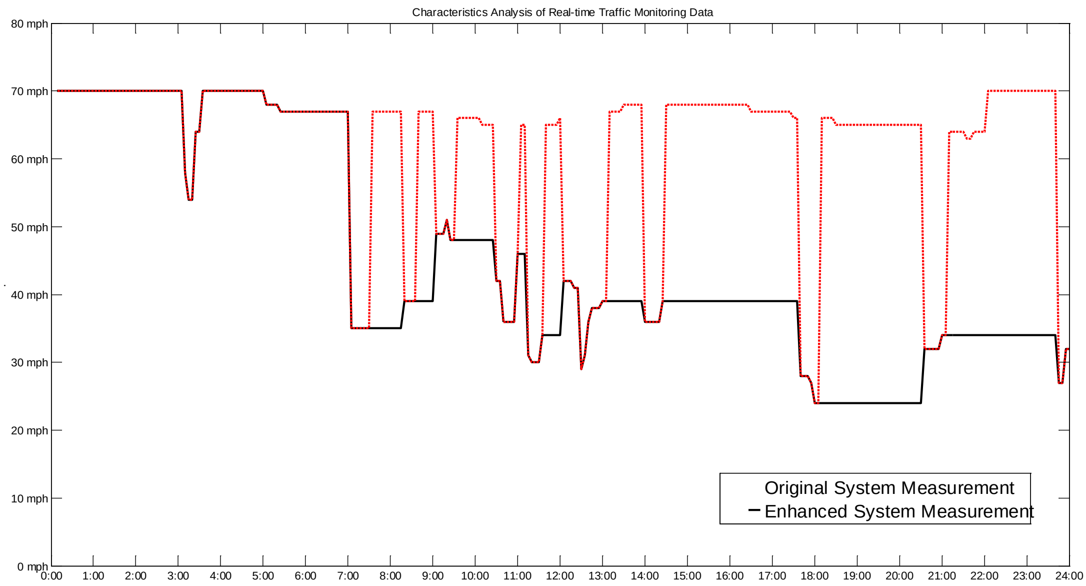

Figure 5 Data Enhancement Case 3 Snow Storm

It is clear that the enhanced measurement reports the speed reduction from the snow storm more clearly and continuously. From the figure, we can see most of the un-trusted system measurements during the snow day were replaced by last trusted non-free flow system measurements. Further study of this case, including statistical comparison of the original and enhanced measurements will presented in the following model evaluation section.

Model Evaluation

Evaluation Design

The February 2008 snow storm from the previous section was chosen to evaluate the performance of the proposed heuristic data enhancement algorithm. Both the original system measurement and enhanced measurement will be compared to traffic speed data generated by loop detectors data in the same event impacted area. Real-time operations loop detector data from the STOC ATMS is aggregated to 5 minute intervals. The equation for calculating the length of event clearance window L_{CLR} in the data enhancement algorithm is based on Equation 3 which is optimized to long term traffic impact event.

Evaluation Indexes

To evaluate the enhanced measurements performance, the following statistical indexes were chosen to examine the difference between the original/enhanced measurement and loop detector data:

ME: Mean Error can be calculated by Equation 4

$$Mean\_Error = \frac{1}{N}\sum_{k=1}^{N}\left(\hat{v}_k - v_k\right) \qquad (4)$$

Where,

v_k : Traffic speed from loop detector data

$\hat{v}_k$: Traffic speed from system measurement (original/enhanced)

MSE: Mean Square Error can be calculated by Equation 5

$$Mean\_Square\_Error = \frac{1}{N}\sum_{k=1}^{N}\left(\hat{v}_k - v_k\right)^2 \qquad (5)$$

MAE: Mean Absolute Error can be calculated by Equation 6

$$Mean\_Absolute\_Error = \frac{1}{N}\sum_{k=1}^{N}|\hat{v}_k - v_k| \qquad (6)$$

Maximum Absolute Error

MARE: Mean Absolute Relative Error can be calculated by Equation 7

$$Mean\_Absolute\_Relative\_Error = \frac{1}{N}\sum_{k=1}^{N}\frac{|\hat{v}_k - v_k|}{v_k} \qquad (7)$$

Evaluation Result and Further Improvements

Results of the statistical evaluation are shown in Table 2 (system measurements before 4 AM were not included to eliminate the disturbance of un-avoidable default free-flow measurements):

TABLE 2 Statistically Compare Original vs. Enhanced system measurement

	ME	**MSE**	**MAE**	**Max. MAE**	**MARE**
Original Measurement	17.2	549.8	19.4	41	54%
Enhanced Measurement	-0.5	99.0	8.4	21	20.1%

From Table 2, we can see the ME of enhanced measurements was almost eliminated, which shows the system does not have an obvious bias. However, the enhanced measurements still have a MARE of 20%, which is 8.4 mph in average. From Figure 7 below, we can see this error was mainly caused by the original difference of the system measurement and loop detector data, which is not eliminated by a data enhancement algorithm. Aside from this difference, the enhanced measurement provides a much more faithful representation of the ground truth loop detector data.

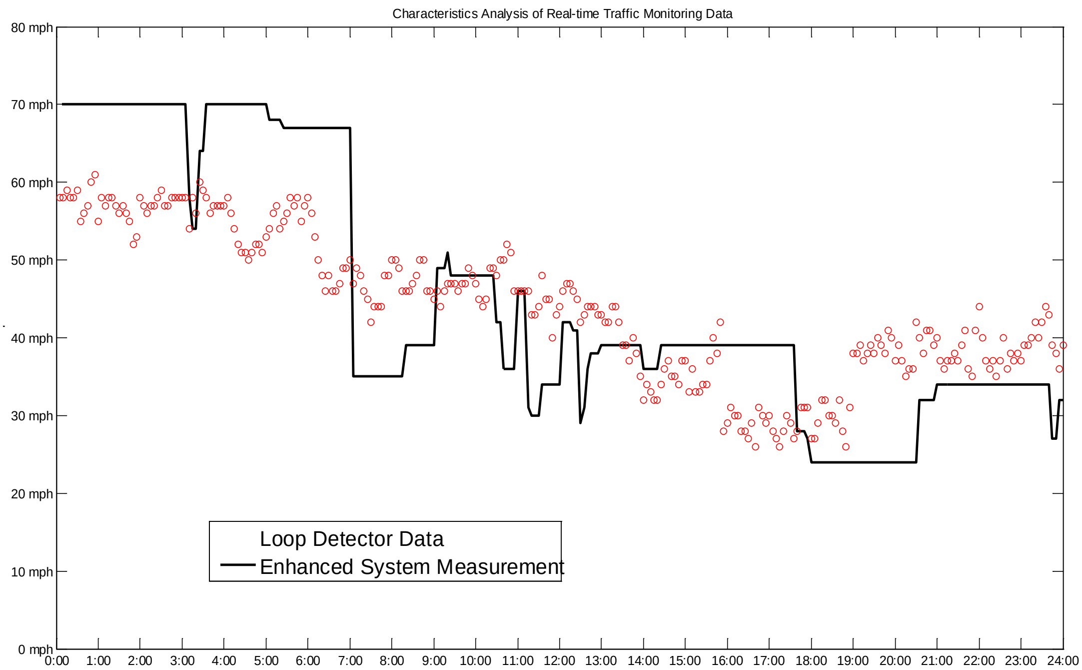

Figure 7 Enhanced Measurement VS Loop Detector Data of Case 3

As shown in Figure 8 and Table 2, the data enhancement algorithm could improve the use of probe system data in a traffic operations control room setting to better monitor real-time traffic flow during long term events. By replacing non-free flow speed data while the event clearance window length L_{CLR}, the enhanced measurements show the similar trend of traffic speed reduction during the snow day compared with the ground truth loop detector data.

Conclusion and Further Research

Currently most of the probe based traffic information systems share the problem of insufficient sampling rate in roadways, especially during nighttime and under the event impacts. Although some probe based traffic monitoring system was aware of this shortcoming and prepare to add a column in their data to indicate whether current measurement is based on real time data, an enhancement algorithm to exclude un-trusted default data based on system speed measurement is still missing. The heuristic data enhancement algorithm proposed in this paper provides a real time system neutral methodology to improve the probe based traffic monitoring system performance under event impacts. Compared to the original system output, the enhanced measurements would help WisDOT's control office to monitor the impact of the events to the traffic flows more precise and continuously.

However, under the impact of a long term event, such as long lasting major snow event or work zone, the traffic monitoring system may lack for sufficient real time measurements for more than 8 hours (e.g., case 3 in section 3). This situation could lead to serious discontinuously reliable system output even after the current data enhancement. As we aware that these type of events in advance (Serious major snow storm is predictable, long term work zone have work plan in DOT), this shortcoming could be overcame by adjusting the equation of calculate length of variable event clearance window L_{CLR}.

Despite the proposed data enhancement algorithm was applied to server major traffic impact events successfully, further studies are required to validate the findings of this study. An automatic method of detecting the event type and switching the equation to calculate the length of event clearance window L_{CLR} could be studied. The optimum equation of calculate event clearance window length could be investigated and the universality of this data enhancement algorithm need to be studied in the traffic monitoring system platform.

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