An Assessment of Loop Detector and RTMS Performance

Benjamin Coifman
Ohio State University

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Automated Diagnostics of Loop Detectors and the Data Collection System in the Berkeley Highway Laboratory- Part II

Benjamin Coifman, PhD
Assistant Professor, Civil and Environmental Engineering and Geodetic Science
Assistant Professor, Electrical Engineering
Ohio State University
470 Hitchcock Hall
2070 Neil Ave
Columbus, OH 43210
Coifman.1@OSU.edu
http://www-ceg.eng.ohio-state.edu/~coifman
614 292-4282
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 two loop sensor models locked up and not provide any data to the controller although they appeared fully functional from the front panel. The median on-time varied 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.

The video was used 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). The RTMS exhibited problems due to occlusion and reflections, while two of the loop sensors exhibited non-negligible problems. Then, the detector data are aggregated and used to evaluate the performance of each sensor under standard operation.

Next, the results of two earlier evaluations of the RTMS are presented. The reports have not been formally published and to address the omission, this section recaps the relevant portions of those two studies in the context of the results presented above. This first effort considered the aggregated data reported by the RTMS using its internal controller emulation in comparison to dual loop detectors. The RTMS occupancy and flow measures are shown to be noisier than loops, though the velocity estimates are almost as good as those from single loops. The second study considers aggregate measurements from the contact closure data, comparing the RTMS against the dual loop detectors. For reference, the work also compared one loop against another in a dual loop detector, with the spacing between loops being greater than the spacing between the reference loops and the RTMS detection zone. As is illustrated in this study, the RTMS shows lane dependent results.
INTRODUCTION

Traffic detectors provide the data that drive most traffic management applications. Loop detectors have been the preeminent detection technology for several decades, but they require closing the right of way during installation and potentially undermine the integrity of the pavement surface if they are not installed prior to paving. As a result there is great interest in emerging technologies that promise traffic detection without the liabilities of loop detectors, many of which have already been deployed in large numbers.

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, different applications can accommodate different levels of detector performance, and one would expect the marginal cost for each additional unit of performance to increase with performance. But the cost function and performance varies from one detector to the next, so it is of utmost importance 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 velocity over 30 sec, 5 min, or 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. In an attempt to address these problems, other studies have compared individual vehicle actuations at one detector against concurrent measurements from another detector within 20 ft, e.g., [5-6]. This approach greatly reduces the possibility that omissions cancel commissions. These studies compared 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, i.e., 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 there are two shortcomings of those studies. First, they 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. Secondly, if used to compare the concurrent measurements of different detector models, questions would undoubtedly arise about which detector made an error whenever a discrepancy occurs.

The present study sets out to 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 (see Figure 1.1 for a photo of these sensors). 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
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.1 The two stations are approximately 2100 ft 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. Visible on the right hand side of Figure 1B is a closed circuit television (CCTV) camera on a 40 ft 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. It is worth noting that the calibration software was difficult to control for novice users; however, it is believed that this deficiency could be overcome with training. To ensure optimal RTMS performance, representatives of EIS aligned and calibrated the unit. Mike Juha, the EIS representative in California at the time, conducted the initial calibration on October 21, 1999. Mr. Juha strongly recommended having a trained professional calibrate the RTMS units. Mr. Juha stated that he believes he could calibrate approximately four devices per day. While at the site, he commented on two site-specific features that reduce the unit's performance. First, the mounting angle of the unit was such that it would reduce performance in lane 5. Second, the site does not have any shoulders in the median; this should reduce the performance on the inside lane in each direction. On the near side of the median, this degradation is due to echoes off of the concrete barrier and, on the far side, due to the microwave "shadow" of the barrier. Mr. Juha said that the shadow would impact performance in the first two lanes on the far side of the roadway and upon his suggestion, it was decided to limit the RTMS to monitoring traffic on the near side of the median. Earlier studies came to a similar conclusion about this shadowing and [1] noted the need for one RTMS unit for each direction in most situations. Although the median may impact performance on the near side, many sites in California and elsewhere do not have median shoulders and the results for lane 1 should be representative of these locations. The analysis includes lane 1 for completeness, but the reader may choose to ignore it based on these comments. Dan Manor, president of EIS, conducted the final calibration on November 3, 1999 and realigned the RTMS unit to eliminate the problems in lane 5. Finally, according to Mr. Juha, the RTMS delays the end of each pulse in the contact closure output by a fixed 0.15 sec to prevent erroneous dropouts. Except where noted in the section on RTMS Performance, this delay was not subtracted from the falling edges. The installation did not use the EIS Interface Card, which reportedly corrects for this extension to replicate the detection zone of a loop.

The following section examines the performance of each of the detectors based on the recent data collection efforts. Next, two earlier studies of the RTMS that have thus far only existed in

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1 Note, these 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.
draft form are formally presented. Finally, this report closes with a brief 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 at Station 7 in eastbound lanes 1-4 during randomly sampled periods. As Figures 1C-D show, both the downstream loop detectors and the RTMS detection zone were readily visible in the CCTV view (see Figure 1.2 for a schematic of Station 7). Finally, the detector data are aggregated and used to evaluate the performance of each sensor under standard operation.

**Distribution of Individual Vehicle Actuations**

This section is predominantly a judicious application of the tools developed in [5-6]. 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,

\[
\text{on\_time} = \frac{\text{effective vehicle length}}{\text{velocity}}
\]

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,

\[
\text{occupancy} = \frac{\sum \text{all on\_times during sample period}}{\text{sample period}} \times 100\%
\]

As noted in [6], during free flow periods most vehicles will be traveling at roughly the same velocity 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) from four loop sensors (only data from the downstream loop is shown) and the RTMS during free flow conditions between noon and midnight on the indicated day in the eastbound lanes at Station 7. 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. 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 the 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. Any on-time below this threshold would either be indicative of a detection error (e.g., splashover, flicker, or simply truncated on-time) or vehicles with pair-wise effective length and velocity that fall within the
shaded region of Figure 2F. Some valid actuations will fall within this shaded region, e.g., motorcycles or a vehicle changing lanes over the detection zone, though many more are likely to be detection error. Consider the comparison across all lanes for each of the sensors shown in Figure 2xzxG. The trends are consistent with the above discussion of the median on-time, e.g., note that the 3M and RTMS curves exhibit almost the largest difference between 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 Figure 2.1-2.2. 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. As such, rather than attempting to devise a correction factor for a given sensor, it may prove to be more efficient to simply devise a calibration for occupancy based applications that can be applied individually to each detector location.

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. 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. 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. Note that no results are reported for the lane if one of the loops 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 are consistent with our earlier efforts that were successful in manually fine-tune the performance of Peek sensor units using the tools presented in [5-6].

Following the procedures of these earlier studies, after matching the pulses from each vehicle between the two loops at a dual loop detector, during free flow conditions the vehicles move too fast for acceleration to cause a significant change in velocity over the 20 ft between the paired loops. Thus, via Equation 1, the on-times from both loops should be almost identical. In this study a moving median of 21 consecutive individual vehicle velocities was taken and the center vehicle is considered free flowing if the median is over 45 mph. The use of a moving median catches transient errors that may make a free flowing vehicle appear to be congested. 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 for each lane at each station for each sensor unit during the free flow periods over the same 19 hr period used in 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, Figures 4.1-4.4 show a scatter plot of the
downstream on-time versus upstream on-time and the complete distribution of the on-time differences for each of the sensors at Station 8. One can clearly see the tight distribution of on-time differences for IST and 3M in Figure 4.1 and 4.4 respectively. Figure 4.2 shows that Reno is generally tight, but the distribution for lane 6 is heavily biased into the negative range. Figure 4.3 shows generally good performance by the Peeks in the four lanes that they functioned, but no results for the two lanes that did not report any downstream data (note that the indicator lights on the front panel correctly flashed with each vehicle passage, but the actuations were not reported to the controller). It is also interesting to note in the scatter plots that IST and Peek appear to block or extend all actuations below 6/60 sec while Reno and 3M do not. The reader should be cautioned that the scatter plots do not show the density of points, one should refer to Figures 2.1-2.2 for an indication of the number of extremely short on-times.

**Manual Validation**

As noted previously, the data from a traffic detector need to be sufficiently accurate since any errors will propagate to decision-making and control actions, and it is of utmost importance 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 come.

Lanes 1-4 at Station 7 were selected 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. For example, the Truck in lane 3 in Figure 1C has begun to obscure completely lanes 1-2 from this vantage point, but the concurrent view from the rooftop (Figure 1B) shows there are two cars in lane 2. The video recording times were pre-selected to capture both free flow and congested periods. After digitizing the video, 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 the RTMS). Three undergraduate students were assigned the task of synchronizing the video to detector data and generating ground truth vehicle passages. All of the students were assigned one of the pairs of five minute windows for each sensor, ensuring that each student would process the same amount of data for each sensor and reduce 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 its detection zone that was offset from the loops.

The research used the Videosync software package (which is 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. Figure 5 shows two sample screen shots from Videosync, in each, the upper left hand corner it shows the current video

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2 In this case the truck is partially obscured by labels superimposed on Figure 1C but the rear of the trailer is visible in lane 3.
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. 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", ... "eb 4d" correspond respectively to the data recorded from the downstream ("d") loop detectors in eastbound ("eb") lane 1 through 4 while the channels prefaced with "gt" contain the manually generated ground truth for the same lanes. Figure 1C shows that the downstream loops are on the left hand side of the video image 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 channels 3-4 and channels 1-2, respectively, on the right side of the figure. The loops in the other two lanes are empty and the detector state is off at this instant for these lanes in the time series. 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 erroneously in lane 2. Label ii is concurrent with the video image shown, a pickup truck in lane 2 is not detected due to the semi-trailer in lane 4 obscuring the "view". Shortly thereafter, while the semi-trailer was still blocking the field of view, a phantom vehicle is detected in lane 1, Label iii, while three vehicles eventually pass in the 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 actually dropped mid trailer, 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, the remaining actuations being clearly over-counting errors. An action is counted even if it overlaps a ground truth pulse by a single sample period of 1/60 sec. The results show the total across all three students and are broken down into free flow, congested, and the two combined. Figure 6B shows the percentage of ground truth pulses that overlapped one or more actuations, with the remaining ground truth being clearly under-counting errors, again presented in the same format as the previous plot. 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. See Figure 6.1 to see 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

3 Another mode, not shown, allows for manually inputting the ground truth data as vehicles enter and leave the detection zones.

4 The loops are barely visible in the video, making it difficult to see them in the included samples.
vehicles from that lane are not included in the ground truth for 3M. Similarly, the reader should recall that at Station 8, two Peek sensors did not report any data for the downstream loop. The results presented in Figure 6 show that the RTMS has the worst performance of the five sensors, followed by Reno. The detail of the errors will be examined shortly, for now, simply 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 on-times recorded by the students. 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 one sample period, 1/60 sec. Figure 7B shows the average absolute on-time error over all of the ground truth pulses. All of the loop sensors were under 1/60 sec while the RTMS had an average 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%. See Figure 7.1 for a detail of these plots shown with a smaller plotting range and Figures 7.2-7.3 for the results broken down by individual students (the student numbers are consistent with those in Figure 6.1).

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 and manually classify the source of each such discrepancy across all three students' data (the software includes the ability to jump from one pulse to the next, updating the video frame and time series plots, then to synchronously "play" the two data sources in forward and reverse).

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., splashover), 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 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. 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 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) and such errors are already evident in Figures 2 and 7. Table 2 shows the errors due to obscured vehicles, both vehicles with on-times shorter than they should be and those missed all together, as well as errors due to reflections, both vehicles that have on-times longer than they should be and those detections that do not correspond to a vehicle in the lane. Finally, the total on 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, 4.6%.

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 not 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 45 ft. 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 2C 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, compare the raw data time series to the ground truth for lane 2 (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. It appears that the IST problem starts when the detector has been occupied for many seconds, though it may simply become readily apparent under these conditions, while occurring at other times as well.

**Analysis of Aggregated Data**

To characterize the impacts of the errors on standard operation, the detector data are aggregated and the performance further evaluated. Just as Figure 4 contrasted the performance of the upstream loop against the downstream loop for individual vehicle actuations, Figure 9 continues the comparison showing the scatter plots of downstream versus upstream occupancy and then repeating the comparison for flow for each loop sensor using 5 min samples in the eastbound lanes at Station 7. Again, if one or both of the detectors in the given lane did not provide data for that sensor, the results are not shown on the plot. In all plots, the majority of the data fall on the diagonal indicating that the data from the upstream loop is very similar to the data from the downstream loop, as expected, but there are several notable exceptions. First, at higher occupancies, most sensors show increased scatter, which one would expect since during the congestion that cause these higher occupancies a vehicle may come to a stop over one detector for several seconds while the other detector is not occupied. The occupancy in lanes 3 and 4 for Peek are skewed significantly, reflecting the errors found in Figure 4. These errors are also reflected in the corresponding flow comparison for Peek, where almost all of the upstream flow data from lane 4 is off the scale, being greater than 3000 vph (see Figure 9.1 for the
corresponding flow versus occupancy for these data, note that the scales change from one plot to the next to ensure that all of the data are shown). Also noteworthy is the fact that almost all lanes of the Reno exhibit significant scatter at higher flows, which is consistent with the flicker problem identified in the manually classification presented in Table 1.

Repeating this exercise for Station 8 and westbound traffic at Station 7, as shown in Figure 9.2-9.3, respectively, once more in most lanes the data fall on the diagonal. At Station 8 The Reno flickering problem became more pronounced in the flow scatter plot, Peak lane 2 showed errors both in flow and occupancy, and 3M lane 3 showed small errors on the flow scatter plot. In the westbound Station 7 data the Reno flickering problem is still present though less pronounced. This time, 3M lanes 2 and 3 showed significant deviation for flow, while IST lanes 1, 2, and 4 show major errors in both flow and occupancy. Four of the IST loops in these lanes reported near 100% occupancy for several hours, as evident in Figure 9.4. Inspection of the individual transition data revealed a problem similar to that shown in Figure 8 only persisting for hours. The one difference being that the times that the detector briefly turns off do not appear to be correlated with vehicle passages, based on data from the other loop in the two lanes where one loop appeared to remain operational, see lane 2 westbound in Figure 9.5 for an example.

IST Error

The recurrence of the IST problem prompted a more detailed search. At the end of the data collection effort, Stations 8 and 9 of the BHL were equipped with IST sensors while Station 7 was reequipped with the manually tuned Peek sensors it had prior to the collection. In an attempt to quantify the extent and magnitude of the errors, the pattern and frequency of these errors at Station 8 and Station 9 (the westbound station parallel to Station 8) were examined for the entire month of October 2003. As a proxy to identify the phenomenon, the investigation searched for two or more sequential off-times below 0.5 sec. Whenever such a sequence was found, the number of pulses, duration, time of day, and day of month were noted. The number and duration yield similar results, so this document will present only the duration results. Subjective evaluation indicated that time of day was not as informative as the traffic conditions, i.e., the errors appear to be more frequent during congestion, but no attempt has been made to show a statistical relationship.

One would expect the occasional short headway and occasional detector error to be caught in this search and be short lived. Indeed, most occurrences of two or more successive short off times lasted less than 5 sec and are excluded from further analysis. This filtering may have also removed many true occurrences of the error that were short lived, but by that very nature, they should have a much smaller impact on aggregate measures. Figure 10.0 shows the distribution of the duration of the errors over all 31 days in October at Station 8, where the span of the vertical axis changes from plot to plot to show the total number of such errors that lasted longer than 5 sec at the given loop. From the top left plot, we see that there were just over 50 such occurrences at the upstream loop in lane 1 at Station 8, the longest of these lasted about 20 sec. Other loops have higher flows and a higher occurrence of the errors, some exceeding 1000 occurrences over the month. Only lane 3 appears to have a significant number of errors that last more than 60 sec (the curve reaches the right hand edge of the plot before it reaches the top of the plot). Figure 10.1 repeats the process for station 9. Here, the loop in lane 6 has not provided data using any sensor card (IST or otherwise) since the opening of the BHL, presumably due to a physical break in the connection. The other lanes appear to show a slightly larger frequency of
the errors compared to Station 8. Furthermore, several loops have non-negligible number of errors that last more than 60 sec (lane 1, 2 and 3, upstream and downstream).

While conducting this work, another problem became apparent, as exemplified in Figure 10.2 from Station 9 on October 22, 2003. Figure 10.2A shows the transition data for lane 1 (upstream below downstream) over a 5 hour period in the morning. There are several long periods where lane 1 downstream is stuck on or stuck off for extended periods while lane 1 upstream is reporting data. Similar "sticking" errors are evident in the upstream loop as well. The other lanes at this station do not exhibit such an error on this day. Figure 10.2B shows a detail of the data from all five working lanes over a half hour period, lane 1 upstream appears to have more transitions than any of the other loops. One would expect this lane to see demand more like lane 2, which is also shown in the figure. Care was taken to verify that this problem was not due to data transmission or processing errors.

Since one would expect the occasional long off-time simply due to lack of demand, the analysis focused on the long on-times. Quantifying the frequency of the stuck-on problem, Figure 10.3 shows the time of day for all on-times in excess of one minute for the entire month of October 2003 at station 8 in each lane (downward pointing triangles for the upstream loop, upward pointing for the downstream loop). The total number observed during the month is shown in the title of each plot. Figure 10.4 repeats the analysis for station 9, where lane 1 appears to have the highest frequency and duration of long on-times, with most occurring during the early morning when traffic should be free flowing and the on-times short. Several of these early morning on-times approach three hours in duration.

As noted with regard to Figure 10.2, lane 1 upstream had the highest number of pulses for any of the loops around 3am. Plotting the cumulative distribution (CDF) of on-times for this loop on the given day in Figure 10.5, for the period between midnight and 6am, most of the on-times are about 6/60 sec, while repeating the distribution for the entire 24 hrs, the center of the distribution exceeds 12/60 sec. Since the typical passenger vehicle traveling at free flow speeds should have an on-time in excess of 12/60 sec, it is possible that the short on-times before 6am may be due an absence of demand in this lane and the sensor card attempting to recalibrate its operating frequency.

**RTMS PERFORMANCE**

Two draft reports have been submitted to Caltrans for feedback regarding performance of the RTMS versus the dual loop detectors at Station 7 based on earlier data collection efforts. The reports have not been formally published and to address the omission, this section recaps the relevant portions of those two studies in the context of the results presented above. Unlike the results presented thus far, the loop sensors were tuned extensively to eliminate discrepancies between the upstream and downstream loops in a given lane. The loop sensors used were a combination of Peek GP6 and Peek GP5 (revision G) and the data were collected between 1999 and 2000.

**Study 1, Aggregated Data Reported by the RTMS**

This first effort considered the aggregated data reported by the RTMS using its internal controller emulation, as logged locally on a PC. Four data collection runs were conducted, the first two are omitted from this report due to possible calibration errors and the use of short
sample periods (10 sec). The remaining two data collection runs, 3 and 4, occurred after Dan Manor's final calibration at the site and the analysis is presented below. It should be noted that the specific timing of the runs were arbitrary, they were selected ahead of time based on convenience of accessing the site and such that each run would include both free flow and congested traffic conditions.

Run 3

Sampling period: 30 seconds
Duration of study: 10 hours
Duration of congestion in study: over 4 hours
RTMS calibration by: Dan Manor

This run attempts to mimic the data that would be collected using conventional 30 second sample periods. The RTMS unit was calibrated by Dan Manor and as a result, these data should be representative of the best possible calibration for the location. Figure 11.0 shows scatter plots for flow comparing both sensor systems, the results are shown in vehicles per sample. Figure 11.1 shows the corresponding scatter plot of occupancy. One can see that relative to the loop detectors the RTMS overestimates occupancy for high values in lane 2 and underestimates in lanes 4 and 5. Overestimation in lane 2 may be due to occlusion from lanes 3-5, but it is not clear why the unit is underestimating this parameter in the outside lanes unless a change in detection zone size from lane to lane impacts the RTMS performance. Figure 11.2 shows the RTMS velocity measurements.

According to the dual loop detector data, the two inside lanes are characterized by few vehicles over 25 feet while approximately 10 percent of the vehicles in the other lanes are over 25 feet. According to Mr. Juha, the RTMS unit estimates velocity in manner similar to what is conventionally used at single loop detectors:

$$\text{estimated velocity} = \frac{\text{flow} \cdot \text{vehicle length}}{\text{occupancy}} \quad (3)$$

However, the RTMS unit excludes all vehicles that occupy the detector for more than three times the current average on-time. Presumably, this exclusion will eliminate most long vehicles from the sample. Another difference is that the RTMS unit continually updates the vehicle length estimate in each zone, to adjust to changing traffic conditions. The presence of long vehicles may have skewed the estimated "vehicle length" in the outer three lanes. In contrast, Figure 11.3 shows the estimated velocity using flow and occupancy from the downstream loop detector. So this figure shows estimated versus measured velocity from loop data. The average effective vehicle length was assumed to be 21 feet in all lanes for the loop estimate. Comparing Figures 11.2 and 11.3, the RTMS appears to be noisier in lane 1 and 2, tighter in lanes 3 and 4, and biased in lane 5.

To quantify the magnitude of errors the work used the root mean squared error (RMSE) and bias of as given parameter over n samples as follows:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{x}_i - x_i)^2}{n}} \quad (4)$$
Bias = \frac{\sum_{i=1}^{n} (\hat{x}_i - x_i^*)}{n} \quad (5)

where \( x_i^* \) is the measured value from the dual loop detector for the i-th sample and \( \hat{x}_i \) is the corresponding measurement or estimate from the RTMS (or in the case of Figure 11.3, from the single loops). The resulting RMSE and Bias for each lane are reported in the first four rows and five columns of Tables 3A and 4A, respectively. For reference, the next five columns show the auto-correlation between successive measurements from the dual loop detector and the final five columns show the auto-correlation between successive RTMS measurements. For flow and occupancy, Table 3A shows that the RMSE of RTMS versus Loop is less than either of the auto-correlations. For the first five columns of Table 4A, a positive value indicates the RTMS, on average, overestimated the given parameter and a negative value indicates the RTMS underestimated it. For comparison sake, Tables 3B and 4B repeat the comparison between RTMS and Loop for flow and occupancy, then in the final five columns, report the comparison between the upstream loop and downstream loop in the given lane (which are further apart than the downstream loop and the RTMS detection zone).

**Run 4**

- Sampling period: 10 seconds
- Duration of study: 10 hours
- Duration of congestion in study: about 4 hours
- RTMS calibration by: Dan Manor

Sampling at 10 second samples, this run attempted to analyze the performance of the RTMS unit running at its fastest sampling period. The results are noisy and given the separation between detectors, comparison might not be merited at such a short sampling period.

**Run 4L**

- Sample period: 300 seconds
- Duration of study: 10 hours
- Duration of congestion in study: about 4 hours
- RTMS calibration by: Dan Manor

Aggregating the data from Run 4 up to 300 second samples, this section repeats the analysis applied to Run 3 for longer samples from the same data. Figure 11.4 shows scatter plots of flow and again, the longer sampling period brought most of the observations to the central axis. Moving to occupancy in Figure 11.5, the figure exhibits the same biases found in Run 3. The RMSE and Bias statistics for this run are reported in Tables 3-4. Note that the RTMS velocity is estimate from RTMS flow and occupancy using Equation 3 since there is no way to aggregate the reported velocity estimates accurately. Had the unit originally been sampling at 300 sec, based on the results for run 3, the velocity reported directly from the RTMS would likely be better than those from the equation. However, the estimates from Equation 3 are presented because they are an indication of how accurately the RTMS measures flow and occupancy.
Primary Findings

This study examined the performance of the RTMS sensor deployed in side fire mode and the following conclusions only apply to this mode of operation. First, the manufacturer's general performance claims are over-ambitious for the RTMS sensor; most measures are not as clean as loop detectors; still, it promises significant cost savings and could be used to (relatively) cheaply provide information where none was previously available. Although the study site was reportedly less than ideal from the manufacturer's standpoint, it is representative of geometry throughout California. Furthermore, the RTMS was not able to monitor the opposing lanes in this geometry. Secondly, since occupancy is strongly correlated with vehicle lengths, the RTMS performs poorly in samples that include few vehicles and the RTMS unit does not do a good job of estimating velocity with short sample periods. While the RTMS occupancy and flow measures are noisier than loops, the velocity estimates are almost as good as those from single loops. Although many operating agencies use single loop detectors estimate velocity, our research has shown that there are several ways to improve upon the quality of these conventional estimates (and presumably the RTMS by extension) [16-19]. In the mean time, it may be advisable not to use the RTMS to estimate velocity for samples less than 5 minutes long (a similar argument could be made for velocity estimation from single loop detectors). Of course, if a higher sampling rate is desired, a moving average or exponential filter could be used on the flow and occupancy measurements.

In light of these issues, the RTMS is still a useful tool in niche applications since it does not require the safety risk or expense associated with lane closures. The unit requires a highly skilled individual for proper calibration and even then, the results are subject to errors. If Caltrans deploys a large number of RTMS units, it should develop the skills in house to properly calibrate the devices. In the mean time, Caltrans should check the performance of any deployed units that were calibrated by novice users.

The RTMS detector has overcome many problems faced by non-invasive detectors, but it appears that the unit's current performance is not comparable to that of a fully functioning loop detector. This result is not surprising, because loop detectors are placed in the lane of interest, whereas a radar sensor must differentiate between many vehicles that may or may not be in the lane of interest. On the other hand, radar sensors are much easier to install and maintain.

Study 2, Contact Closure, Velocity, and Occupancy Data Reported by the RTMS

This second study considers aggregate measurements from the contact closure data. The RTMS performance is compared to the closest loop detector in the given lane, denoted as the second loop in Figure 1.2. This choice was made for several reasons, first, loop detectors are the de facto standard in California and most other states. Second, the performance of the loops used in this study has been validated using microscopic data analysis tools [5-6]. Third, other research has demonstrated the reproducibility of the loop measurements from this detector station with those at neighboring stations in the process of reidentifying vehicle measurements between stations [20-21]. The reidentification work requires accurate measurement of vehicle passages, on times, velocities and lengths in each lane, independently at two different detector stations. Fourth, as noted above, earlier studies found that properly installed loop detectors provided very accurate count measurements [1-3]. Of course the detection zones are spatially separated, to quantify any errors due to this spacing, the analysis is repeated comparing the first loop in the dual loop detector to the second.
Using the time-space plane, Figure 12.0 shows an example of a vehicle passing through the three detection zones of a single lane from Figure 1.2. The controller records a pulse from each detector, consisting of a rising edge and falling edge, as shown in Figure 1B. The difference between the falling edge and the rising edge is simply the on-time, denoted in the figure as $OT_1$, $OT_2$, $OT_R$, respectively for the first loop, second loop and RTMS zone in the given lane. Based on the spatial limitations shown in Figures 1.2 and 12.0, it is clear that a vehicle must pass the first loop, then the second loop, then the RTMS. The vehicle may not completely pass one detector before it begins passing the next. To deduce the distance between detection zones, the pulses were sorted by the time of their rising edge. All pulses that are observed at the first loop are matched to the subsequent pulse at the second loop, while all pulses at the RTMS are matched to the preceding pulse at the second loop. In the event that a pulse at the second loop is matched to exactly one pulse at the first loop and one pulse at the RTMS, we can measure the traversal time between detectors, denoted $TTL$ and $TTR$ in Figure 12.0. The spacing between the loops is known to be 20 feet and one can measure individual vehicle velocity, $v$, using the following equation:

$$v = C \times \frac{20}{TTL}$$

where $C$ is a constant to convert the units to mph. The location of the RTMS detection zone varies by lane and the two different detection systems will measure the start of vehicles differently. Figure 13 shows the distribution of the ratio $TT_R/TT_L$ for each lane. These plots only use cases where there is a single pulse at all three detectors and the dual loop velocity is greater than 50 mph. Note that parts 1-5 of this figure correspond respectively to the given lane numbers (1 inside, 5 outside and the RTMS unit is closest to lane 5). This five-part figure convention will be used throughout this section. Returning to the figure at hand, the solid line in each plot is based on the rising edges and clearly shows that the RTMS detection zone begins less than 20 feet downstream of the beginning of the second loop detection zone in each lane. Repeating the traversal time calculations using the falling edge of the same pulses yield the dashed lines in these plots. These distributions show that the RTMS detection zone ends less than or equal to 20 feet downstream of the end of the second loop detection zone in each lane.

The actual size of the loop detection zone should be approximately 6 feet, but it was not measured.

Using the median values from the distributions in Figure 13, columns 2-3 in Table 5, one can estimate the distance to the leading and trailing edge of the RTMS detection zone, columns 3-4 in the table. The extra width of the RTMS detection zone compared to the second loop is simply the difference between the two distances, and is shown in the last column of the table. The reader should note that according to Mr. Juha, 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 falling edges in Figure 13 or Table 5. So the trailing edge of the RTMS detection zone should be much closer to the second loop.

Figure 14 compares the CDF of the flow difference relative to the second detector using 5 min samples, $q_2-q_R$ and $q_2-q_1$. The mean and median are close to zero in all lanes, but the RTMS has a larger variance compared to the first loop. Separating the data into two groups based on speed and into two groups based on flow, the resulting distributions are shown in the top and bottom plots in Figure 15, respectively. Note that the flow threshold, 1000 vph, corresponds to 83.3 vehicles per 5 min. As one might expect, the variance increases at high flows simply due to the
fact that the samples have more vehicles and thus a larger difference can occur. One also observes a larger variance at lower speeds, which might be due to a sensor having difficulties differentiating between vehicles in higher density traffic. Once more, the first loop data are closer to the second loop than the RTMS data are, even though the spatial relationships are the opposite. The first few columns of Table 6 show the average absolute percent error for all samples that had a non-zero flow at the second loop, \( \frac{|q_1 - q_R|}{q_1} \) and \( \frac{|q_1 - q_1|}{q_1} \). Except for lane 1, the RTMS flow is within 10 percent of the second loop, while the first loop is within three percent for all lanes. The remaining columns of Table 6 subsample the data by the flow threshold and then again by the velocity threshold used in Figure 15. The RTMS error increases at low velocity in lanes 2 and 5 while dropping in lanes 3 and 4 at lower velocities. The RTMS error increases in all lanes at low flow. Similar trends are evident in the loop data, though the relative change is much smaller for the loops.

Repeating this analysis using the 5 min occupancies, Figure 16 shows the CDF of the difference relative to the second detector, \( \frac{\text{occ}_2 - \text{occ}_R}{\text{occ}_2} \) and \( \frac{\text{occ}_2 - \text{occ}_1}{\text{occ}_2} \). Note that before measuring \( \text{occ}_{c2} \), the recorded OTR was shortened by 0.15 sec in this figure and the subsequent analysis in this section to remove the extension delay on the falling transition. The mean and median in lanes 1-2 are similar for the first loop and RTMS, but again the variance is larger for the RTMS. As one moves to the outside lanes, closer to the RTMS unit, there is a clear bias in the RTMS measurement. The RTMS underestimates occupancy relative to the second loop. In contrast, the first loops only show a slight increase in variance as one moves to the outer lanes. Figure 17 repeats the subdivision by average velocity and flow. Once more the RTMS shows a larger discrepancy relative to the second loop at lower velocities. Some of this error is due to the spatial separation between the detection zones, as is evident in the first loop distribution. Recall that the first loop is further away from the second loop than the RTMS detection zones. The first few columns of Table 7 show the average absolute percent error for all samples that had a non-zero occupancy at the second loop, \( \frac{|\text{occ}_2 - \text{occ}_R|}{\text{occ}_2} \) and \( \frac{|\text{occ}_2 - \text{occ}_1|}{\text{occ}_2} \). The average error for loop 1 ranges between 1.5 percent and 2.7 percent across the lanes. The average error from the RTMS is best in lane 3, at 8.8 percent and degrades as one moves away from this lane, reaching a maximum of 57.4 percent error in the outside lane. The remaining columns of Table 7 subsample the data by the flow threshold and then again by the velocity threshold used in Figure 15. Interestingly, at low velocities, the RTMS performance improves in the lanes closest to the sensor unit but degrades in lanes further from the sensor. The first loops show slightly higher error at low velocities compared to their performance at higher velocities, with a maximum of 6.0 percent. Returning to the RTMS, one sees a slight increase in the occupancy percent error at lower flows for the near lanes, with significant degradation in lanes 4 and 5. These results are important, not only did the RTMS sensor show large errors relative to the second loop, but the magnitude of those errors depend on the lane. These results suggest that it would be difficult to derive a simple correction factor.

Comparing across lanes, Figure 18 shows the flow versus occupancy plots for the second loop and the RTMS sensor zones. For reference, a triangle is superimposed on each plot in this figure and the triangle is identical in all of the plots. The loop detectors provide similar results in all lanes during free flow conditions, i.e., the distribution around the left-hand side of the triangle is similar in the top plots of this figure. While the RTMS shows lane dependent results during free flow conditions. At higher occupancies, the RTMS appears to yield higher flow relative to the loop detector, with a pattern that changes from one lane to the next.
This analysis was also conducted using 30 sec samples with similar results, as shown in Tables 8-9. Highlighting the differences compared to the 30 sec data, 5 min flow from the first loop improves by roughly a factor of three. The RTMS performance improves slightly in the lanes closest to the RTMS, but remains roughly the same in lane 2 and has degrades in lane 1. The 5 min loop occupancy performance improves by roughly a factor of two while the RTMS performance does not change significantly.

For reference, Figure 19 provides an overview of traffic conditions throughout the entire sample. These plots show the five min flow, occupancy and velocity from the dual loop detectors versus time since midnight on the first day. There were two periods of congestion during the data collection, the first around 18 hrs and the second around 39 hours. Notice that early on the morning of the second day that lanes 1-3 were closed for about six hours due to maintenance activity downstream of the detector location. The data from these lane closures were excluded from the results in Tables 6-9 because the second loop reported zero values during these periods.

All of the analysis up to this point has focused on the contact closure output from the RTMS, as fed through a traffic controller. But as noted above, the RTMS unit is capable of providing traffic data without the need of a controller. Shifting the focus to the data directly available from the RTMS, like a single loop detector, the RTMS sensor is capable of measuring vehicle passages and on-times, which can be used to measure flow and occupancy and then estimate velocity using Equation 3 and the proprietary techniques noted above. The RTMS was set to report data in 30 sec samples, so the following analysis uses this sampling period.

Figure 20 shows the measured velocities from the dual loops, the estimated velocities from the RTMS and the two plotted together for a single day. This day was selected because it has the greatest mix of traffic conditions: free flow, an extended period of early morning lane closures, and congestion. The most prominent errors occur during the early morning hours. Ignoring lane 1, we see the RTMS occasionally detects vehicle in lanes 2-3 during the period that they are closed. Presumably these errors could be eliminated by the manufacturer or accounted for in a traffic management system, e.g., via checking the corresponding occupancy or comparing across lanes. In lanes 4-5, the RTMS significantly underestimates velocity for several samples. To put these errors in context, consider Figure 21. The top plot uses points to show the estimated velocity from Equation 3 applied to the second loop 30 sec flow and occupancy on a day that only had free flow conditions. For reference, the measured velocities from dual loops are shown with a solid line. Obviously, the constant vehicle length used in Equation 3 will scale the velocity estimates. We set this length using the following relationship:

\[
\text{vehicle length} = \text{mean} \left( \frac{\text{measured velocity} \cdot \text{occupancy}}{\text{flow}} \right)
\]  

(7)

The resulting lengths are noted on each plot. In practice, one would expect some error that would bias the estimates from Equation 3.

The second plot shows the corresponding velocity estimates reported by the RTMS unit (points) and the measured velocity from the dual loops. The velocity estimates are biased, too low in lanes 1-2 and too high in lanes 4-5, because the RTMS does not have the benefit of measured velocity to calculate the estimated lengths. Instead, the RTMS continually updates the estimated vehicle length. One would expect similar errors from any conventional single loop detector. What is important is the fact that in lanes 3-4, the RTMS exhibits a lower variance than the
single loop data in the top plot. The single loop detector significantly underestimates velocity several times during the early morning hours due to a higher percentage of trucks in the vehicle fleet and the fact that the assumed vehicle length is too low for these samples. In the outside lanes, the RTMS was able to identify and eliminate many of these errors. Of course other strategies can be used to eliminate such errors from single loops or RTMS data [16-19]. In any event, the dual loop velocity is superior to what would be available from single loops or the RTMS.

The third plot on each page shows the estimated velocity from Equation 3 applied to the RTMS 30 sec flow and occupancy as reported by the contact closure output (less 0.15 sec per pulse). Again, the measured velocities from the dual loop are shown with a solid line for reference. Equation 7 was used to calculate the constant length for this plot and again the resulting lengths are shown on each plot. This estimate shows significantly greater variance than the two preceding estimates. Also note that the estimated length for the single loop ranges between 19.95-20.75 ft across all lanes, but the RTMS length ranges between 10.62 and 18.8 ft for lanes 2-5. This increased variance implies some inconsistency in occupancy and/or flow measurement across lanes by the RTMS.

Unfortunately, we were not able to perfectly synchronize the RTMS and controller clocks for this study, so it is not possible to conduct one-to-one comparisons between the two outputs at a microscopic scale. Presumably the flow and occupancy measurements from the RTMS should be identical to what was derived from the contact closure output. To test this supposition, the bottom plots show the estimated velocity from Equation 3 applied to the RTMS 30 sec flow and occupancy as reported directly from the RTMS unit. The errors are greatest in this plot due to the fact that the logged data are rounded or truncated to integer values. As noted in [18], such rounding can lead to significant errors at low occupancy (i.e., large percent error but small absolute magnitude). These integer values may be due to the RTMS unit or the PC logging software provided by EIS. This question will be examined further in a moment. Meanwhile, continuing with the velocity analysis, Figure 21 shows the RTMS velocity estimates can be good during free flow conditions. Zooming in on the data from Figure 20, Figure 22 shows the velocity estimates at the start and end of the congestion period. In this figure, the RTMS estimates are shown with a line connecting each individual measurement while the dual loop measurements are shown with a step function (one point at the start and one point at the end of each sample period). The aforementioned biases are evident during the free flow periods. The RTMS shows few large transient errors in these plots even though the period between 17.5 and 18.5 hours is characterized by stop and go traffic.

Significant discrepancies were found between the loop occupancy and the RTMS occupancy as measured by the controller. To verify that these results are representative of the RTMS, Figure 23 compares the occupancy measured directly by the RTMS unit and the occupancy measured from the RTMS contact closure data via the controller. The top plots show 24 hours of data from each lane, in each plot the two lines fall virtually on top of one another. The lower plots in these figures show the difference between the two curves. The RTMS sample period is slightly longer than 30 sec. The two time series are in phase at approximately 16 hrs and as a result, the individual sample differences are smaller at this point. However, an error in one sample due to being slightly out of phase should be offset by an opposite error in the next sample. The mean difference, or bias, is shown at the top of each plot and is roughly 0.5 percent occupancy. This value is exactly what one would expect if the data reported directly from the RTMS has the
decimals truncated. Because the scale in the top plots obscure the details, Figure 24 shows three different hour long periods from Figure 23. The top plots show the period between 11-12 hrs, which exhibited high free flow occupancies. The middle plots show the period between 15-16 hrs, which exhibited high congestion occupancies. The bottom plots show the period between 23-24 hrs, which exhibited low free flow occupancies. The truncated occupancies are clearly evident in the bottom plot. Note that the vertical scales are different in each hour long period, but consistent across all five lanes. The strong correlation between the two time series occupancies, direct from the RTMS and via the controller, verifies Mr. Juha's statement that the RTMS delays the end of each pulse in the contact closure output by a fixed 0.15 sec. Reportedly, the most recent revision of the RTMS does not truncate occupancy to integer percent.

**Primary Findings**

This study examined the performance of the RTMS sensor deployed in side fire mode against loop detectors. The deployment and data represent what would be available from an RTMS unit without the benefit of loop detectors for calibration. The study site is representative of geometry throughout California and it was noted that the RTMS was not able to monitor the opposing lanes in this geometry. Prior to reporting results, aside from the issues mentioned in the Introduction, the representatives from EIS did not raise any concerns about the deployment. For reference, the work also compared one loop against another in a dual loop detector. The analysis consisted of aggregate data comparisons. The work used the redundancies of the dual loop detector to verify the performance of each loop in a given lane. It also showed that the two loops were further apart than the RTMS was from the closest loop. Hence, the first loop should provide an upper bound on the expected errors in the RTMS data due to the spatial separation of detection zones in a given lane.

From the aggregate data, consistent with earlier studies, the RTMS flow measurements are within 10 percent of those measured by the loops, while the two loops were within 3 percent of one another. These flow measurements should be good enough for many operations applications but may not be good enough for calculating average annual daily travel (AADT). The RTMS occupancy measurements showed significant discrepancies relative to the loops, ranging between 13 and 40 percent and these errors show an apparent lane dependency. These results suggest that it would be difficult to derive a simple correction factor. Even if one excludes the results from both lane 1 and lane 5, the occupancy measurements may not be good enough for applications such as traffic responsive ramp metering. When evaluating both the flow and occupancy performance, the reported percentages exclude periods in which the second loop did not measure any vehicles (including the lane closure). Qualitative analysis showed the RTMS velocity estimates are comparable to a single loop detector station, but inferior to actual measurements from dual loop detectors. When comparing between pairs of lanes, the loop detectors provide more consistent measurements than the corresponding RTMS detection zones.

These findings are consistent with those of the Caltrans Traffic Operations Program Data Collection Functional Requirements Task Force. The task force noted that in areas without existing loops, the RTMS can be deployed in side fire mode to, "quickly fill in gaps where detection is poor, non existent, or out due to construction. It must be accepted that this data is significantly less than perfect, but some data is always better than none." [22]
Of course all of the figures are presented in this document, allowing the reader to assess the performance of the RTMS and reach their own conclusions. After all, the appropriateness of the detector depends on the applications, detection network and a host of other factors that are far beyond the scope of this work.

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 even more important that a detector performs as expected. Each sensor was deployed following conventional guidelines and the data evaluated at multiple resolutions, included 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, 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 as to how best to incorporate such tests in future controller software. Other errors would likely require a field visit to adjust, 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. As was shown with the Distribution of Individual Vehicle Actuations, the RTMS has a larger detection zone than the loops, while the apparent size of the detection zone varied even from one sensor model to the next for the same loop. 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 shown 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 location.

The IST sensor also exhibited an unusual error where it will stick on, partitioned with brief flickers off, which according to the manufacturer is related to the auto-calibration of the sensor frequencies. In the short term, it may be possible to avoid this error by manually selecting the operating frequencies, but this speculation has yet to be tested. The IST sensor would also occasionally fail by simply sticking on or sticking off for long periods.

Returning to the RTMS, count/flow and on-time/occupancy are generally noisier than loops, though errors of omission are roughly balanced by errors of commission in counts (Table 2).
Perhaps surprisingly though, the estimated velocity reported by the RTMS, (not as calculated from the RTMS contact closure data) are almost as good as conventional estimates from single loop detectors. While conventional single loop estimates appear to be sufficient for many operating agencies, there are many ways to improve the estimates significantly that have yet to enter standard practice [16-17] or further clean up conventional estimates [18-19].

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REFERENCES


Figure 1, (A) Sample video frame shot from a 30 story building viewing Station 8. (B) Sample video frame shot from a 30 story building viewing Station 7. (C) Sample video frame shot from a Caltrans CCTV camera (visible in part B) viewing Station 7. (D) Still photo from the ground showing the configuration of Station 7.
Figure 1.1, The four loop sensors tested, left to right: Peek, Reno, 3M, and IST.
Figure 1.2, Schematic of the data collection site at Station 7 in the BHL.
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 velocities 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.
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Figure 18-1, Lane 1

flow versus occupancy, second loop, T=300, 1172 samples

flow versus occupancy, RTMS, T=300, 1172 samples
Figure 18-2, Lane 2

flow versus occupancy, second loop, $T=300$, 1186 samples

flow versus occupancy, RTMS, $T=300$, 1186 samples
Figure 18-3, Lane 3

flow versus occupancy, second loop, T=300, 1194 samples

Flow versus occupancy, RTMS, T=300, 1194 samples
Figure 18-4, Lane 4

flow versus occupancy, second loop, T=300, 1195 samples

flow versus occupancy, RTMS, T=300, 1195 samples
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flow versus occupancy, second loop, T=300, 1195 samples

flow versus occupancy, RTMS, T=300, 1195 samples
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Figure 19.5: Flow, occupancy, and velocity throughout the study, 5 min samples, as measured by the dual loop detector in Lane 5.
Figure 20-1

speeds from dual loops, lane 1, 5/26/00, T=30sec, 909 empty samples

time of day (h)
velocity (mph)

speeds from RTMS, lane 1, 5/26/00, T=30sec, 753 empty samples

time of day (h)
velocity (mph)

comparison between the two, x=dual loop, o=RTMS

time of day (h)
velocity (mph)
Figure 20-2

speeds from dual loops, lane 2, 5/26/00, T=30sec, 756 empty samples

speeds from RTMS, lane 2, 5/26/00, T=30sec, 656 empty samples

comparison between the two, x=dual loop, o=RTMS
Figure 20-3

speeds from dual loops, lane 3, 5/26/00, T=30sec, 627 empty samples

speeds from RTMS, lane 3, 5/26/00, T=30sec, 404 empty samples

comparison between the two, x=dual loop, o=RTMS
Figure 20-4

speeds from dual loops, lane 4, 5/26/00, T=30sec, 41 empty samples

speeds from RTMS, lane 4, 5/26/00, T=30sec, 81 empty samples

comparison between the two, x=dual loop, o=RTMS
Figure 20-5

speeds from dual loops, lane 5, 5/26/00, T=30sec, 4 empty samples

speeds from RTMS, lane 5, 5/26/00, T=30sec, 22 empty samples

comparison between the two, x=dual loop, o=RTMS
Figure 21-1

estimated speeds from single loop, lane 1, 5/28/00, 886 empty smpls, l=20.5ft, 27 smpls over 100mph

estimated speeds from RTMS, lane 1, 5/28/00, 987 empty samples

estimated speeds from rtms q & occ, lane 1, 5/28/00, 803 empty samples, l=18.93ft, 313 over 100mph

estimated speeds recorded RTMS q & occ, lane 1, 5/28/00, 800 empty samples, l=20.11ft, 585 over 100mph
Figure 21-2

Estimated speeds from single loop, lane 2, 5/28/00, 145 empty samples, l=20.52ft, 9 samples over 100 mph

Estimated speeds from RTMS, lane 2, 5/28/00, 197 empty samples

Estimated speeds from RTMS Q & OCC, lane 2, 5/28/00, 129 empty samples, l=18.66ft, 109 over 100 mph

Estimated speeds recorded RTMS Q & OCC, lane 2, 5/28/00, 122 empty samples, l=17.67ft, 375 over 100 mph
Figure 21-4

estimated speeds from single loop, lane 4, 5/28/00, 30 empty smpls, l=20.75ft, 0 smpls over 100mph

estimated speeds from RTMS, lane 4, 5/28/00, 45 empty samples

estimated speeds from RTMS q & occ, lane 4, 5/28/00, 24 empty samples, l=16.7ft, 39 over 100mph

estimated speeds recorded RTMS q & occ, lane 4, 5/28/00, 27 empty samples, l=15.32ft, 250 over 100mph
estimated speeds from single loop, lane 5, 5/28/00, 34 empty smpls, l=19.95ft, 5 smpls over 100mph

estimated speeds from RTMS, lane 5, 5/28/00, 132 empty samples

estimated speeds from rtms q & occ, lane 5, 5/28/00, 25 empty samples, l=10.62ft, 73 over 100mph

estimated speeds recorded RTMS q & occ, lane 5, 5/28/00, 25 empty samples, l=10.03ft, 214 over 100mph
Figure 22-1

(speeds from RTMS, lane 1, 5/26/00)

time of day (h)
velocity (mph)

(speeds from RTMS, lane 1, 5/26/00)

time of day (h)
velocity (mph)
Figure 22-2

Graphs showing speeds from RTMS, lane 2, 5/26/00.
speeds from RTMS, lane 3, 5/26/00

Figure 22-3
speeds from RTMS, lane 4, 5/26/00

Figure 22-4
Figure 22-5

speeds from RTMS, lane 5, 5/26/00

Figure 22-5 shows the velocities from RTMS, lane 5, for the day 5/26/00. The graph plots the time of day (h) on the x-axis and velocity (mph) on the y-axis.
Figure 23-1

RTMS occupancy as reported by the RTMS (red), and via the controller, (green), lane 1, 5/26/00

RTMS occ via controller - RTMS occ via RTMS, mean difference 0.3293 percent
Figure 23-2

RTMS occupancy as reported by the RTMS (red), and via the controller, (green), lane 2, 5/26/00

RTMS occ via controller - RTMS occ via RTMS, mean difference 0.4112 percent
Figure 23-3

RTMS occupancy as reported by the RTMS (red), and via the controller, (green), lane 3, 5/26/00

RTMS occ via controller - RTMS occ via RTMS, mean difference 0.4587 percent
Figure 23-4

RTMS occupancy as reported by the RTMS (red), and via the controller, (green), lane 4, 5/26/00

RTMS occ via controller - RTMS occ via RTMS, mean difference 0.5198 percent
RTMS occupancy as reported by the RTMS (red), and via the controller, (green), lane 5, 5/26/00

RTMS occ via controller - RTMS occ via RTMS, mean difference 0.5701 percent
Figure 24-1

details of RTMS occ reported by the RTMS, x’s, and controller, o’s, various scales, lane 1

- Top graph: Time of day (h) vs. occupancy (%)
- Middle graph: Time of day (h) vs. occupancy (%)
- Bottom graph: Time of day (h) vs. occupancy (%)
Figure 24-2

details of RTMS occ reported by the RTMS, x’s, and controller, o’s, various scales, lane 2

Figure 24-2

details of RTMS occ reported by the RTMS, x’s, and controller, o’s, various scales, lane 2
Figure 24-3

Details of RTMS occ reported by the RTMS, x's, and controller, o's, various scales, lane 3.
Figure 24-4

details of RTMS occ reported by the RTMS, x’s, and controller, o’s, various scales, lane 4

Figure 24-4
Figure 24-5

details of RTMS occ reported by the RTMS, x’s, and controller, o’s, various scales, lane 5
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<td>254</td>
<td>98</td>
<td></td>
</tr>
<tr>
<td>Percent</td>
<td></td>
<td></td>
<td>0.5%</td>
<td>0.0%</td>
<td>0.2%</td>
<td>0.3%</td>
<td></td>
</tr>
</tbody>
</table>

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

* 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.

* The 3M sensors did not report any data in lane 1.

* 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.

* 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.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Conditions</th>
<th>Lane</th>
<th>Vehicles</th>
<th>Obscured Vehicles</th>
<th>Reflections</th>
<th>Total errors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>total</td>
<td>short on-time</td>
<td>missed</td>
<td>long on-time</td>
</tr>
<tr>
<td>RTMS</td>
<td>Free flow</td>
<td>1</td>
<td>261</td>
<td>5</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>394</td>
<td>4</td>
<td>17</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>389</td>
<td>2</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>406</td>
<td>2</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>RTMS</td>
<td>Congested</td>
<td>1</td>
<td>425</td>
<td>7</td>
<td>57</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>522</td>
<td>8</td>
<td>31</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>429</td>
<td>8</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>484</td>
<td>10</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>RTMS</td>
<td>Total</td>
<td></td>
<td>3310</td>
<td>46</td>
<td>151</td>
<td>145</td>
</tr>
<tr>
<td>Percent</td>
<td></td>
<td></td>
<td></td>
<td>1.4%</td>
<td>4.6%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

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

* Including "Other errors", "Obscured Vehicles" and "Reflections", excluding "Errors during lane change maneuvers."
Table 3a, RMSE for the various runs. First five columns are RTMS versus loop, the next five columns are loop(n+1) versus loop(n) and the final five columns are RTMS(n+1) versus RTMS(n). These last ten columns are included for reference.

<table>
<thead>
<tr>
<th>units</th>
<th>run</th>
<th>T (sec)</th>
<th>RMSE RTMS vs. Loop, lane #</th>
<th>RMSE Loop(n+1) vs. Loop(n), lane #</th>
<th>RMSE RTMS(n+1) vs. RTMS(n), lane #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>RTMS measured</td>
<td>3</td>
<td>30</td>
<td>234.4</td>
<td>253.0</td>
<td>217.5</td>
</tr>
<tr>
<td>flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTMS measured</td>
<td>3</td>
<td>30</td>
<td>2.5</td>
<td>6.7</td>
<td>3.8</td>
</tr>
<tr>
<td>occupancy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTMS measured</td>
<td>3</td>
<td>30</td>
<td>13.2</td>
<td>10.2</td>
<td>5.9</td>
</tr>
<tr>
<td>vel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>loop estimated</td>
<td>3</td>
<td>30</td>
<td>6.8</td>
<td>3.7</td>
<td>7.5</td>
</tr>
<tr>
<td>velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTMS measured</td>
<td>4</td>
<td>L 300</td>
<td>74.3</td>
<td>62.0</td>
<td>51.8</td>
</tr>
<tr>
<td>flow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTMS measured</td>
<td>4</td>
<td>L 300</td>
<td>0.8</td>
<td>2.8</td>
<td>0.9</td>
</tr>
<tr>
<td>occupancy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTMS estimated</td>
<td>4</td>
<td>L 300</td>
<td>20.0</td>
<td>18.1</td>
<td>10.5</td>
</tr>
<tr>
<td>velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>loop estimated</td>
<td>4</td>
<td>L 300</td>
<td>5.9</td>
<td>2.5</td>
<td>8.2</td>
</tr>
<tr>
<td>velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3b, RMSE for the various runs. First five columns are RTMS versus loop, the next five columns are the upstream loop versus downstream loop in the given lane.

<table>
<thead>
<tr>
<th>units</th>
<th>run</th>
<th>T (sec)</th>
<th>RMSE RTMS vs. Loop, lane #</th>
<th>RMSE upstr loop vs dnstr loop, lane #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>flow</td>
<td>3</td>
<td>30</td>
<td>234.4</td>
<td>253.0</td>
</tr>
<tr>
<td>occupancy</td>
<td>3</td>
<td>30</td>
<td>2.5</td>
<td>6.7</td>
</tr>
<tr>
<td>flow</td>
<td>4</td>
<td>L 300</td>
<td>74.3</td>
<td>62.0</td>
</tr>
<tr>
<td>occupancy</td>
<td>4</td>
<td>L 300</td>
<td>0.8</td>
<td>2.8</td>
</tr>
</tbody>
</table>
Table 4a, Bias for the various runs. The columns correspond to those of the previous table. For the first five columns, a positive value indicates the RTMS, on average, overestimated the given parameter and a negative value indicates the RTMS underestimated it.

<table>
<thead>
<tr>
<th>units</th>
<th>run</th>
<th>T (sec)</th>
<th>Bias RTMS vs. Loop, lane #</th>
<th>Bias Loop(n+1) vs. Loop(n), lane #</th>
<th>Bias RTMS(n+1) vs. RTMS(n), lane #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1  2  3  4  5</td>
<td>1  2  3  4  5</td>
<td>1  2  3  4  5</td>
</tr>
<tr>
<td>RTMS measured flow</td>
<td>3</td>
<td>30</td>
<td>39.7 57.5 -10.5 -30.7 110.2</td>
<td>-0.7 -1.1 -0.9 -1.0 -1.1</td>
<td>-0.5 -1.2 -1.0 -0.6 -1.3</td>
</tr>
<tr>
<td>RTMS measured (%)</td>
<td>3</td>
<td>30</td>
<td>0.2  2.4  -0.8  -3.0  -5.7</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
</tr>
<tr>
<td>RTMS measured vel</td>
<td>3</td>
<td>30</td>
<td>-8.5  -6.9  -2.5  1.1   7.5</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
<td>0.4  0.0  0.0  0.0  0.0</td>
</tr>
<tr>
<td>loop estimated velocity</td>
<td>3</td>
<td>30</td>
<td>2.4  1.7  -0.9  -0.9  1.6</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
</tr>
<tr>
<td>RTMS measured flow</td>
<td>4 L</td>
<td>300</td>
<td>47.9  25.6 -12.5 -37.0  74.4</td>
<td>-1.5 -0.6 -0.6 -1.7 -2.9</td>
<td>-0.8  0.2  0.0 -1.2 -2.9</td>
</tr>
<tr>
<td>RTMS measured (%)</td>
<td>4 L</td>
<td>300</td>
<td>0.3  0.8  -0.5  -2.0  -3.8</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
</tr>
<tr>
<td>RTMS estimated vel</td>
<td>4 L</td>
<td>300</td>
<td>-5.6  12.4  1.9  1.9   37.3</td>
<td>-0.2  0.0  0.0  0.0  0.0</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
</tr>
<tr>
<td>loop estimated velocity</td>
<td>4 L</td>
<td>300</td>
<td>1.2  1.0  -4.8  -9.8  -4.6</td>
<td>-0.2  0.0  0.0  0.0  0.0</td>
<td>0.0  0.0  0.0  0.0  0.0</td>
</tr>
</tbody>
</table>

Table 4b, Bias for the various runs. The columns correspond to those of the previous table. For the last five columns, a positive value indicates the upstream loop, on average, overcounted the given parameter.

<table>
<thead>
<tr>
<th>units</th>
<th>run</th>
<th>T (sec)</th>
<th>Bias RTMS vs. Loop, lane #</th>
<th>Bias upstr loop vs dnstr loop, lane #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1  2  3  4  5</td>
<td>1  2  3  4  5</td>
</tr>
<tr>
<td>flow</td>
<td>3</td>
<td>30</td>
<td>39.7 57.5 -10.5 -30.7 110.2</td>
<td>-2.3 -2.2 -0.5 -3.5 7.0</td>
</tr>
<tr>
<td>occupancy</td>
<td>3</td>
<td>30</td>
<td>0.2  2.4  -0.8  -3.0  -5.7</td>
<td>0.0  0.0  0.5  0.3  0.7</td>
</tr>
<tr>
<td>flow</td>
<td>4 L</td>
<td>300</td>
<td>47.9  25.6 -12.5 -37.0  74.4</td>
<td>-1.6 -1.0 -1.3 -1.5  7.8</td>
</tr>
<tr>
<td>occupancy</td>
<td>4 L</td>
<td>300</td>
<td>0.3  0.8  -0.5  -2.0  -3.8</td>
<td>0.0  0.0  0.3  0.3  0.6</td>
</tr>
</tbody>
</table>
Using the median values of TT to calculate the distance to the RTMS detection zone,

<table>
<thead>
<tr>
<th>lane</th>
<th>rising edge ratio, RTMS/loops</th>
<th>falling edge ratio, RTMS/loops</th>
<th>distance between loop 2 and RTMS detection zones: leading edge (ft)</th>
<th>trailing edge (ft)</th>
<th>extra RTMS detection zone width (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4167</td>
<td>1.0909</td>
<td>8.3</td>
<td>21.8</td>
<td>13.5</td>
</tr>
<tr>
<td>2</td>
<td>0.3636</td>
<td>1</td>
<td>7.3</td>
<td>20</td>
<td>12.7</td>
</tr>
<tr>
<td>3</td>
<td>0.3077</td>
<td>0.9231</td>
<td>6.2</td>
<td>18.5</td>
<td>12.3</td>
</tr>
<tr>
<td>4</td>
<td>0.3571</td>
<td>0.8462</td>
<td>7.1</td>
<td>16.9</td>
<td>9.8</td>
</tr>
<tr>
<td>5</td>
<td>0.5385</td>
<td>0.6875</td>
<td>10.8</td>
<td>13.8</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 6. Average absolute percent error in 5 min flow for the first loop and RTMS relative to the second loop

<table>
<thead>
<tr>
<th>lane</th>
<th>all</th>
<th>v &gt; 45 mph</th>
<th>v &lt; 45 mph</th>
<th>q &gt; 1000 vph</th>
<th>q &lt; 1000 vph</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of samples</td>
<td>1st loop RTMS</td>
<td>1st loop RTMS</td>
<td>1st loop RTMS</td>
<td>1st loop RTMS</td>
</tr>
<tr>
<td>1</td>
<td>1172</td>
<td>0.8%</td>
<td>31.5%</td>
<td>988</td>
<td>0.7%</td>
</tr>
<tr>
<td>2</td>
<td>1186</td>
<td>0.7%</td>
<td>8.9%</td>
<td>1003</td>
<td>0.6%</td>
</tr>
<tr>
<td>3</td>
<td>1194</td>
<td>0.9%</td>
<td>5.1%</td>
<td>1027</td>
<td>0.9%</td>
</tr>
<tr>
<td>4</td>
<td>1195</td>
<td>1.1%</td>
<td>5.9%</td>
<td>1086</td>
<td>1.1%</td>
</tr>
<tr>
<td>5</td>
<td>1195</td>
<td>1.0%</td>
<td>6.5%</td>
<td>1079</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

Table 7. Average absolute percent error in 5 min occupancy for the first loop and RTMS relative to the second loop

<table>
<thead>
<tr>
<th>lane</th>
<th>all</th>
<th>v &gt; 45 mph</th>
<th>v &lt; 45 mph</th>
<th>q &gt; 1000 vph</th>
<th>q &lt; 1000 vph</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># of samples</td>
<td>1st loop RTMS</td>
<td>1st loop RTMS</td>
<td>1st loop RTMS</td>
<td>1st loop RTMS</td>
</tr>
<tr>
<td>1</td>
<td>1172</td>
<td>1.8%</td>
<td>57.4%</td>
<td>988</td>
<td>1.6%</td>
</tr>
<tr>
<td>2</td>
<td>1186</td>
<td>1.2%</td>
<td>12.9%</td>
<td>1003</td>
<td>0.8%</td>
</tr>
<tr>
<td>3</td>
<td>1194</td>
<td>2.6%</td>
<td>8.8%</td>
<td>1027</td>
<td>2.5%</td>
</tr>
<tr>
<td>4</td>
<td>1195</td>
<td>1.5%</td>
<td>22.1%</td>
<td>1086</td>
<td>1.4%</td>
</tr>
<tr>
<td>5</td>
<td>1195</td>
<td>2.7%</td>
<td>40.0%</td>
<td>1079</td>
<td>2.6%</td>
</tr>
</tbody>
</table>
Table 8, Average absolute percent error in 30 sec flow for the first loop and RTMS relative to the second loop

<table>
<thead>
<tr>
<th>lane</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9275</td>
<td>1.9%</td>
<td>17.4%</td>
<td>7880</td>
<td>1.7%</td>
<td>17.6%</td>
<td>598</td>
<td>2.7%</td>
<td>13.6%</td>
<td>1945</td>
<td>1.9%</td>
<td>9.2%</td>
<td>7330</td>
<td>1.9%</td>
<td>19.9%</td>
</tr>
<tr>
<td>2</td>
<td>10920</td>
<td>2.0%</td>
<td>8.1%</td>
<td>9629</td>
<td>1.8%</td>
<td>7.1%</td>
<td>1031</td>
<td>3.9%</td>
<td>17.4%</td>
<td>6531</td>
<td>2.0%</td>
<td>7.1%</td>
<td>4388</td>
<td>2.0%</td>
<td>9.7%</td>
</tr>
<tr>
<td>3</td>
<td>11420</td>
<td>2.6%</td>
<td>7.0%</td>
<td>10070</td>
<td>2.4%</td>
<td>6.4%</td>
<td>1067</td>
<td>4.1%</td>
<td>12.5%</td>
<td>7356</td>
<td>2.5%</td>
<td>6.1%</td>
<td>4062</td>
<td>2.9%</td>
<td>8.8%</td>
</tr>
<tr>
<td>4</td>
<td>11830</td>
<td>3.1%</td>
<td>8.0%</td>
<td>10700</td>
<td>2.9%</td>
<td>7.9%</td>
<td>1108</td>
<td>3.8%</td>
<td>8.1%</td>
<td>8227</td>
<td>2.8%</td>
<td>6.6%</td>
<td>3606</td>
<td>3.5%</td>
<td>11.0%</td>
</tr>
<tr>
<td>5</td>
<td>11860</td>
<td>2.7%</td>
<td>10.0%</td>
<td>10540</td>
<td>2.5%</td>
<td>9.6%</td>
<td>1280</td>
<td>3.4%</td>
<td>12.1%</td>
<td>7828</td>
<td>2.4%</td>
<td>6.8%</td>
<td>4036</td>
<td>3.1%</td>
<td>16.1%</td>
</tr>
</tbody>
</table>

Table 9, Average absolute percent error in 30 sec occupancy for the first loop and RTMS relative to the second loop

<table>
<thead>
<tr>
<th>lane</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
<th># of samples</th>
<th>1st loop</th>
<th>RTMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9275</td>
<td>4.2%</td>
<td>35.4%</td>
<td>7880</td>
<td>4.0%</td>
<td>36.5%</td>
<td>598</td>
<td>3.7%</td>
<td>16.0%</td>
<td>1945</td>
<td>2.7%</td>
<td>17.0%</td>
<td>7330</td>
<td>4.7%</td>
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