Battery saving communication modes for wireless freeway traffic sensors

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ABSTRACT

Efficient management of a freeway network requires continuous decision-making based on measured traffic conditions. These measurements usually come from fixed-point sensors deployed in such a manner as to require "always-on" communication links that are polled at regular intervals. Upon receiving the sensor data at a Traffic Management Center (TMC) most of the time no action is taken in response to the information, leading to unnecessarily high power consumption for the frequent transmissions. This fact becomes burdensome for wireless sensors that rely on batteries either to last through periods without sufficient illumination for solar power or for the entire lifespan of the sensor if it has no external power supply. Radio transmissions are a large power draw, so each transmission that can be avoided directly translates into longer battery life.

To reduce communication frequency without a significant loss in the quality of information this paper develops a distributed freeway surveillance system that pre-filters the data at the sensor unit. Five communication modes are developed that assess the value of the measurements before making the send/do-not-send decision. Key to this event-driven approach is the fact that the receiving end is an intelligent part of the distributed surveillance system, i.e., given the lack of transmission the TMC side will know how to interpret the evolving traffic state at the sensor location in the context of previously received information.

1 INTRODUCTION

Freeway surveillance from fixed-point sensors to measure the traffic state is important for efficient operation, effective management and the safety of the users. Applications include ramp metering, traveler information, and incident detection. Typically data are collected about the operational condition of the freeway network using spatially distributed sensors that transmit data to a central system for decision-making processes. Conventionally these freeway surveillance systems employ a fixed-time communication structure where each sensor is polled by a central server to collect the current traffic state at the sensor location. Most of the time the response to the information is simply that no action is necessary. This fact becomes burdensome for wireless sensors that rely on batteries either to last through periods without sufficient illumination for solar power [1-3] or for the entire lifespan of the sensor if it has no external power supply [4]. Radio transmissions are a large power draw, so each transmission that can be avoided directly translates into longer battery life. In fact lower transmission frequency is often used by [3] at night to prolong battery power, but it is done at the expense of responsiveness.

To reduce significantly the required number of transmissions per sensor location without sacrificing responsiveness this work develops the new approach of a decentralized, event-driven surveillance system. In this approach the first step of the decision-making process is done at the senor unit rather than the central server. In this scheme the sensor units in the field assess the value of recent observations and will only choose to transmit recent data if it reflects enough deviation from the last reported data or historical daily trends for that location, i.e., whether or not knowledge of the observed conditions at the sensor have a chance of impacting a response from the central server. Key to this event-driven approach is the fact that the receiving end is an intelligent part of the distributed surveillance system and given the lack of transmission the central server side will know how to interpret the evolving traffic state at the sensor location in the context of previously received information, e.g., no transmission means conditions are stable or conditions are following the established historical daily trends.

1.1 Centralized versus Decentralized Structure

Centralized systems offer conceptually simpler corridor or regional management since extensive information is available both temporally and spatially for processing. In the traditional centrally controlled system, the communication network must support a continual communication link between many field controllers and the central server, constantly moving both data and control commands. The local processing power and memory in the field may be minimal, only enough to carry out the commands issued by the central facility and store recent sensor data collected for transmission, while large volumes of raw, unprocessed data would typically be transmitted from the field. In a fully distributed system the reverse is true; control is totally localized, with information and control messages transmitted only when major deviations are detected or when special needs exist for changes to the field devices. The decentralized systems rely more extensively on processing resources in the field with greater capabilities to filter and analyze the data, thereby greatly reducing the number of data transmissions. Provided care is taken to ensure that the set of feasible states are known in the absence of communication, the amount of information available from a decentralized communication system can approach that of a centralized system.

The underlying principle in the decentralized surveillance structure is that communication is needed only when the data transfer has informational value and can provide additional knowledge about the freeway system under surveillance. This information is valuable if knowledge of it could result in a response by the central server (most likely located in a traffic management center, TMC), to a change in the current state of the system. Thus, in a relatively simple architecture, when no data are transferred from the field devices, the TMC could assume that the current state is similar to the last reported state from the sensors or expected state of the system from historical trends. Of course this assumption about the current state can be erroneous when the communication link to the central server is broken or when the field device is malfunctioning. To ensure that *no news is good news* it is envisioned that the field sensors will send data on a lower frequency even when no control actions are warranted. These periodic connections can also be used to transmit summary data, allowing the field detector to update the historical daily trend or support post hoc planning applications that require data over an extended time frame. Meanwhile, there are numerous errors that can impact the underlying quality of the sensor data. Real traffic data are noisy even when a sensor is performing perfectly so the sensor units will need to incorporate strategies to account for inhomogeneous vehicles, e.g., [6-9]. Of course many real sensors may not perform perfectly, so the sensor unit will also need to include diagnostics to ensure that the sensor is operating correctly, e.g., [10-15], or be able to automatically request a maintenance call if there are any problems.

The types of data and resolution required for traffic management applications depend on the specific application and data processing algorithm. The set includes real time applications like freeway incident detection, freeway ramp metering, traveler information systems; and offline applications like traffic data collection for planning, system performance evaluation and archival or historical purposes [5]. Conventionally these applications are developed and deployed for a centralized surveillance structure. Briefly discussing the impacts of a decentralized structure on the applications: Real time applications like freeway incident management, traveler information, and ramp metering systems will not be affected significantly if the design of the decentralized surveillance and communication structure is done appropriately to allow a quick response. In fact this paper develops and tests several communication modes that are capable of supporting these real time applications. Offline applications often require data over extended time frames. The decentralized communication algorithm can be designed to collect and store data locally and then transmit it to center at low frequency. As noted above, these low frequency transmissions can be used by the TMC to also verify that the sensor unit is operational. Hence, provided care is taken, the performance of offline applications is less likely to be affected by the decentralized structure.

1.2 Overview

The remainder of this paper develops several approaches to reduce the transmission frequency from sensor units in the field without a significant loss in the quality of information received at the TMC. Then the various approaches are evaluated in the context of actual detector data both to tabulate the reduction in transmissions and the impacts on the quality of information at the TMC. The paper then closes by summarizing the findings and presenting the conclusions of this work.

2 DECENTRALIZED SURVEILLANCE AND CONTROL ALGORITHMS

This section develops five related distributed surveillance algorithms to greatly reduce the number of data transmissions without sacrificing the performance of traffic management applications. Different applications require differing rates of data transfer, for instance, incident management requires data transfer at a higher frequency during incident detection and clearance with lower rates other times, traveler information may only require data transfer when the operating speeds change significantly. The amount of data transferred also varies from location to location and one might expect a large amount of data transferred from a location that experiences high traffic volume and longer periods of congestion as compared to a remote location that rarely sees congestion. Section 2.1 develops several algorithms to pre-filter data in the field and only initiate communication when the information might benefit decision-making. These algorithms differ primarily in the criteria for the pre-filtering decisions, subject to the goals of reducing transmission frequency and improving the benefits from those data that are transmitted.

2.1 Algorithms for Different Communication Scenarios

Below we present a conceptual overview of the communication modes developed for decentralized surveillance in the increasing order of transmissions made. The algorithms apply threshold value tests to aggregated sensor data by comparing measurements against maximum and minimum acceptable values to validate the data as well as make a decision about the need for communication. The methodology developed is generic and could be modified for other sampling periods, possibly with some changes to thresholds. To identify the trends and relationship between traffic variables and to make the decision to transmit, the algorithms use a single measure of flow, occupancy and speed. The data are cleaned using the algorithm presented in [7] to ensure the sensor data are as accurate as possible. In the event that a sensor does not measure flow or occupancy, it is a simple modification to the algorithms to only use the metrics provided by the sensor. While the specific format of the communication messages is beyond the scope of the current work, there will be two types of transmissions: real time updates whenever the sensor chooses to transmit information; and low frequency status reports to ensure that: the TMC knows that the sensor is still operational even if it is otherwise silent, the TMC knows how many transmissions were made since the previous status report, any summary information necessary for offline applications (e.g., measuring average daily traffic), and diagnostic information about how well the sensor is performing. While acknowledging the importance of the status reports for a robust decentralized system, the focus of this paper is the impacts on real time operation, i.e., the information conveyed from the real time updates. This paper develops the following five different communication modes for the real time transmissions:

Mode 1: Free-flow or congested

From an operations standpoint the most important information for a traffic surveillance system is to determine reliably and quickly whether the facility is free flowing or congested. Mode 1 seeks to minimize the number of transmissions while conveying this state change. The algorithm identifies the traffic state locally and sends a single transmission when the speeds at the sensor unit first drop below a threshold, e.g., 50 mph on a 65 mph facility, indicating that the facility is likely congested. To reduce the sensitivity to transient events the algorithm must see N consecutive samples below the threshold before deciding to transmit the state change, where N could be set to 2 or 3 for 30 sec samples. Once the congested state has been transmitted the algorithm then waits until speed rises above the threshold, e.g., 60 mph on the same 65 mph facility, at which point a single transmission is sent to indicate that the facility has returned to free flowing.

Mode 2: Multiple thresholds drop

Operating agencies are often interested in quantifying the magnitude of congestion for applications like estimating traveler delay. These applications need more information about the congested traffic state than simply whether or not the facility is congested. Often the onset of congestion on a freeway is typified by speeds slowly deteriorating and then the speeds remain at a particular level for extended period. The level at which the speeds become stable might vary from day-to-day and is influenced by demand, location, and weather. Knowing this level on a given day can help applications, e.g., traveler information. To this end, the Mode 2 transmits information about the traffic speed dropping below each of multiple thresholds when the facility becomes congested until the speed becomes stable or reaches a lower bound, throughout, no increase in speed is reported until the facility returns to free-flow conditions. The different threshold ranges for a freeway with posted free-flow speed of 65 mph could be set at 50 mph, 40 mph, 30 mph and 20 mph. So the speed between consecutive samples during a stable traffic state is allowed to vary within the range of 10 mph. Of course a different threshold range can be used depending upon the needs of the specific application. Like Mode 1, the algorithm waits until N consecutive samples below a given threshold (or above the recovery threshold) before deciding the state has changed.

Mode 3: Multiple thresholds drop and recovery

While Mode 2 follows dropping speeds it does not report any improved conditions until free-flow is observed. In Mode 3, the algorithm is similar to Mode 2, transmitting data when the traffic drops below several thresholds but it also reports any partial recovery by tracking increasing speeds too. The rising speed thresholds are followed because data transmitted in Mode 2 may not be sufficient for some applications. The criteria for transmitting information to report the decreasing speeds are similar Mode 2; however, to avoid erroneous "recovery" signals due to transient high speeds within a queue the algorithm has to see M successive samples above a given threshold before deciding the state has changed, where M and N may differ.

Mode 4: Significant deviation from last reported state

Modes 1-3 check whether the traffic state falls in pre-defined ranges and information is only transmitted whenever a set of conditions for a given range is satisfied. This approach may not be able to capture a sharp variation in speeds that does not last for many samples. For applications like incident management, operating agencies seek to identify and localize the source of delay as quickly as possible and any abrupt sharp changes in measured traffic speeds helps expedite this localization. To reduce any delays Mode 4 is developed to provide quicker response without increasing significantly the number of transmissions. Mode 4 is similar to Mode 3 except if conditions are stable and speeds change by 20 mph from the last transmission the sensor unit will transmit immediately rather than waiting the full N or M samples.

Mode 5: Highest frequency when congested

In general detector data are usually of greatest interest to the TMC when the traffic is congested at the sensor unit location. Like the other modes, Mode 5 does not transmit data during free-flowing periods, as the freeway speeds can easily be estimated if it is known that the freeway is not congested. If the facility is not free flowing then the algorithm transmits data to the TMC at the highest frequency, i.e., every sample, until free-flow conditions return. Since most facilities are uncongested for the majority of the time, this approach can reduce the number of transmissions without reducing measurement precision.

Multi-mode operation

Regardless of the primary mode of operation, the algorithms can be designed to incorporate information about both recurring and special events. For example, often a TMC is only staffed for a part of the day and the data transmitted from the sensor units are only used in real-time while the TMC is occupied. If the surveillance system is designed with the possibility of two-way communication between the field device and the TMC, then the TMC could potentially ask the sensor units to stop sending data during specific hours or days. In this case the sensor units would cease transmitting the real time updates and only transmit the low frequency status reports during the "off" hours. On the other hand, planned special events like national holidays or major sporting events are likely to alter the traffic flow patterns. To respond to these events the algorithm might be set to shift to a different communication mode with lower or higher transmission frequency to meet the demands of the given type of event.

The detailed description of these algorithms can be found in Appendix A of [16]. The default value of N were set for 30 sec samples and are as follows: N = 2 samples in Mode 1; N = 5 samples in Modes 2-4 (except for the recovery to free flow which is 2 samples) and M = 5 in Mode 3-4; in Mode 5 N = 2 samples during free flow and the sensor unit will transmit every sample during congestion.

2.2 Constructing synthetic time series of speed at the TMC

Many traffic management applications use time series speed as an input. In conventional traffic monitoring networks all of the data from the sensor units are transferred at a fixed rate, directly yielding the time series at the TMC. In the event-based system, such a time series has to be reconstructed using the limited amount of information transmitted. For all five modes a simple synthetic time series of speed can be estimated by assuming that speed stays at the last reported value until such time that the field algorithm sends more information, while estimates for free-flow periods are assumed to be constant, e.g., the posted free flow speed.

A more sophisticated algorithm could be developed where the daily trends are tracked and instead of responding to deviations from the last reported state, the algorithms at the field sensors and reconstruction algorithms at the TMC use deviations from the typical day. Other possible additions include having the sensor unit in the field send a measure of confidence with the rate of change of speed. Coupling these measures of confidence with long term trends extracted from historical data, one can possibly obtain better estimates. Other traffic state estimation algorithms and time series forecasting algorithms that employ extrapolative forecasting methods may also help improve the accuracy of the synthetic time series, e.g., [17], but were not considered in this research.

3 ANALYSIS OF THE ALGORITHMS AND THEIR USEFULNESS

While this work is intended for low power, wireless sensor units, the actual development simply requires traffic data. To this end the work uses time series data from loop detector stations along several corridors, collected over several months. These time series data provide the ground truth for which the different operating modes can be compared against in terms of the information retained after greatly reducing the number of transmissions. The threshold values used in this work for each mode were developed empirically using historical data collected from 40 loop detector stations on I-70/71 corridor in Columbus, OH and 97 loop detector stations on SR-101 thorough San Francisco, CA.

Figure 1 compares the time-series speed for a typical station (northbound Station 107) on I-70/71 in Columbus, OH, across the five modes on a randomly chosen weekday. The plots show the time series speed after passing through the data-cleaning algorithm developed in [7] and the synthetic time series constructed using the methodology described in the previous section. Plots A-E are for communication Modes 1-5 respectively. The horizontal axis shows the 30-second sample number starting at 1 from 12:00 a.m. A second horizontal axis at the bottom of plot E shows the time of the day. As can be observed from the plots the synthetic times series follows the raw underlying data in all cases and it does so with increasing precision as the mode number increases. This result should not be surprising since the increasing mode number generally corresponds to increasing the number of transmissions, and thus, the amount of information transferred. Mode 4 follows the underlying time series closely without requiring many transfer points because of the pre-filtering logic used for the transmission decision. The synthetic time series in Mode 2 and 3 deviate considerably from the input series because Mode 2 only transmits information as speeds drop past thresholds separated by 10 mph, while Mode 3 also does so as speeds increase past these thresholds.

Figure 2 shows the average number of transmissions made by stations during one month, expressed as a percentage of the daily samples collected in the field on the I-70/71 corridor. Plots A-E show the percentage of transmissions for Mode 1-5 respectively. The daily numbers of transmissions at a station are summed up for both northbound and southbound direction lanes. Although not shown in the figure, the average numbers of transmissions on weekend day were observed to be lower than those for weekdays. A horizontal axis at the bottom of the figure shows the location of the Central Business District (CBD) and the relative distance of the detector stations from the CBD. As expected, the number of transmissions is smallest for Mode 1 and largest for Mode 5 (note the different vertical scale for plot E). The transmission frequency for Modes 1-4 are comparable to each other, with all stations transmitting on average fewer than once for every 100 samples in the field. As observed in the figure, the numbers of transmissions for all communication modes are highest for stations close to the CBD, while the remote stations require few transmissions. This distribution is not surprising because the stations near the CBD observe longer periods of congestion and higher traffic volumes compared to remote stations that typically do not see recurring congestion. Table 1 summarizes the results of Figure 2 showing the mean and maximum number of transmissions across the 40 stations. To get the percentages shown in the figure, one should divide the values in the table by the maximum feasible number of transmissions, 2880 samples per day. Note that the reporting frequency is higher in Mode 1 than Modes 2 and 3 because the default settings have Mode 1 using $N = 2$ samples to make the transmission decision while Modes 2 and 3 use $N = 5$ samples.

So far this section has shown the results for a month of data from I-70/71 in Columbus, Ohio (this month differed from that used in the aforementioned calibration period). The analysis was repeated on four other freeways in California with similar results (4 loop detector stations on I-80 in Berkeley, 8 loop detector stations on SR-51 through Sacramento, 18 loop detector stations on I-15 through San Diego, and 40 loop detector stations on I-405 through Los Angeles). Table 2 presents the maximum across all stations of the daily station average from the given month for: absolute error between the synthetic time series and measured speed, percentage absolute errors for the synthetic time series and measured speed, and the ratio of the number of transmissions per number of samples. The results are broken down by mode and these measures exhibit similar trends on each of the corridors. Although the thresholds used by each communication mode were developed using only data from I-70/71 and SR-101, the thresholds were the same for each of the freeway segments analyzed. The similarity of the performance measures for all freeways suggests that the calibrations could be transferrable.

3.1 Case study: traveler information systems

This section investigates the performance of the decentralized surveillance algorithms on travel times. There are two common methods to estimate travel times along a corridor that is instrumented with several sensor units. First consider the *instantaneous travel time estimate* calculated at the time of departure- one would commonly take the segment length and divide by the most recent speed measurement on all links between the origin (O) and destination (D) and then sum these link travel times together. While this approach is the best that can be done in real time without using models or historical data, these instantaneous estimates are prone to large errors because they do not capture changes in traffic conditions before a given link is reached. Alternatively, using archived data, one can obtain a more accurate travel time estimate by working backwards from the arrival at D, and stepping back one link at a time. Only now using the given link speed at the time the vehicle actually traveled on that link. These *virtual vehicle travel time* estimates are more representative of what is actually experienced by drivers compared to the instantaneous estimates.

This paper adopts the virtual vehicle travel time estimation, though similar performance is found when using the instantaneous estimates. To this end, the freeway is divided into segments with each segment starting midway between two adjacent sensor units. The time space plane is segmented into a grid, with each cell taking the speed measurement corresponding to that time and link. The travel time between two locations (O and D) is computed by moving a virtual vehicle in the time space plane with a speed determined by its current time and link, and the travel time on the freeway is the sum of the individual link travel times. By repeating this process for an entire day, one can estimate the travel-time time series for a given O-D pair along the freeway. By dividing the travel-time time series with the distance between the O and D, *average trip speed* time series can be obtained. This work computed the link travel times using the complete data set and then repeated the calculation susing the synthetic time series arising from each communication mode. Figure 3 compares the virtual vehicle travel time and average trip speed using all data (conventional method), Mode 1, Mode 4 and Mode 5 for a typical O-D pair. The plots A and B are for a randomly chosen weekday's data and the plots C and D are for the average of one month's data, all collected on a 4.4 mile long section of I-70/71 northbound in Columbus, OH. Only three communication modes are shown for clarity. Mode 1 and 5 represent the lower and upper bound for amount of information transmitted and Mode 4 is of special interest due to its accuracy and quick response time in transmitting change of speed while otherwise maintaining a low transmission frequency. As can be observed from the plots, the estimates of Mode 5 are closest to the conventional methodology and Mode 1 deviates the most. The estimates of Mode 4 also follow the conventional methodology closely, which is encouraging considering the significant difference in the number of transmissions between Modes 4 and 5. The time series plots of travel time and trip speed appear smooth because combining data across several sensor locations reduces much of the noise. This smoothing of travel time is acceptable for many applications since people usually travel long distances on a freeway. The plots are further smoothed when an average across a month of data is taken. Figure 4 shows several scatter plots comparing average estimated travel times and trip speeds, comparing the results for the given mode against those when using all of the speed data using the same data set as in Figure 3C-D. The first column of subplots compare the travel time estimates and the second column compare the corresponding average trip speed estimates. The top row of plots is for Mode 1; middle row of plots for Mode 4; and the bottom row of plots for Mode 5. Once more Mode 5 performs the best and Mode 1 the worst. Notice that the Mode 1's performance deteriorates considerably in the presence of larger travel times, i.e., congestion. Mode 4 shows mixed results and Mode 5 performs well during congestion as well as free-flowing periods.

4 DISCUSSION AND CONCLUSIONS

Freeway management and control requires up to date information about the operational condition and status of the network. Conventionally fixed-point surveillance systems are deployed and they are polled at regular intervals from a central location, with a given sensor unit only responding when polled. These systems require the transmission of all of the data, yet most of the time the response to the data is simply that no action is necessary. This fact becomes burdensome for wireless sensors that rely on battery power. Radio transmissions are a large power draw, so each transmission that can be avoided directly translates into longer battery life. In fact lower transmission frequency is often used by [3] at night to prolong battery power when solar power is unavailable, but it is done at the expense of responsiveness. To reduce significantly the required number of transmissions per sensor location without sacrificing responsiveness this work developed a new approach for a decentralized, event-driven surveillance system. In this approach the first step of the decision-making process is done at the senor unit rather than the central server. In this scheme the sensor units in the field assess the value of recent observations and will only choose to transmit recent data if it reflects enough deviation from the last reported data or historical daily trends for that location, i.e., whether or not knowledge of the observed conditions at the sensor have a chance of impacting a response from the central server. These new communication modes are compatible with existing sensor units, e.g., [18] presents an incident detection algorithm that would be compatible with Mode 2 or higher.

The methodologies were tested off-line with 30 second aggregate data collected from a diverse set of freeways and it was insensitive to site-specific characteristics. Communication Modes 1-4 required transmission of less than 2 percent of the samples on all locations. Mode 5 required transmission of less than 2 percent of samples for remote locations and as high as 21 percent of samples for locations that observe extended periods of congestion. The number of transmissions for all communication modes was found to be highest for sensor units close to the CBD, while the remote sensor units required few or no transmissions. The average error in speed estimates obtained using information transmitted by each Mode was less than 8 mph for all modes and locations. The time-series speed estimates as compared to measured speed for Modes 4 and 5 showed the best performance.

4.1 Calibration of the Algorithms

The surveillance algorithms apply threshold value tests to identify trends and make a decision about the need to transmit information to the TMC. The threshold values can be location and communication mode specific. In some cases the algorithms will have to be recalibrated and thresholds reset to account for the specific geometrical and physical nature of the roadway being monitored or the detectors being used, e.g., a sensor unit located near a diverge might require different threshold than it would otherwise require. In such cases, if historical data are available, the data can be used to set the thresholds and calibrate the algorithm. In the absence of historical data the sensor units can be deployed with the thresholds developed in this work and allowed to calibrate themselves for a few days before the output can be used reliably and confidently. The low frequency status reports can be combined to construct long-term trends of flow, occupancy and speed from the summary data at a given sensor unit. The thresholds are re-calibrated using [7] based on long-term trends, e.g., a given facility should be free-flowing for the majority of a 24 hour period and therefore the time series of speed reported by the algorithms should have most of the samples above the free-flow threshold and less than a reasonable maximum feasible value. Similarly if the long-term profile indicates that the sensor unit exhibits high degree of flicker, i.e., the traffic speed frequently and quickly changing between free-flow and congestion, then the time for which the algorithm waits to identify a given trend has to be increased. This mechanism also helps the algorithms adapt to time-of-day, day-of-week, and seasonal trends. Ideally the sensor unit would incorporate data cleaning algorithms similar to [6-15] to calibrate for the given sensor's behavior and catch any chronic sensing errors.

5 ACKNOWLEDGEMENTS

This material is based upon work supported in part by the National Science Foundation under Grant No. 0127944 and by the California PATH (Partners for Advanced Highways and Transit) Program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation. The Contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. This report does not constitute a standard, specification or regulation.

6 REFERENCES

[1] http://www.imagesensing.com/products/radar-detection.html, accessed 7/24/2015

[2] http://www.wavetronix.com/en, accessed 7/24/2015

[3] http://speedinfo.com/

[4] http://www.sensysnetworks.com/, accessed 7/24/2015

[5] Margiotta, R., *State of the Practice for Traffic Data Quality*, white paper prepared for Office of Policy Federal Highway Administration Washington, D.C., 2002. http://www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/13768.html

[6] Coifman, B., Dhoorjaty, S., and Lee, Z., "Estimating Median Velocity Instead of Mean Velocity at Single Loop Detectors," *Transportation Research: Part C,* vol 11, no 3-4, 2003, pp 211-222.

[7] Jain, M., Coifman, B., "Improved Speed Estimates from Freeway Traffic Detectors," *ASCE Journal of Transportation Engineering,* Vol 131, No 7, 2005, pp 483-495.

[8] Coifman, B., Neelisetty, S., "Improved Speed Estimation from Single Loop Detectors with High Truck Flow," *Journal of Intelligent Transportation Systems,* Vol 18, No 2, 2014, pp 138-148.

[9] Turochy, R., Smith, B., "A new procedure for Detector Data Screening In Traffic Management Systems", *Transportation Research Record 1727*, 2000, pp127-131

[10] Coifman, B., "Using Dual Loop Speed Traps to Identify Detector Errors," *Transportation Research Record no. 1683,* Transportation Research Board, 1999, pp 47-58.

[11] Chen, C., Kwon, J., Skabardonis, A., Varaiya, P., "Detecting Errors and Imputing Missing Data for Single Loop Surveillance Systems," TRB, *Transportation Research Record 1855*, 2003, pp 160-167.

[12] Coifman, B., Dhoorjaty, S., "Event Data-Based Traffic Detector Validation Tests," *ASCE Journal of Transportation Engineering,* Vol 130, No 3, 2004, pp 313-321.

[13] Lee, H., Coifman, B., "Identifying and Correcting Pulse-Breakup Errors from Freeway Loop Detectors," *Transportation Research Record 2256,* 2011, pp 68-78.

[14] Lee, H., Coifman, B., "Quantifying Loop Detector Sensitivity and Correcting Detection Problems on Freeways," *ASCE Journal of Transportation Engineering,* Vol. 138, No. 7, 2012, pp 871-881.

[15] Lee, H., Coifman, B., "Identifying Chronic Splashover Errors at Freeway Loop Detectors," *Transportation Research-Part C,* Vol 24, 2012, pp 141-156.

[16] Coifman, B., Distributed Surveillance and Control on Freeways, Assistance to Caltrans for Assessment of Communications Needs and Solutions, TO 4133 Final Report, Part II, University of California - PATH, 2004.

[17] Kwon, J., Coifman, B., and Bickel, P., "Day-to-Day Travel-Time Trends and Travel Time Prediction from Loop-Detector Data," *Transportation Research Record no. 1717,* Transportation Research Board, 2000, pp 120-129.

[18] Coifman, B., Mallika, R., "Distributed Surveillance on Freeways Emphasizing Incident Detection and Verification," *Transportation Research Part A,* Vol 41, No 8, 2007, pp 750-767.

Table 1, Maximum and mean number of daily transmissions per station on I-70/71 corridor in Columbus, OH, across 40 stations for February 2002 data.

Mode	Number of transmissions	
	Maximum	Mean
1	28	6
2	25	5
3	26	7
4	30	9
5	413	71

Table 2, Performance over a month of data from different corridors: I-70/71 in Columbus, OH; I-80 in Berkeley, CA; SR-51 in Sacramento, CA; I-15 in San Diego, CA; and I-405 in Los Angeles, CA.

	Mode	Max across stations of the mean daily Absolute Error (mph)	Max across stations of the mean daily % Absolute Error	Max across stations of the mean daily % of Transmissions
I-70/71	1	4.0	10.3	0.97
	2	4.2	8.6	0.87
	3	4.0	8.2	0.90
	4	3.9	7.6	1.04
	5	3.2	5.7	14.34
I-80	1	5.8	22.3	0.39
	2	4.8	12.5	0.50
	3	4.5	11.6	0.66
	4	4.1	11.8	0.82
	5	3.1	7.6	25.17
SR-51	1	6.5	26.8	0.52
	2	5.7	13.7	0.56
	3	5.5	13.3	0.59
	4	4.9	13.8	0.77
	5	5.4	13.7	15.89
I-15	1	6.4	34.1	0.33
	2	6.7	11.7	0.36
	3	5.5	11.0	0.43
	4	4.8	10.1	0.70
	5	4.4	9.8	11.88
I-405	1	8.1	38.3	0.60
	2	7.6	27.9	0.69
	3	7.6	26.4	0.78
	4	7.4	25.1	0.82
	5	7.3	24.2	21.05

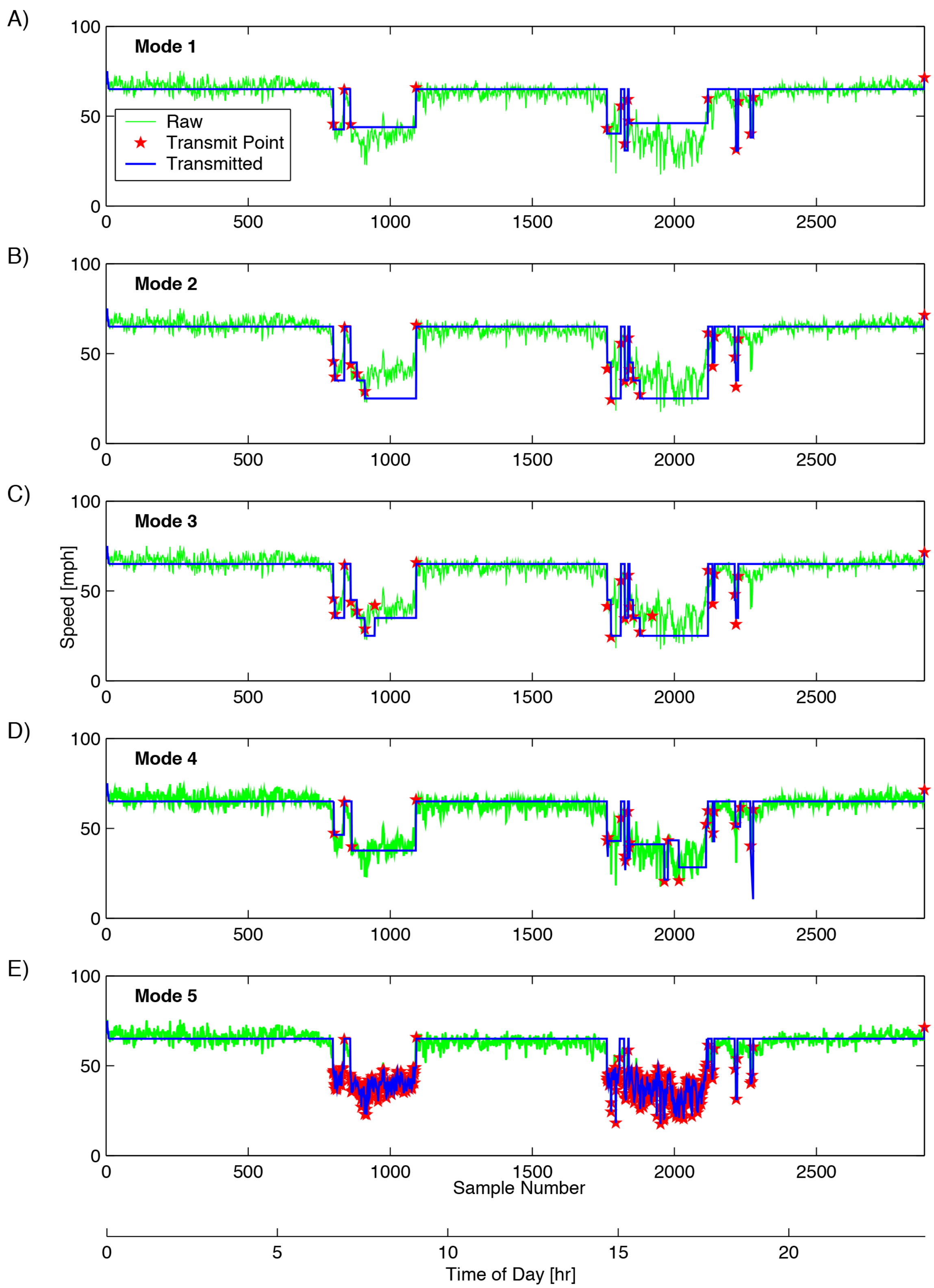

Figure 1, Time series of raw speeds, transfer points and synthetic speed at Station 107 Northbound on I-70/71 for a randomly selected weekday. Plots A-E are for Modes 1-5, respectively.

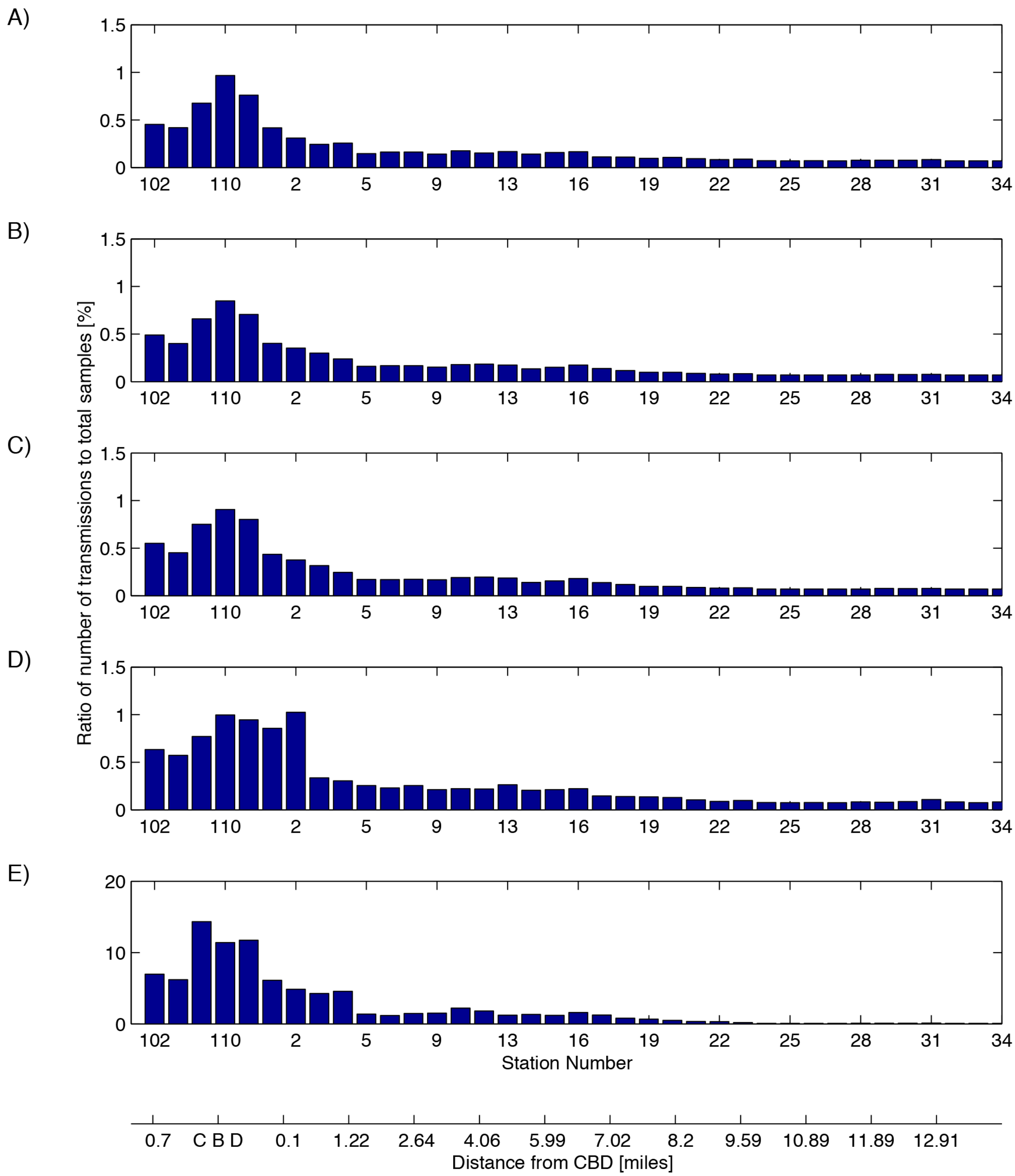

Figure 2, Average number of transmissions made by each station, expressed as a percentage of samples in the field on the I-70/71 corridor at Columbus, OH for the data from February 2002. A-E show the percentage of transmissions by Modes 1-5, respectively. Note the change in vertical scale on plot E for Mode 5.

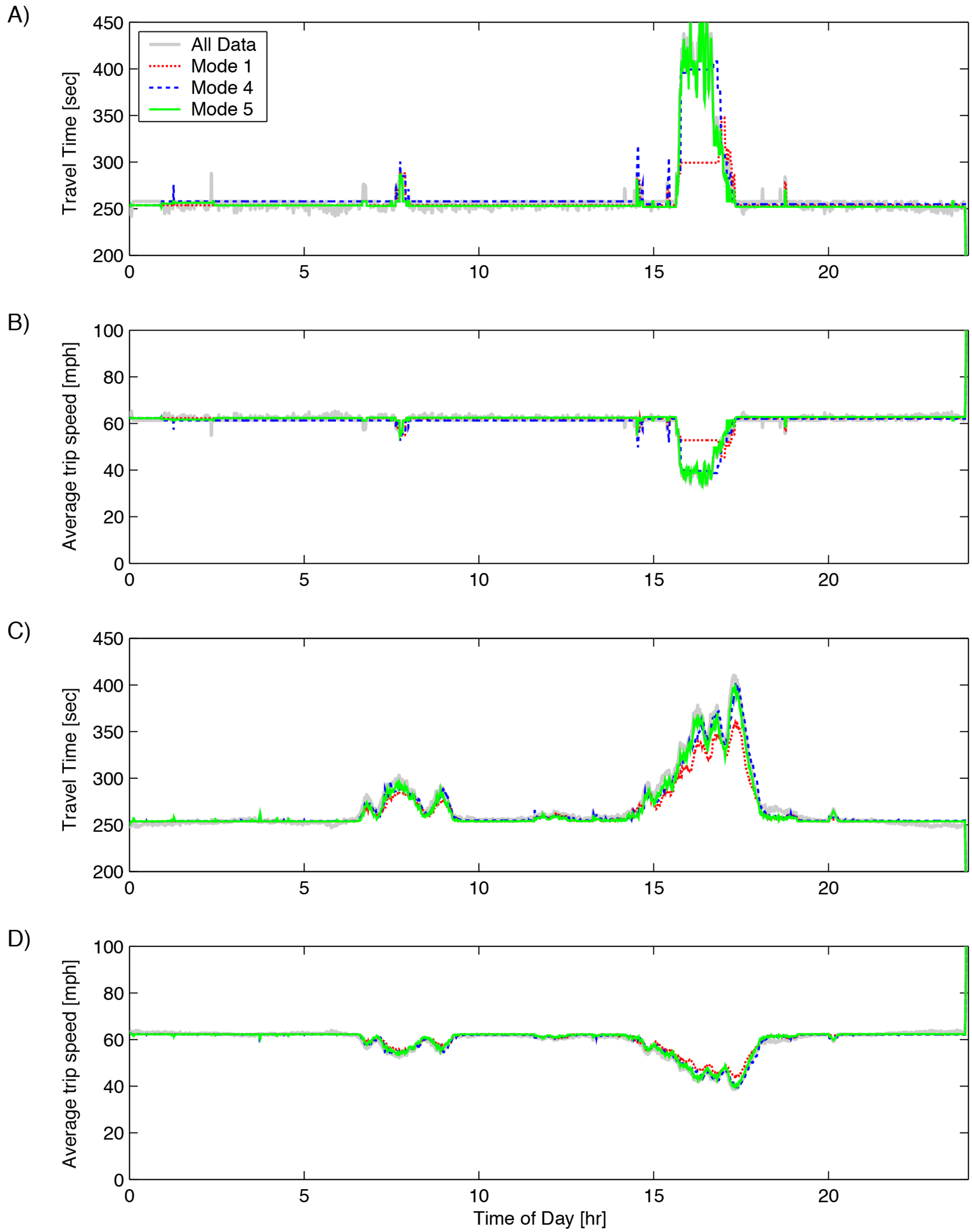

Figure 3, (A) Travel time and (B) average trip speed using all data, Mode 1 data, Mode 4 data and Mode 5 data on a typical weekday from Station 106 to Station 9 northbound on I-70/71 (4.4 mi). Daily average across one month of data for (C) travel time and (B) average trip speed for the same link and modes.

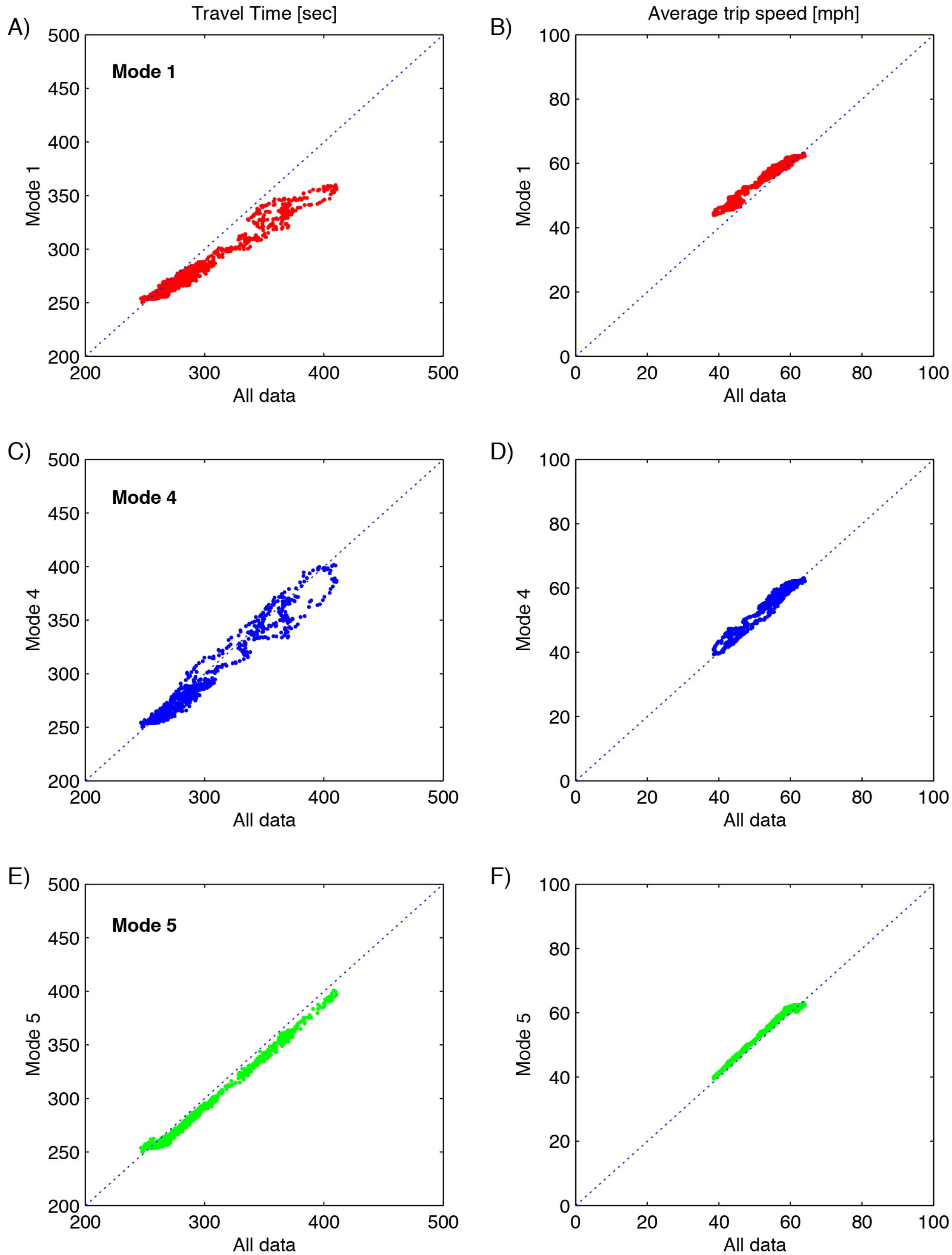

Figure 4, Scatter plots comparing the results from the given mode's synthetic speeds versus the same measure calculated from all of the raw data. The left column of plots shows the trip time and the right column shows the average trip speed from Station 106 to Station 9 northbound on I-70/71 (4.4 mi) from the daily average across one month of data from (A)-(B) Mode 1, (C)-(D) Mode 4, and (E)-(F) Mode 5.