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Vehicle Level Evaluation of Loop Detectors and the Remote Traffic Microwave Sensor

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ABSTRACT

Traffic detectors support most traffic management applications, so it is important that a detector performs as expected. This study evaluates the performance of four loop sensor models and the Remote Traffic Microwave Sensor (RTMS), adding to the body of sensor performance knowledge through the use of new analytical techniques. The study collected contact closure data from all five of the detectors and concurrent video data. Each loop sensor was deployed following Caltrans guidelines for at least 24 hours across dual loop detectors in each lane of I-80, north of Oakland, CA.

The research examined various distributions of the individual vehicle actuations from each of the detectors. This exercise found some of the loop sensors locked up and did not provide any data to the controller although they appeared fully functional from the front panel. The sensitivity appears to vary between the RTMS and the loop sensors, as well as from one loop sensor model to the next, which means the occupancy measurements will also change. Detailed analysis of the sensors used the video to manually validate each vehicle passage over extended periods, pre-selected at random, with the errors classified by type (e.g., non-detected vehicle) and source (e.g., due to a lane change maneuver). As presented herein, the RTMS exhibited problems due to occlusion and reflections, while two of the loop sensors exhibited non-negligible problems.

Finally, the methodology used in this paper can easily be extended to validate other detectors and detection technologies.

Subject Headings: Traffic Surveillance, Sensors, Evaluation, Traffic Management, Highways

INTRODUCTION

Traffic detectors provide data to most traffic-responsive management applications. The data from a traffic detector need to be sufficiently accurate since any errors will propagate to decision-making and control actions. The detector cost should be balanced with the benefit it provides since it is impossible to eliminate all errors. But the cost function and performance varies from one detector to the next, so it is important that a detector performs as expected. To this end, there have been numerous studies comparing aggregate data from one detector against concurrent measurements from another detector (e.g., a loop detector versus an emerging detector technology) or manual validation, e.g., [1-4]. These studies typically average flow, occupancy and/or speed over fixed periods ranging between 30 sec and 15 min. The long sample periods greatly simplify calibration and comparison between concurrent measurements, but they also allow errors of omission to cancel errors of commission, e.g., within a given sample missed vehicle can cancel vehicles that are counted more than once. To address these problems, other studies have compared individual vehicle actuations at one detector against concurrent measurements from another detector, e.g., [5-6]. These studies examined concurrent measurements from two identical detectors, so any discrepancy would be indicative of a problem in that model. Based on these comparisons it was shown that there is a large variation from manufacturer to manufacturer in the performance of loop detector sensor units, the electronics that drive the loop detector. So the physical loop in the pavement will yield different results depending on which sensor unit is driving it. But those studies may not catch an error if both detectors exhibit it, e.g., if both detectors systematically "drop out" in the middle of semi-trailer trucks, and the tests cannot be used alone to compare concurrent measurements of different detector models since questions would arise about which detector made an error whenever a discrepancy occurs.

The present study sets out evaluate the performance of four loop sensor models and the Remote Traffic Microwave Sensor (RTMS) manufactured by Electronic Integrated Systems (EIS) [7-8] to facilitate comparison between the different detectors while addressing many of the shortcomings of the earlier studies. The loop sensors included the conventional Peek GP6 [9] and Reno A&E [10] Model 222 detectors, as well as the reportedly higher performance 3M [11] and IST [12] Model 222 detectors. Working in the Berkeley Highway Laboratory (BHL) [13], the study collected contact closure data from all five of the detectors, recording the state at 60 Hz, using controller software developed by Caltrans and previously deployed in [13-14].

Each loop sensor was deployed for at least 24 hours across dual loop detectors in each lane on I-80, north of Oakland, CA, at the two detector stations shown in Figure 1A-B. Except for switching the sensor units, all of the other hardware remained unchanged throughout the data collection. The sensors were installed following Caltrans guidelines and care was taken to ensure that the operating frequency of adjacent sensors differed. Beyond verifying that the indicator lights flashed in correspondence to vehicle passages (replicating what a technician would do in the field), no further fine-tuning was conducted. (Note that the two stations were previously equipped with Peek sensors that had been meticulously calibrated using the tools presented in [5-6], these calibrated sensors were removed for the study of the loop sensors and the Peek GP6 sensors analyzed in this study were installed new out of the box they were shipped in from the manufacturer). The two stations are approximately 640 m apart, station 8 covers six eastbound lanes and station 7 covers five lanes in each direction. Both stations are visible from the rooftop of the 30 story Pacific Park Plaza building and approximately two hours of concurrent video was collected from this vantage point for each sensor, spanning free flow and congested traffic conditions (in fact Figure 1A-B are frames from this video). Visible on the right hand side of Figure 1B is a closed circuit television (CCTV) camera on a 12 m pole. This camera was used to monitor lanes 1-4 eastbound in a close up view, as shown in Figure 1C, during the same periods the stations were filmed from the rooftop.

The RTMS unit was mounted lower on the CCTV pole in late 1999 in accordance with the manufacturer's specifications and was operational throughout the entire data collection effort. The RTMS was hardwired to the controller input file. To ensure optimal RTMS performance, representatives of EIS aligned and calibrated the unit. They noted that the lack of median shoulders will degrade operation in the inside lane due to echoes off the concrete barrier. Since many urban freeways do not have median shoulders the results for lane 1 should be representative of these locations and the results are included for completeness. According to the EIS representatives, the RTMS delays the end of each pulse in the contact closure output by a fixed 0.15 sec to prevent erroneous *dropouts*. This delay was not subtracted from the measurements.

The remainder of this paper examines the performance of each of the detectors, closing with a discussion and conclusions.

ANALYSIS

This section begins by examining various distributions of the individual vehicle actuations from each of the detectors over 24 hours. Next, the video was digitized and correlated with the detector data for manual validation of each vehicle passage during randomly sampled periods. As Figures 1C-D show, both the downstream loop detectors and the RTMS detection zone were visible in the CCTV view. Although space constraints prevent the presentation, the detector data were also aggregated and used to evaluate the performance of each sensor under standard operation (see [15] for details).

Distribution of Individual Vehicle Actuations

When a vehicle enters the detection zone the detector turns on, and similarly when the vehicle leaves the detector turns off. The on-time of this pulse is simply duration that the detector is on for a given vehicle. At the microscopic scale,

$$\text{on\_time} = \frac{\text{effective vehicle length}}{\text{velocity}} \tag{1}$$

where the effective vehicle length is the sum of the physical length of the vehicle and the length of the detection zone. On-time is related to occupancy via the following equation,

$$\text{occupancy} = \frac{\sum \text{on\_times during sample}}{\text{sample period}} \cdot 100\% \tag{2}$$

As noted in [6], during free flow periods most vehicles will be traveling at roughly the same speed and thus, Equation 1 shows that the distribution of on-times should roughly be proportional to the distribution of effective vehicle lengths. Figures 2A-E show the cumulative distribution function (CDF) of the on-times from the four loop sensors (only data from the downstream loop is shown) and RTMS during free flow conditions between noon and midnight on the indicated day in the eastbound lanes at Station 7. To reduce the impact of transient errors, a moving median of 21 consecutive individual vehicle speeds was taken and the center vehicle is considered free flowing if the median is over 72 km/h. Note that two lanes do not have data for the 3M sensor due to the sensors locking up in these lanes and not providing any data. This error should be easily fixed by adjusting the sensitivity levels on the sensor units, but the error was not identified until after the data collection effort, nonetheless, its occurrence is indicative of another detector error. A similar error occurred with the Peek sensors at two of the downstream loops at Station 8. In both cases, the front panel of the sensor did not show any indication of a fault.

These plots show that for a given sensor, the median on-time is similar across all five lanes, except for the RTMS in lane 5, which differed significantly from the other lanes. However, the median on-time changes from one sensor to the next. The median on-time for the RTMS is almost twice as large as some of the loop sensors, indicating a significantly larger detection zone, which is consistent with the on-time extension provided by the RTMS in the contact closure data in absence of EIS Interface Cards. Similarly, the median on-time for IST is larger than the other loop sensors, presumably related to the sensitivity of the different sensors. Note that all five plots of on-time CDF have a vertical line at 11/60 sec for reference. This threshold was chosen because most passenger cars have an effective length of at least 6m and traveled at speeds below 120 km/h at this location. Any on-time below this threshold would either be indicative of a detection error (e.g., detecting a vehicle that is actually in another lane, so called splash-over) or vehicles with pair-wise effective length and speed that fall within the shaded region of Figure 2F, e.g., motorcycles. Figure 2G compares the number of samples below 11/60 sec across all lanes for each of the sensors. The trends are consistent with the median on-time, e.g., the 3M and RTMS curves exhibit virtually the largest difference between any two curves even though the data were collected concurrently at the same station on the same day.

This process was repeated at Station 8 for both the upstream and downstream loops, as shown in [15]. Here, all four of the sensors exhibited significantly larger number of on-times below 11/60 sec, with IST climbing to about 10% and Reno climbing to 50% below the threshold.

Interestingly, both Peek and Reno exhibited a lower median on-time at Station 8 while IST and 3M median on-times were similar at the two stations. Of the four sensors, the IST exhibits the greatest similarity between the on-time distributions for the eastbound lanes at the two stations.

The fact that the center of the on-time distribution changes from one sensor to the next means that occupancy measurement will also change across the sensors via Equation 2. The nature of this occupancy shift was not investigated in the present study, though as shown with the changes between the two stations, it is likely to include site-specific parameters. So rather than attempting to find a correction factor for a given sensor, it may prove more efficient to devise a calibration for occupancy based applications that can be applied individually to each detector station.

Now consider the fact that most vehicles should actuate both loops in a dual loop detector, so an actuation at one detector should uniquely match an actuation at the other, whenever such a unique match does not exist either one loop failed to detect a vehicle, the other loop made a spurious detection, or a vehicle may have been changing lanes over the dual loop. Explicitly tallying how many unmatched pulses are observed at each dual loop for each sensor over the 19 hr long period between 14:00 and 9:00 the next day provides an indication of the sensors consistency. In this case, if N pulses are observed at one loop for a single pulse at the other loop it is tallied as N-1 unmatched pulses for the first loop. A lane change maneuvers over the dual loop is not an error and could result in an unmatched pulse, but such maneuvers are infrequent except in heavy weaving locations and in fact most vehicles that change lanes over a dual loop should still be detected by both of the loops given the close spacing between the loops. The test sites are not heavy weaving locations, and in any event, one would assume the number of lane change maneuvers to be similar across days, allowing for relative comparison between the sensors. Figure 3 shows the percentage of pulses that were unmatched in each lane, at each station, both upstream and downstream loops, for each loop sensor unit. Each lane shown in this plot had over 10,000 vehicles during the observation period, with most lanes having between 20,000 and 30,000 vehicles. No results are reported for the lane if one of the loops in the dual loop did not provide data. IST exhibited the best performance on this test, followed by 3M. Peek and Reno exhibited poor performance in some of the lanes and good performance in others, which is consistent with our earlier efforts that were successful in manually fine-tune the performance of Peek sensors using [5-6].

Following the procedures of [5-6], during free flow conditions the vehicles move too fast for acceleration to cause a significant change in speed over the 6.1 m spanning the paired loops. Thus, via Equation 1, after matching pulses the on-times from both loops should be almost identical. Once more a moving median of 21 consecutive individual vehicle speeds was taken and the center vehicle is considered free flowing if the median is over 72 km/h. For each of these free flowing vehicles the difference between the on-times within the dual loop is calculated. Allowing an error of two sample periods, Figure 4 shows the percentage of all such on-time differences that are greater than 2/60 sec during the free flow periods in the data used for Figure 3. In fact the trends are similar in both figures, which would suggest that the source of the unmatched pulses is related to the bad on-time differences. For reference, see [15] for scatter plots of the on-times and distributions of the on-time differences.

Manual Validation

As noted previously, it is important that a detector performs as expected, the ideal detector should always turn on/off whenever a vehicle enters/exits the detection zone and only change states at these times. Practical detectors should approach the ideal, but fall within some level of tolerance that may vary from application to application. To aid decision makers, this section quantifies just how close to ideal each of the detectors came in the study.

Lanes 1-4 at Station 7 are used for this analysis because of the ease of precisely determining the timing of detection events from the CCTV view (Figure 1C) while also having the secondary view of the far lanes from the rooftop view (Figure 1B) whenever a truck occludes the CCTV. Three non-overlapping pairs of five minute long windows were selected for each sensor (one free flow and one congested within each pair), for a total of 30 min per sensor (including RTMS). Three students were assigned the task of synchronizing the video to detector data and generating ground truth vehicle passages, each processing a different pair of windows for each sensor, thereby reducing the chance that individual biases may influence the final results. The students were simply told that the loop detector data on different days came from different sensors and were not given any further background about the loop sensors. Out of necessity, they were told about the RTMS detection zone being slightly downstream of the loop detectors and when processing the pair of five minute windows for the RTMS they generated a separate set of ground truth data for it.

The students used Videosync, a software package being developed by Caltrans Division of Research and Innovation, as the primary tool for this data reduction effort, allowing the direct comparison between concurrent detector and video data [16]. Figure 5 shows two screen shots from Videosync, in each, the upper left hand corner shows the current video frame, with navigation controls below. In the mode shown, the right hand side shows the time series of the traffic state on up to eight channels, where a channel may correspond to raw detector data or ground truth data (another mode, not shown in this paper, allows for manually inputting the ground truth data as vehicles enter and leave the detection zones). The center of the time series, highlighted with a dark vertical line, corresponds to the instant of the video frame. In Figure 5A, the channels labeled "eb 1d" through "eb 4d" correspond respectively to the data recorded from the downstream loop detectors in lanes 1-4, respectively, while the channels prefaced with "gt" contain the manually generated ground truth for the same lanes. The downstream loops are on the left hand side of the video image (Figure 1C) and in Figure 5A one car is about halfway across the loop in lane 2 while another car has just entered the loop in lane 1, as evident by the pulses in the first four rows on the right side of the figure. The loops in the other two lanes are empty and time series show them as being off at this instant. Comparing the raw data to the ground truth, the two time series would be identical for an ideal sensor, but three errors are evident in Figure 5A: the loop in lane two flickers off for one sample as a vehicle leaves (Label i). Secondly, the loop in lane 3 twice erroneously flickers on for a single sample period (Label ii) concurrent with the error in lane 2.

Similarly, Figure 5B shows a sample from the RTMS, once more the numeral in the channel name denotes the lane number, now however, the raw data is prefaced "RTMS" and the RTMS ground truth is prefaced "gt RTMS". Note that the time scale, indicated by "graph width" above the time series plot, is larger than the previous example. Several errors are apparent in the example. First, Label i highlights a splash-over, where a vehicle from an adjacent lane is also counted in lane 2. Label ii is concurrent with the video frame shown, the semi-trailer in lane 4 occludes a pickup truck in lane 2. Later, while the semi-trailer is still in front of the sensor a phantom vehicle is detected in lane 1, Label iii, while three vehicles eventually pass in that lane during and after this actuation. Another phantom vehicle is detected in lane 3, Label iv, also presumably due to the semi-trailer, which the RTMS briefly drops, Label v. Another phantom vehicle is later detected in lane 3, Label vi.

A Matlab program was written to quantify the differences between the raw and ground truth data across all three students. As a first step, Figure 6A shows the percentage of actuations that overlapped ground truth pulses, summed across all three students, the remaining actuations being clearly over-counting errors by the given detector. An actuation is counted even if it overlaps a ground truth pulse by a single sample period of 1/60 sec. For reference, Table 1 tallies the total number of actuations included in this figure. Figure 6B shows the percentage of ground truth pulses that overlapped one or more actuations, with the remaining ground truth pulses being clearly under-counting errors by the given detector. Ideally there should be a one-to-one match between the ground truth and raw data, so Figure 6C shows the percentage of ground truth pulses that overlapped exactly one actuation ([15] shows the results broken down by individual student). Since the intent of this research is to evaluate the performance of operational detectors, these results exclude the fact that one out of the four 3M sensors did not report any data, i.e., the vehicles from that lane are not included in the ground truth for 3M. Figure 6 shows that the RTMS has the worst performance of the five sensors, followed by Reno, note that the over-counting errors roughly balance the under-counting errors for these two sensors.

Figure 7 compares the on-times reported by the sensor against the ground truth. If multiple actuations intersect a ground truth pulse, to address the possibility of the sensor dropping out in the middle of a vehicle, the sum of the actuation on-times is used in the comparison. Figure 7A shows the bias between the on-times reported by the sensors and the ground truth on-times. All of the sensors had a bias under 1/60 sec. Figure 7B shows the average absolute on-time error across the ground truth pulses. Each loop sensor was under 1/60 sec while the RTMS had an average absolute error over 7/60 sec. Figure 7C shows the percentage of pulses that had an on-time error. All of the loop sensors were under 10%, with 3M being the best at about 2%, while the RTMS was around 40%. Even with the aid of Videosync, the accuracy of the ground truth on-times is limited, after completing the data reduction the students were questioned about their technique. When the actuation appeared to be within 2/60 sec of being correct they tended to use the times recorded by the detector, so in general, the on-time comparisons show results that are slightly better than reality.

Further code was written in Matlab to mark the following differences in an unused channel of the Videosync file: too few actuations for a ground truth pulse, too many actuations for a ground truth pulse, and an on-time difference greater than 3/60 sec. The author then used Videosync to review the data to manually classify the nature of each discrepancy from each student's data and the original video.

Table 1 shows the net results summed across all three students for the 120 lane-minutes reduced for each sensor and the total number of vehicles observed broken down into three length classes (as measured by the loop detectors). Many of the errors were due to lane change maneuvers over the detection zone. These errors are further broken down into *over-counting non-flicker* (e.g., splash-over from a vehicle in another lane), *over-counting flicker* (e.g., the detector turns off and back on while a vehicle is traversing it), *short on-time*, and *under-count* if the vehicle is not detected at all. IST and Peek tended to detect vehicles changing lanes in both lanes, while the Reno and 3M sensors tended to underestimate the on-time of vehicles changing lanes in one lane while not detecting them in the second. The lane change maneuver problem seems to be a trade off between over and under counting, based on sensitivity. In each case, the number of such errors are noted on the table and their percent (relative to the total number of vehicles) is low in all cases. Ideally these errors should be addressed, but it does not look like it would be a major problem unless the loops are in a heavy weaving section.

Except for the RTMS, all remaining errors are listed under Other Errors. In the case of the RTMS, as evident in Figure 5B, many errors appear to be due to occlusion and these are reported separately in Table 2, while Table 1 includes only those errors that are not clearly attributable to occlusion or reflections by other vehicles. In reviewing the data, it was clear that there was significantly higher variance in the on-times from the RTMS (both systematic lane to lane and seemingly random from vehicle to vehicle), consistent with the results already presented in Figures 2 and 7. Table 2 shows the errors due to obscured vehicles and to reflections. The total of the non-lane change maneuver errors made by the RTMS (summed from Table 1 and 2) are reported in the final three columns. Note that the percent of vehicles missed, 4.8%, is almost balanced by the percent of non-vehicle, false detections, 5.6%. The difference is even smaller if one excludes the false detections due to flicker (4.6% of the total detections).

Returning to Table 1, the last two columns explicitly subset two errors from the rest, *drop mid-semi* and *missed motorcycle*, and the numbers reported in these columns are <u>not</u> included in the supersets, *flicker* and *undercount*, respectively. For all columns, the percentages are relative to the total number of vehicles except for *drop mid-semi*, which is relative to the number of vehicles over 13.5 m. All of the loop sensors had a few problems with motorcycles, particularly when they travel between lanes.

Two non-negligible problems became apparent in the loop data during this review. First, as shown in Table 1, Reno had a tendency to flicker, particularly during congestion, with over five percent of the actuations being these false positives, e.g., Figures 2G and 5A. Second, IST will occasionally slip into a mode where they correctly detect a vehicle, turn off for 1/60 sec and then immediately turn back on when they should be off. Figure 8 shows a sample of this error in Videosync, comparing the raw data time series to the ground truth for lane 2 one sees that for several successive vehicles the detector only turns off briefly and then turns back on when it should remain off (note that the graph width is larger than Figure 5). According to the manufacturer, the observed pattern is related to the auto-calibration the sensors use to coordinate operating frequencies across different loops and IST was the only sensor included in the study that had this feature. This auto-calibration feature allows easier installation since the technician does not have to manually set the frequencies and promises to correct for interference problems between loop sensors that would be impossible for a technician to identify under conventional deployment conditions. The feature could be turned off, but given the fact that the error was not identified until after the data collection, all of the study data from the IST sensors include this problem. It appears that the problem starts when the detector has been occupied for many seconds, though it may simply become readily apparent under these conditions, while briefly occurring at other times as well. Presumably this problem could be avoided by manually selecting the operating frequencies (which is the only option available with the other loop sensors in this study), but this speculation was not tested. Caltrans has since reported that IST has revised the sensors and eliminated this auto-calibration problem.

CONCLUSIONS

This study set out to evaluate the performance of four loop sensor models and RTMS. A traffic sensor needs to be sufficiently accurate since any errors will propagate to decision-making and it is important that a detector performs as expected. Each sensor was deployed following conventional guidelines and the data evaluated at multiple resolutions, including the distribution of individual vehicle actuations, manual validation, and trends in conventional aggregated data.

Each sensor examined in this study exhibited problems. Most of these problems could be identified and corrected with additional fine-tuning in the data processing by the controller or data aggregator, such as was done for [13-14]. However, this added effort is not currently employed by most operating agencies. So the results should be representative of conventional practice. Discussions continue with operating agencies as to how best to incorporate such tests in future controller software. Other errors would likely require a field visit to correct, such as the non-operational 3M and Peek sensors. The Reno sensor tended to flicker on for short periods in absence of a vehicle in the detection zone, this problem could likely be addressed in the controller software, but such a solution is less than ideal. Many errors were due to lane change maneuvers over the detection zone. IST and Peek tended to detect such vehicles in both lanes, while the Reno and 3M sensors tended to underestimate the on-time of vehicles changing lanes in one lane while not detecting them in the second. The lane change maneuver problem seems to be a trade off between over and under counting, based on sensitivity. Ideally these errors should be addressed, but it does not look like it would be a major problem unless the loops are in a heavy weaving section.

Some systemic errors emerged, such as the difference in the RTMS performance for the furthest lanes (occlusion) and nearest lanes (smaller detection zone). This systematic change in performance is important to note for traffic responsive ramp metering and other applications that rely on occupancy. The RTMS count and on-time are generally noisier than loops, though errors of omission are roughly balanced by errors of commission in counts (Table 2). The RTMS also has a larger detection zone than the loops, while even across the four models of loop sensors the apparent size of the detection zone varied from one model to the next for the same physical loop in the pavement. These variations will impact the magnitude of the occupancy measurement.

They could likely be corrected with the sensitivity settings in the sensors, but as was noted with the comparison between loops in the same direction at the two stations, it is likely that site-specific factors are at least as important as the sensitivity setting. It may prove to be more efficient to simply devise a calibration for occupancy based applications that can be applied individually to each detector station.

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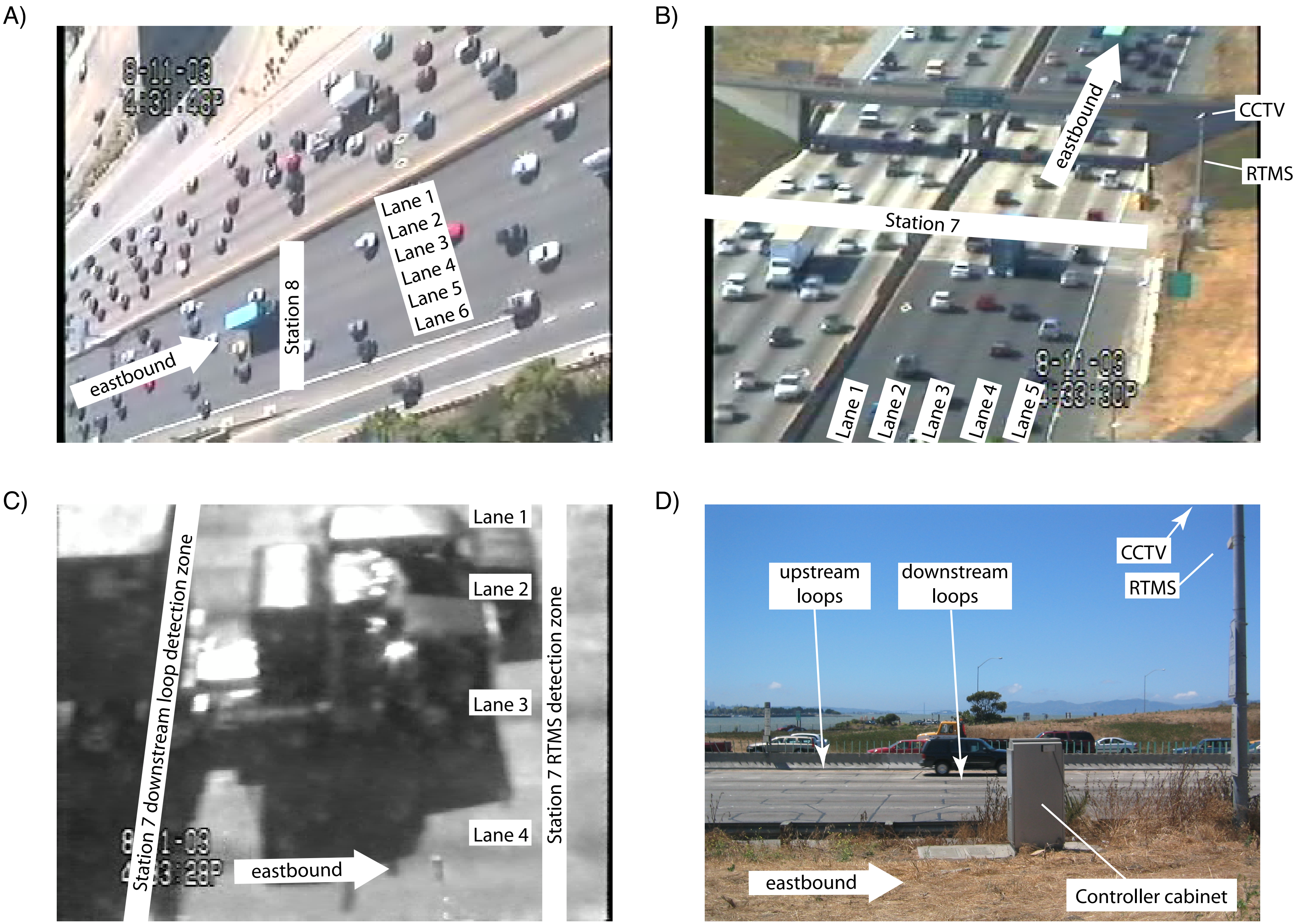

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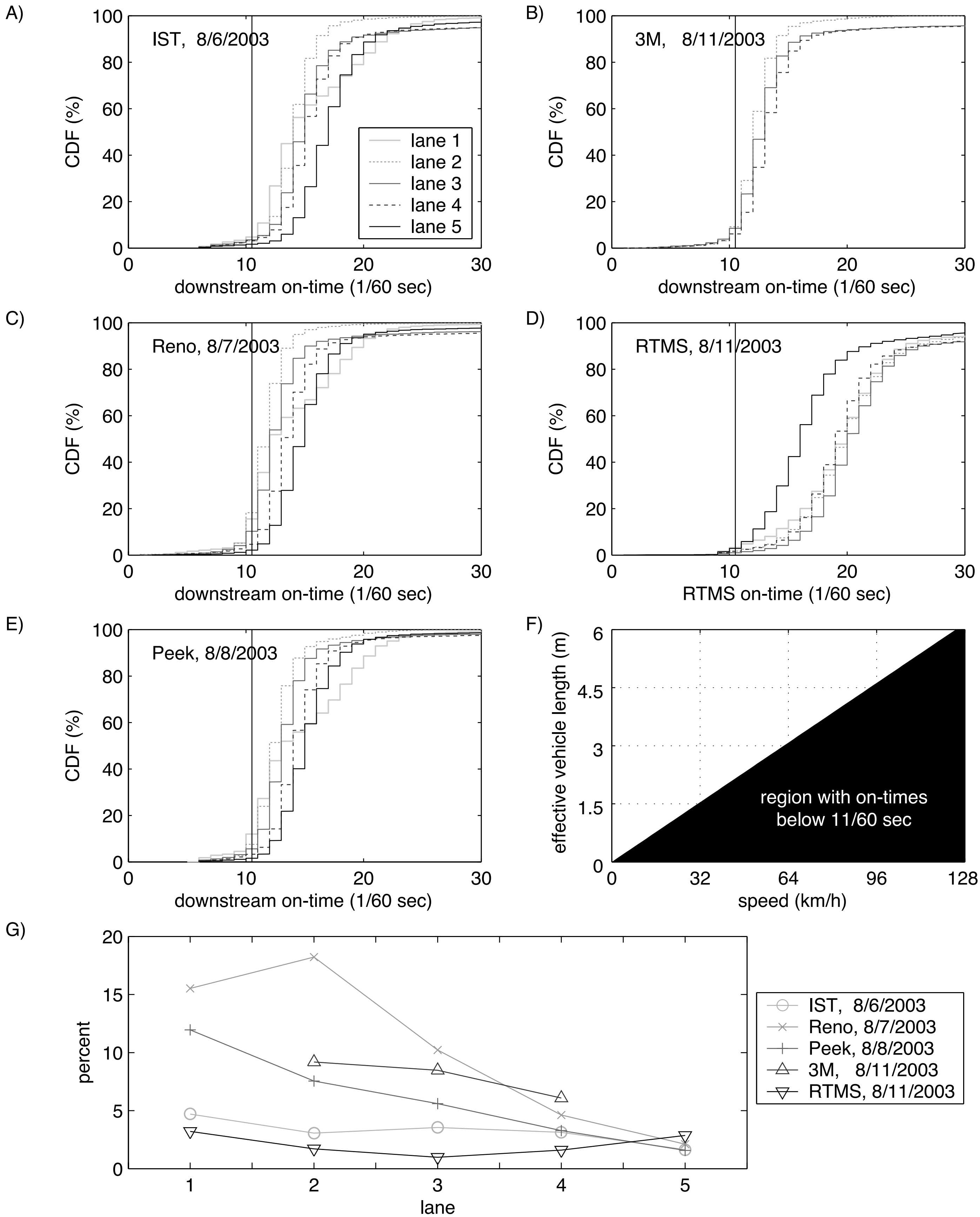

Figure 2, (A)-(E) CDF of downstream on-times at Station 7 during free flow on the given day for IST, 3M, Reno, RTMS, and Peek, respectively. (F) The pair-wise set of vehicle speeds and effective lengths that would result in an on-time below 11/60 sec. (G) Percent of free flow actuations that fall below 11/60 sec for each detector.

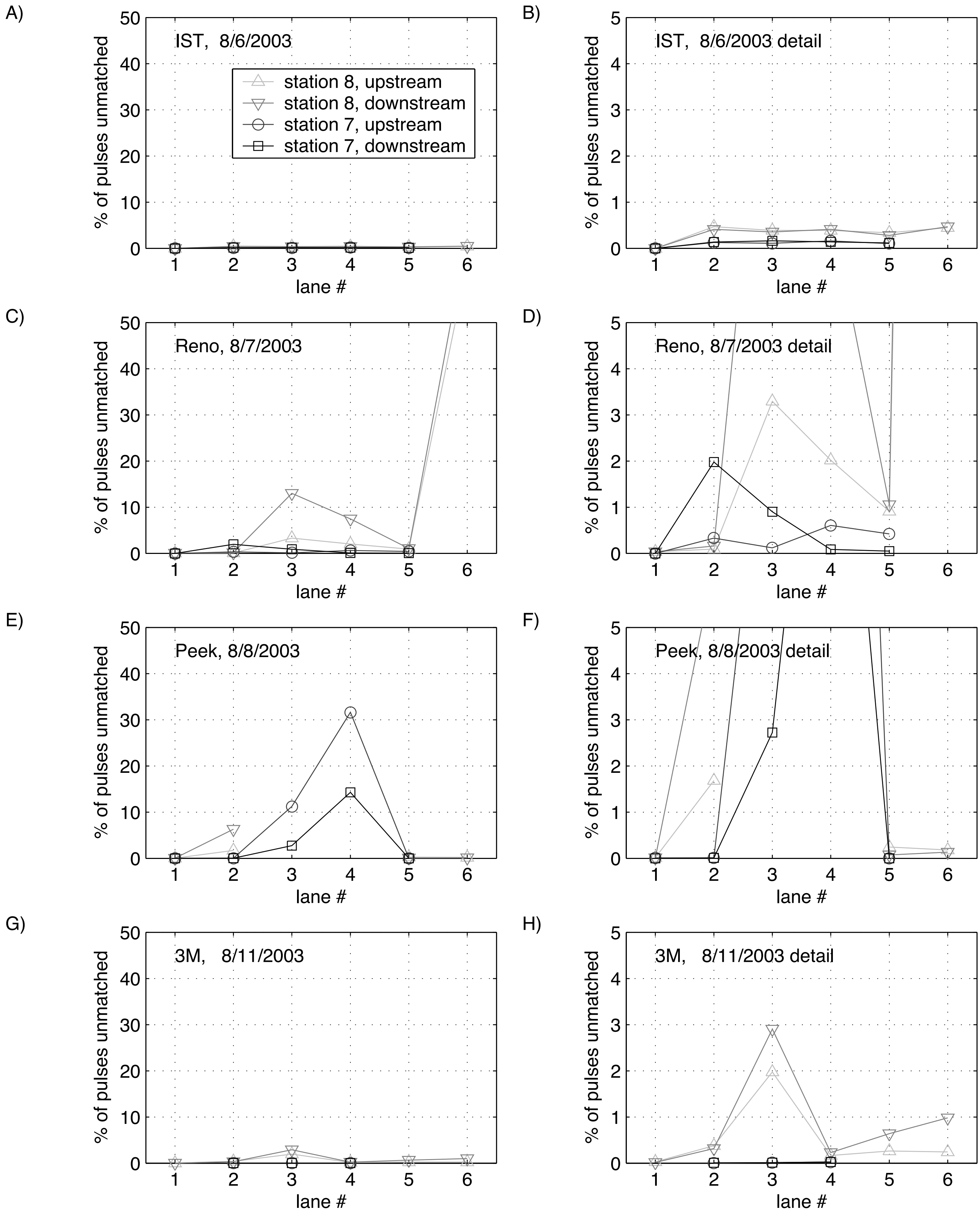

Figure 3, Total percent of unmatched pulses at each loop in the eastbound dual loop detectors at each station for each of the loop sensors at the two stations. The left column shows the results on a large vertical scale while the right column zooms in on the same plots. The rows correspond to IST, Reno, Peek and 3M, respectively.

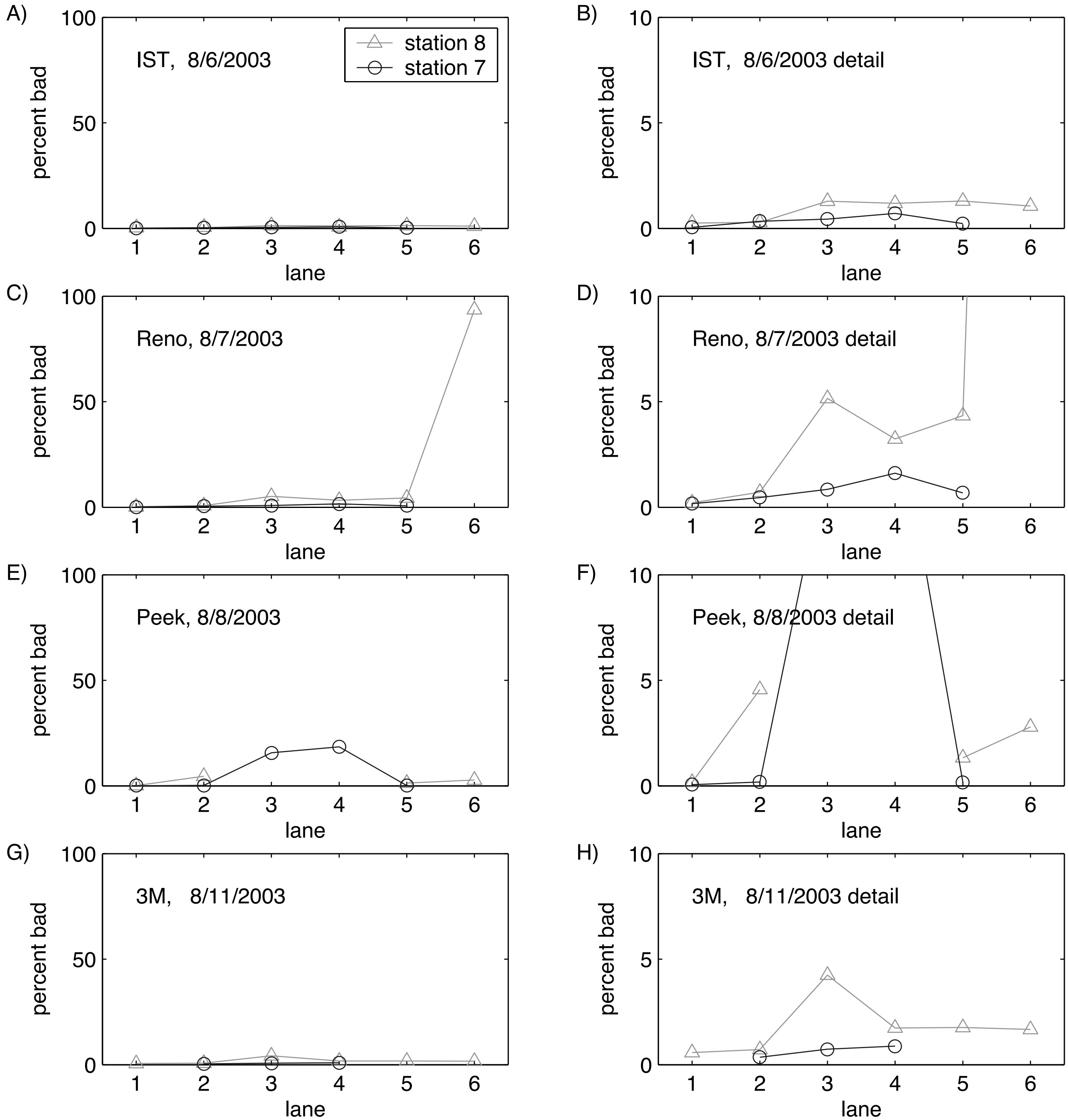

Figure 4, Total percent of on-time differences during free flow conditions that are greater than 2/60 sec at each eastbound dual loop detector for each of the loop sensors at the two stations. The left column shows the results on a large vertical scale while the right column zooms in on the same plots. The rows correspond to IST, Reno, Peek and 3M, respectively.

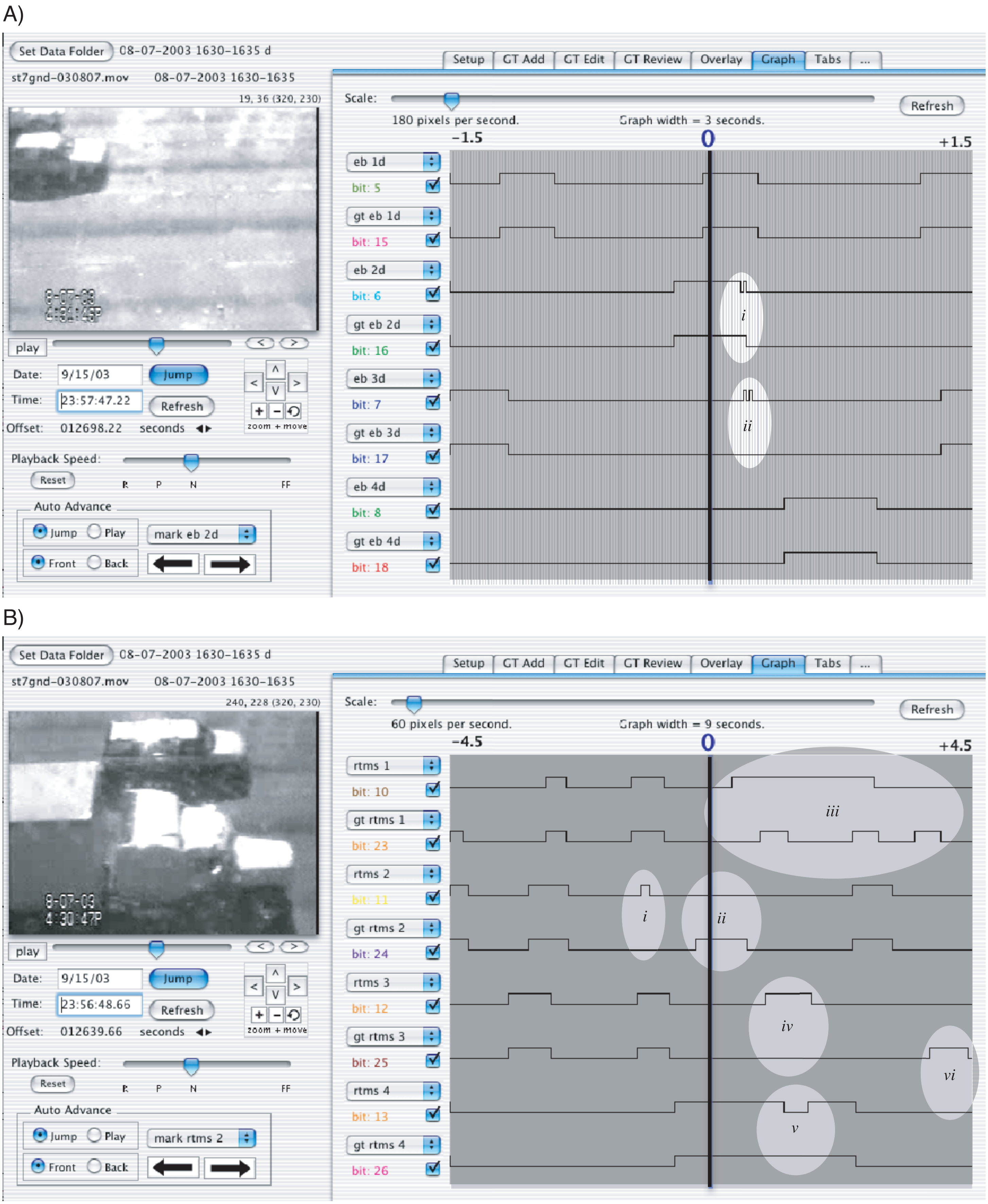

Figure 5, Two examples of the Videosync display showing several detector states synchronized with concurrent video, using lighter shaded ovals, (A) errors made by the Reno loop sensor are highlighted, (B) several errors made by the RTMS during a congested period are highlighted.

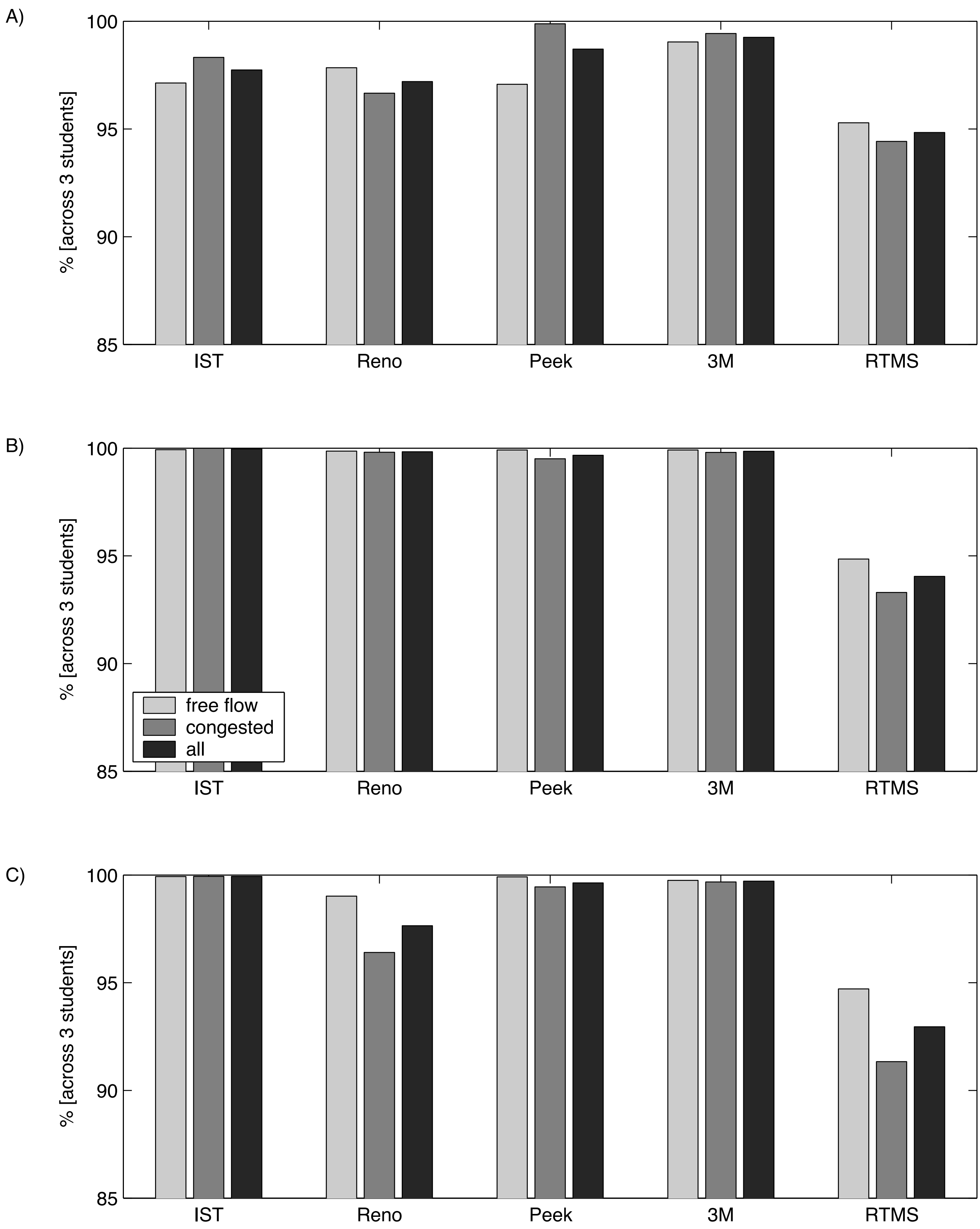

Figure 6, Summing the results from all three students for each sensor, (A) the percent of actuations that overlapped ground truth. (B) The percent of ground truth that overlapped one or more actuations. (C) The percent of ground truth that overlapped EXACTLY ONE actuation.

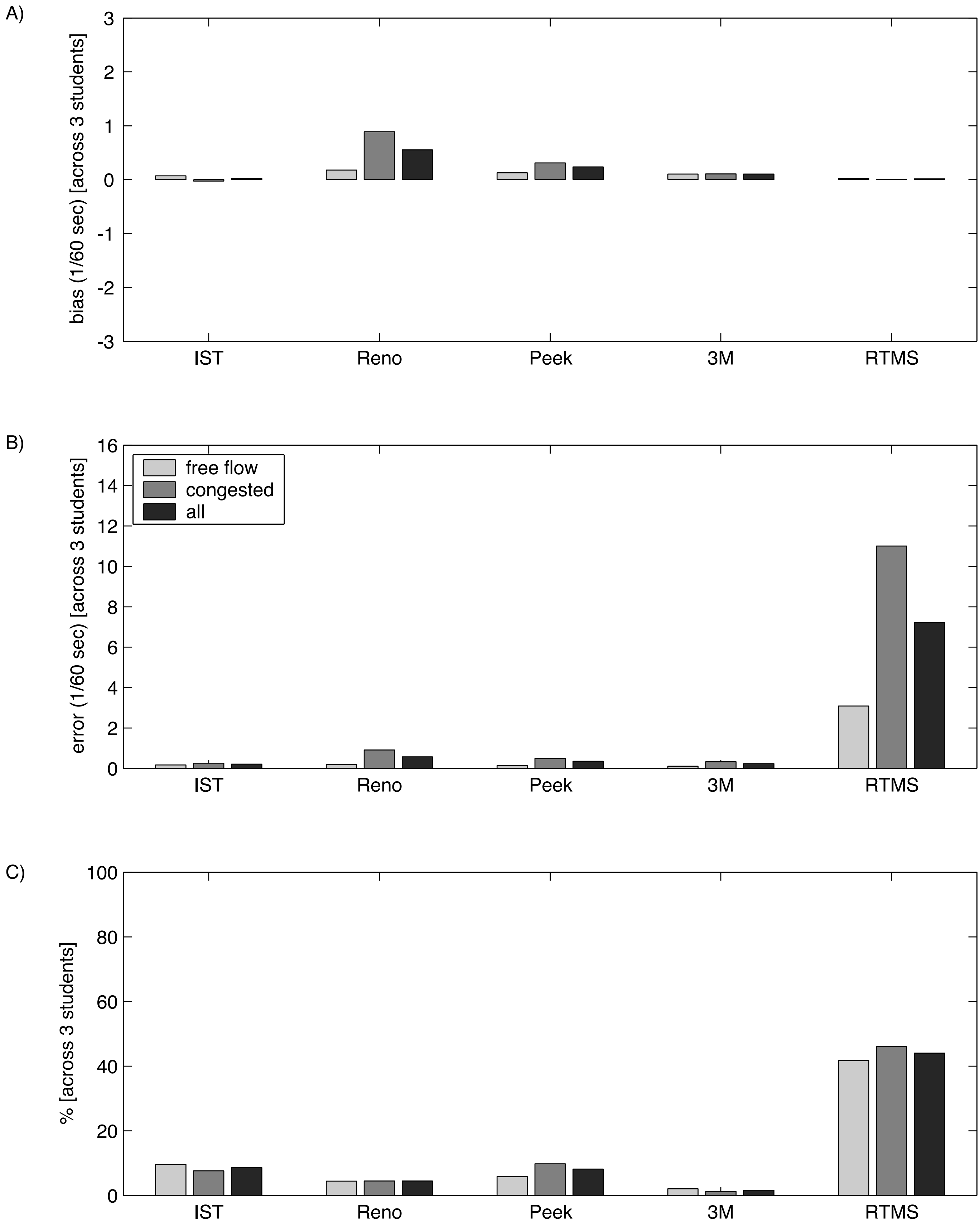

Figure 7, Summing the results from all three students for each sensor, (A) the average on-time bias over all vehicles. (B) The average absolute on-time error over all vehicles. (C) The percentage of vehicles with an on-time error.

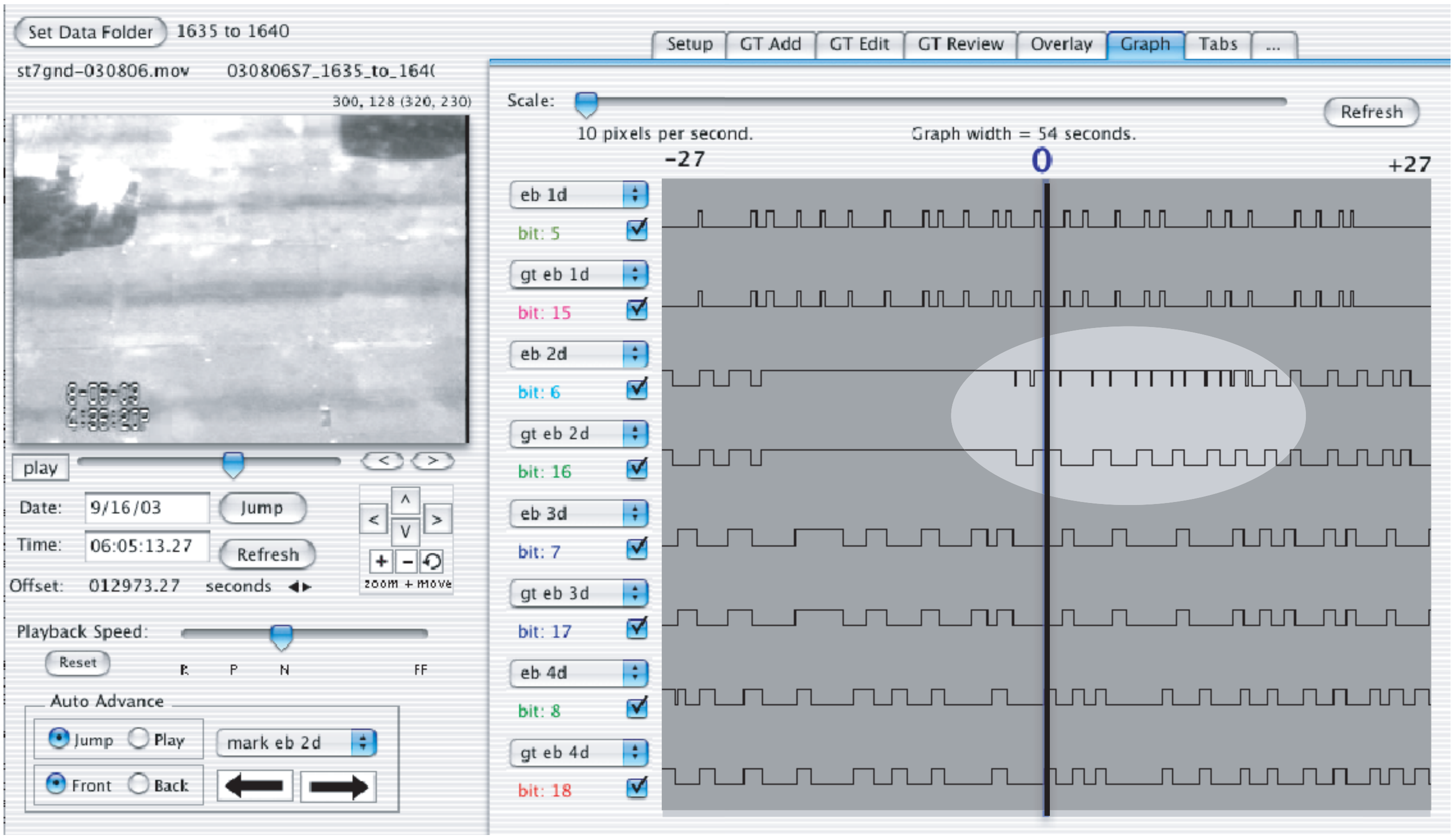

Figure 8, An example of a unique error exhibited by the IST cards (highlighted with a lighter shaded oval), reportedly related to auto-calibration.

Table 1, Summary of manual detector validation.

			Vehicles [a]				Errors during Lane Change Maneuvers				Other errors [b]					
Sensor	Conditions	Lane	total	0-7.5m	5.5-13.5m	over 13.5m	Overcount non-flicker	Overcount flicker	Short On-time	Under-count	Major on-time error	Overcount non-flicker	Overcount flicker	Under-count	Drop mid-semi	missed motorcycle
IST	Free flow	1	272	207	65	0	1	0	2	0	0	0	0	0	0	0
		2	426	317	109	0	13	0	1	0	0	0	0	0	0	0
		3	391	261	96	34	15	0	1	0	0	0	0	0	0	1
		4	420	290	107	23	12	0	2	0	0	0	0	0	0	0
IST	Congested	1	407	318	83	6	0	0	0	0	0	0	0	0	0	0
		2	409	356	50	3	1	0	1	0	0	13	0	0	0	0
		3	361	274	52	35	4	0	3	0	0	6	0	0	0	0
		4	391	338	49	4	3	0	0	0	4	2	0	0	1	0
IST	Total		3077	2361	611	105	49	0	10	0	4	21	0	0	1	1
	Percent						1.6%	0.0%	0.3%	0.0%	0.1%	0.7%	0.0%	0.0%	1.0%	0.0%
Reno	Free flow	1	268	259	9	0	0	0	2	0	2	0	0	0	0	1
		2	389	381	7	1	2	1	6	0	2	15	3	0	0	1
		3	366	309	32	25	2	1	6	0	0	5	0	0	6	0
		4	395	336	32	27	4	0	5	0	0	1	0	0	4	0
Reno	Congested	1	449	434	6	9	0	0	1	0	0	0	0	0	0	0
		2	339	333	6	0	0	0	0	0	1	14	60	0	0	1
		3	294	261	12	21	1	1	2	0	0	8	38	0	2	0
		4	371	358	8	5	1	0	1	1	0	0	0	0	1	0
Reno	Total		2871	2671	112	88	10	3	23	1	5	43	101	0	13	3
	Percent						0.3%	0.1%	0.8%	0.0%	0.2%	1.5%	3.5%	0.0%	14.8%	0.1%
Peek	Free flow	1	117	110	4	3	3	0	1	0	0	0	0	0	0	0
		2	372	366	6	0	2	0	4	0	0	0	0	0	0	0
		3	239	236	1	2	5	0	4	0	0	0	0	0	0	0
		4	181	174	5	2	6	0	0	0	0	0	0	0	0	1
Peek	Congested	1	457	423	23	11	0	0	0	0	1	0	0	0	0	2
		2	412	402	10	0	0	0	0	0	3	0	0	0	0	4
		3	289	276	7	6	1	0	0	0	3	0	0	0	1	0
		4	214	206	5	3	1	0	4	0	1	0	0	1	0	0
Peek	Total		2281	2193	61	27	18	0	13	0	8	0	0	1	1	7
	Percent						0.8%	0.0%	0.6%	0.0%	0.4%	0.0%	0.0%	0.0%	3.7%	0.3%

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Table 1 (continued)

Sensor	Conditions	Lane	Vehicles [a] total	0-7.5m	5.5-13.5m	over 13.5m	Errors during Lane Change Maneuvers: Overcount non-flicker	Overcount flicker	Short On-time	Under-count	Other errors [b]: Major on-time error	Overcount non-flicker	Overcount flicker	Under-count	Drop mid-semi	missed motorcycle
3M	Free flow	1 [c]	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		2	422	408	14	0	1	0	2	0	0	0	0	0	0	0
		3	386	333	24	29	5	0	7	1	0	0	0	0	0	0
		4	415	368	23	24	4	0	6	0	0	0	0	0	2	0
3M	Congested	1 [c]	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		2	560	550	9	1	1	0	2	0	1	0	0	2	0	1
		3	468	410	17	41	5	0	3	0	0	0	0	0	2	0
		4	504	474	17	13	2	0	5	0	0	0	0	0	0	0
3M	Total		2755	2543	104	108	18	0	25	1	1	0	0	2	4	1
	Percent						0.7%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.1%	3.7%	0.0%
RTMS [d]	Free flow	1 [e]	261	157	19	0	1	0	1	0	2	0	0	3	0	0
		2	394	353	41	0	5	0	1	1	3	5	0	1	0	0
		3	389	320	49	20	3	0	1	3	0	0	0	0	0	0
		4	406	341	45	20	2	0	1	5	1	0	0	3	2	1
RTMS [d]	Free flow	1 [e]	425	261	20	6	0	0	0	0	0	0	0	0	0	3
		2	522	500	21	1	1	0	0	1	3	2	6	0	0	0
		3	429	351	32	46	2	0	1	0	1	1	6	0	0	0
	Percent	4	484	446	27	11	3	0	0	0	0	3	17	0	0	0
RTMS [d]	Total		3310	2729	254	98	17	0	5	10	10	11	29	7	2	4
	Percent						0.5%	0.0%	0.2%	0.3%	0.3%	0.3%	0.9%	0.2%	2.0%	0.1%

[a] Since the errors are small, the count is reported as measured by the dual loop detectors.

[b] Some errors could be classified in to several columns by definition. For clarity, each observed error is counted in exactly one column, e.g., "drop mid-semi" could be considered a special case of "Overcount flicker", but each occurrence is only counted in one column or the other.

[c] The 3M sensors did not report any data in lane 1.

[d] There was significantly higher variance in the on-times from the RTMS (both systematic lane to lane and seemingly random from vehicle to vehicle), less attention was placed on catching these errors than with loops, i.e., the threshold for identifying an on-time error for a loop sensor is less than the threshold used for the RTMS.

[e] One of the three evaluators used RTMS data concurrent with the 3M data set, so length data were not available in lane 1 for that individual and these vehicles are excluded from the length numbers.

Table 2, RTMS overcounting and undercounting due to occlusions and reflections.

Sensor	Conditions	Lane	Vehicles [a]	Obscured Vehicles		Reflections		Total errors [b]		
			total	short on-time	missed altogether	long on-time	overcount non-vehicle	total missed	total non-vehicles detected	total non-vehicles, non-flicker detected
RTMS	Free flow	1	261	5	16	3	22	19	22	22
		2	394	4	17	25	18	18	23	23
		3	389	2	7	10	9	7	9	9
		4	406	2	9	4	4	12	6	4
RTMS	Congested	1	425	7	57	16	19	57	19	19
		2	522	8	31	57	43	31	51	45
		3	429	8	5	6	13	5	20	14
	Percent	4	484	10	9	24	14	9	34	17
RTMS	Total		3310	46	151	145	142	158	184	153
	Percent			1.4%	4.6%	4.4%	4.3%	4.8%	5.6%	4.6%

[a] Since the errors are small, the count is reported as measured by the dual loop detectors.

[b] Including "Other errors" (from Table 1), "Obscured Vehicles" and "Reflections", excluding "Errors during lane change maneuvers" (from Table 1).