Quantifying Loop Detector Sensitivity and Correcting Detection Problems on Freeways

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ABSTRACT

Loop detectors are the most commonly used vehicle detector for freeway management. A loop detector consists of a physical loop of wire embedded in the pavement connected to a sensor located in a nearby cabinet. The sensor detects the presence or absence of vehicles over the loop and typically allows a user to manually select the sensitivity level of operation to accommodate for a wide range of responsiveness from the physical loop. In conventional practice, however, it is difficult to know the physical loop's responsiveness, which makes selecting the appropriate sensitivity level difficult. If the sensitivity and responsiveness are poorly matched it will degrade the detector's data and the performance of applications that use the data, including: traffic management, control, and traveler information.

To resolve this often overlooked problem, this paper presents an algorithm to assess how well a loop detector's sensitivity is set by calculating the daily median on-time from the data reported by the loop detector. The algorithm can be incorporated into conventional controller software or run off-line. The result can be used both to correct the detector on-times for an inappropriate sensitivity setting in software (e.g., via a multiplicative correction factor) and to trigger an alarm to dispatch a technician to adjust the hardware sensitivity. Plotting the daily median on-time over months or years can show how the detector performance evolves. The approach is then transposed to dual loop detectors to identify and correct for inaccurate spacing between the paired detectors. Finally the methodology is evaluated by comparing the loop detector speeds against the concurrent velocities from a GPS equipped probe vehicle. While the focus of this paper is on loop detectors, with only minor modification the algorithm should also be applicable to other detector technologies that emulate loop detector operation, e.g., side-fire microwave radar.

INTRODUCTION

Loop detectors are the most commonly used vehicle detector for automated surveillance in freeway management. A loop detector consists of a *physical loop* of wire embedded in the pavement connected to a *sensor* located in a nearby cabinet. A typical loop detector station will have either one or two loop detectors per lane, i.e., single or dual loop detectors, respectively. Conventional single loop detectors can measure flow, q, (the number of vehicles per unit time) and occupancy, occ, (the percent time the detector is occupied). From these measurements one can estimate average speed, but not measure it. Dual loop detectors overcome the speed estimation problem; they can measure individual vehicle speeds from the known loop spacing and the difference in arrival times at the two loops, and then calculate the average speed.

When a vehicle passes over the physical loop, the presence of the vehicle changes the loop's inductance. The sensor compares the loop's inductance against a threshold to establish the presence or absence of a vehicle over a loop detector. The change in inductance depends on the physical loop's responsiveness as well as the spatial relationship between the vehicle and physical loop (e.g., the distance between a loop detector and the undercarriage of a vehicle, and the ratio of the surface area of the loop and of the vehicle body, Day et al. 2009). We use the term "responsiveness" to capture the impact from the physical characteristics of a given loop detector instillation (e.g., the depth of the wires and design standards of the loop detector, Hamm and Woods 1992; pavement condition and pavement material, Cherrett et al. 2000). The responsiveness varies from loop to loop, so a loop sensor typically has a user selectable sensitivity setting to control for the wide range of feasible loop responsiveness that bias the inductance change. The higher the user sets the sensitivity level, the more readily the sensor will detect a vehicle, i.e., the larger the detection zone. However, the size of the detection zone also depends on the physical loop's responsiveness and in conventional practice it is difficult to know the responsiveness, which in turn makes it difficult to select the appropriate sensitivity setting on the sensor. A loop detector will yield poor performance if the sensitivity setting is not well matched to the physical loop's responsiveness. Such errors in turn impact the detector's data, e.g., underestimated or overestimated speed due to the discrepancy of the expected effective vehicle length and the actual effective vehicle length. These errors will degrade the performance of the traffic control decisions and traveler information based on the detector's data.

Reviewing the literature, there have been a few investigations of the loop detector sensitivity from individual vehicle actuations. Chen and May (1987) examined the ratio of a detector's average on-time relative to the average on-time of all detectors at the detector station. This on-time ratio test provided an indication of a detector's status (e.g., sensitivity setting) relative to the other detectors at the station. However, because of the relative comparison, if all of the loop detectors have a similar sensitivity setting error, Chen and May's test should fail to catch it, or if some lanes have a truck prohibition it may yield a false positive. They explicitly considered detector sensitivity in two tests, first they showed that the sensitivity setting will bias aggregate occupancy measurements and noted the importance of tuning all of the detectors in a corridor to the same bias (implicitly assuming that the responsiveness would be similar across all of the physical loops at the different stations). Second, they sought to eliminate detector dropouts in the middle of long vehicles by increasing the sensitivity, though the magnetometers used in the test continued to dropout even at high sensitivity. Neelisetty and Coifman (2004) developed a mode on-time test as one measure of loop detector performance and Coifman and Lee (2006) refined it. The test is applied individually to each loop in each lane and the mode on-time is found over 24 hrs. Assuming that most vehicles indeed have an effective length corresponding to a passenger vehicle, and travel at free flow speeds, the mode on-time should fall in a small range. If the 24 hr mode on-time from a detector is outside the expected range, they surmised a detector error or transient event. Some efforts have sought to leverage the redundant measurements in a dual loop detector, e.g., Coifman (1999) compared the on-times between the upstream and downstream detectors in a given lane to look for discrepancies, which in turn would reveal a sensitivity error at just one of the detectors in the pair. However, like Chen and May (1987), it would not catch an error that impacted both detectors similarly. Cheevarunothai et al. (2006) extended these ideas, after comparing the paired loop's on-times like Coifman (1999) they used the measured speed and on-time to measure effective vehicle lengths. They compared the observed distribution of lengths against an expected distribution of short vehicle lengths. If the two distributions differed by too much, the detector was suspected to be in error, either due to an inappropriate sensitivity or an inaccurate spacing between the given dual loops.

Most of these earlier studies simply sought to identify detectors with chronic problems, without explicitly focusing on detector sensitivity. Measurement errors from incorrect sensitivity have not received sufficient attention. This paper addresses the problem directly, developing a method to identify and often negate the impact of such sensitivity errors. The approach is then transposed to dual loop detectors to identify and correct for inaccurate spacing between the paired detectors.

The remainder of this paper is organized as follows; first, we develop a means to quantify detector sensitivity and show how the sensitivity can change over time. Then a methodology is developed to correct for unexpected sensitivity errors at a single loop detector. This same approach is extended to also correct for errors in the assumed effective spacing at dual loop detectors and we discuss extending the methodology further to emerging detector technologies that emulate loop detector operation, e.g., side-fire microwave radar. Next, the loop detector method is validated against concurrent velocity measurements from a GPS equipped probe vehicle. Finally, we present our conclusions.

IDENTIFICATION OF A LOOP DETECTOR WITH INCORRECT LOOP SENSITIVITY

Our method begins by re-implementing the 24 hr mode on-time test (Coifman and Lee 2006) to instead use the daily median on-time. However, we go much further, focusing the effort explicitly on detector sensitivity, then we validate the results using independent measurements, develop correction factors to accommodate sensitivity errors, extend to dual loop detector spacing, and examine trends over years. This study uses the I-71 corridor in Columbus, Ohio. The corridor is 14 miles long, with dual loop detector stations roughly every mile and usually two single loop detector stations between successive dual loop detector stations. The facility is fairly unique because all of the stations report the individual vehicle actuations to the traffic management center, rather than discarding the individual measurements immediately after the controller calculates q, occ and average speed. Much of this paper focuses on tests that can be applied at single loop detectors, in which case, at the dual loop detectors we will arbitrarily select the upstream detector and approach it as if it were a single loop detector. Obviously both loops in the dual loop detectors are used for the spacing analysis.

Daily Median On-time Test

Each on-time measurement at a loop detector depends on the effective vehicle length, L, and vehicle speed, v, via Equation 1. The effective vehicle length is the sum of the physical length of the vehicle and the size of the detection zone. The latter depends on the loop responsiveness and the sensor sensitivity. If the sensitivity setting matches the physical loop's responsiveness, the assumed detection zone size will correspond to the actual detection zone size.

$$\text{on-time} = \frac{L}{v} \tag{1}$$

Although speed and length vary from vehicle to vehicle, over a 24 hour period at a typical detector, most of the vehicles should be free flowing and the majority should be passenger vehicles. Thus, over 24 hr of a day, the median on-time (termed the *daily median on-time*) at a loop detector should usually correspond to the effective length of a passenger vehicle at free flow speeds. For example, Coifman and Lee (2006) found approximately 90% of the individual effective vehicle lengths observed at one dual loop detector station fell between 18 and 22 ft (as will soon become clear, in the present work the initially assumed effective vehicle length does not have to be accurate, the proposed methodology will scale it to the correct value). While the free flow speed depends on several factors, e.g., road geometry, access points and characteristics of the lanes (Dixon et al. 1999), for the purposes of this work the free flow speed does not need to be known precisely, it can either be estimated from the posted speed limit or measured with a radar gun. The daily median on-time should fall in a small range. The exact range will depend on the detection technology, size of the detection zone, speed limit, and so forth, but the expected range will be captured in the assumed effective vehicle length used to estimate speed. For example, assuming that most effective vehicle lengths indeed fall in the 18 to 22 ft range (as they do for the 6 ft loop detectors in Columbus, Ohio) and drivers usually obey the posted speed limit in free flow conditions, the daily median on-time should fall between 13/60 and 16/60 sec at 55 mph and between 11/60 and 14/60 sec at 65 mph (alternatively, one could employ a small tolerance for v, which would yield a similar range of feasible on-times). The further the daily median on-time falls outside this expected range, the more indicative it is of unexpected conditions, either due to a transient event (e.g., a snowstorm) or an improper match between the sensitivity setting and the physical loop's responsiveness. Transient events can be addressed by looking at the results from several days or avoiding results on days with known incidents. If the location is known to have many hours of recurring congestion, the test can be modified to exclude congested traffic (either by time of day, day of week, or via the macroscopic data); though care must be taken to ensure that the late night hours are not over-represented since these periods are often characterized by a higher percentage of trucks in the flow (Coifman 2001).

Fig. 1 shows daily median on-time at each loop detector in the I-71 corridor on May 1, 2005. The horizontal axis presents the stations in sequential order in the corridor from south to north. The speed limit is 55 mph between stations 102 and 112, then increases to 65 mph for the remaining stations and the range of expected daily median on-time is shown with horizontal dashed lines. Lane 1 is the left-most lane (i.e., median) and the lane numbers increase to the right. Roughly 57% of the loop detectors (61 of 107 northbound and 61 of 108 southbound) show the daily median on-time fell outside of the expected range of on-times. For example, the detectors in all three lanes at station 14 northbound show the daily median on-time is lower than the expected range of daily median on-time. Some stations also show a large difference of on-time across neighboring lanes, e.g., the daily median on-time of lane 2 at station 2 northbound is 5/60 sec lower than the other lanes. The daily median on-time trends on this particular day are similar the rest of the month (May 2005, not shown), indicating that the sample date did not include a severe transient event. So the sensitivity setting does not appear to be well matched to the responsiveness at the majority of the detectors in this corridor. If one were to choose a higher assumed speed (e.g., assuming most drivers travel 5 mph over the limit) the expected range would move down but discrepancies would remain. Aside from large geometric changes between stations 102 and 1, the corridor is fairly homogeneous, i.e., a given lane should exhibit similar median values across station 1 through 27 but that clearly does not occur, every lane has median values both above and below our target range. The stations are inconsistently calibrated, which will degrade the aggregate speed and occupancy.

Change of Loop Detector Sensitivity over Time

While the daily median on-time is assumed to be nearly constant over extended periods (with occasional transient deviations due to non-recurring events), the daily median on-time trend may abruptly jump to a new value if a technician changes the sensitivity or the responsiveness is impacted by environmental changes, e.g., when the loop begins to fail or lanes are shifted for construction. Fig. 2(a) shows the daily median on-time at station 3 northbound by lane over eight years. The horizontal axis shows the cumulative day since the station became operational and the vertical axis shows the daily median on-time. Vertical delineations on the plot show the start of each month, denoted by the first letter of the month's name. In all four lanes the daily median on-time is stable for long periods, but all four lanes show two abrupt changes (May 23, 2002 and June 9, 2009). After the first five months (January 2002 through May 2002), it stabilizes for approximately seven years. The cause of the first shift was unknown, while the second shift arose due to an engineer increasing the detector sensitivity in response to a request by our team. As noted in Lee and Coifman (2011), we recently found station 3 exhibited detector dropout errors. To fix this problem, we asked the operating agency (the Ohio Department of Transportation) to increase the detector sensitivity setting of all loop detectors at station 3. The change was made on June 9, 2009 and the engineer reported that the sensitivity levels in all lanes at the station were increased from “Normal” to “High”. In turn, the daily median on-time increased by more than 20% after the change.

Station 23 northbound exhibits a more turbulent trend, abruptly changing several times over eight years, as shown in Fig. 2(b). As with the vast majority of the detector stations in the corridor, even with all of the changes, away from the abrupt jumps all of the detectors exhibit stable trends. After several adjustments, it stabilizes for approximately two years starting in May 2002. The daily median on-time in lane 2 dramatically dropped in July 2004, and the daily median on-time in lane 1 increased after October 2004. These trends continued for almost two years, then both detectors went off line for several months. When they returned, the daily median on-time in each lane took a new value. Closer examination of the station 23 data revealed that lane 2 was set to pulse mode between July 2004 and June 2006. When a loop detector is set to pulse mode it reports a constant on-time for all vehicle passages, independent of their actual on-times (an option commonly used at signalized intersections). Thus, when a single loop detector is set to be pulse mode, it becomes impossible to estimate speed in that lane. This error in lane 2 persisted for two years before the operating agency corrected it, illustrating how these conceptually simple errors can be very difficult to catch.

Correction of Measurement Errors Due to Incorrect Loop Detector Sensitivity and Dual Loop Spacing

Detector Sensitivity at Single and Dual Loop Detectors

Conventionally speed is estimated at single loop detectors via Equation 2 for fixed sample periods ranging from 30 sec to 5 min. However, some trucks may be four times longer than the mean effective vehicle length. When trucks are present they extend the given sample's mean on-time and thus, reduce the estimated speed relative to the true speed. To reduce susceptibility to these long vehicles (as well the opposite problem arising from short actuation detector errors such as "flicker"), we calculate a more robust estimate of speed via Equation 3, approaching the accuracy of dual loop detector measurements (Coifman et al. 2003). In either case, since the length and speed cannot be measured directly at a single loop detector, the effective vehicle length is usually assumed to be some constant value, e.g., 20 ft. As noted earlier, this effective length includes the size of the detection zone, which is a function of the sensitivity and responsiveness. If the detection zone differs from the assumed size, then $\tilde{L}$ should be adjusted accordingly or speed will generally be underestimated or overestimated. Unfortunately, it is difficult to directly measure the size of the detection zone.

$$\text{mean}(v) = \frac{\tilde{L} \times q}{\text{occ}} = \frac{\tilde{L}}{\text{mean (on-time)}} \tag{2}$$

where,

$\tilde{L}$ = the assumed constant effective vehicle length.

$$\text{median}(v) = \frac{\tilde{L}}{\text{median (on-time)}} \tag{3}$$

Coifman et al. (2003) only applied Equation 3 to short duration sample periods, ranging from 30 sec to 5 min to follow the time-series evolution of speeds. We will use subscript i to denote these short duration sample periods. In the present study we also extend the sample period and use Equation 3 to calculate the daily median speed, and we use subscript J to denote these longer samples. This daily median is insensitive to typical daily variations in traffic speeds, thereby isolating the impacts of the detector sensitivity setting. Using a 20 ft effective vehicle length for all of the detectors, Fig. 3 shows the cumulative distribution function (CDF) of the estimated loop speed at each loop detector from Equation 3 and the daily median on-time from Fig. 1. The detectors are segregated into two groups by the posted speed limit. For the 55 mph group, 74% (31 of 42) of the detectors yield daily median speeds within 5 mph of the speed limit and 12% (5 of 42) are more than 10 mph above the limit. For the 65 mph group, 32% (55 of 173) of the detectors yield daily median speeds within 5 mph of the speed limit, 30% (52 of 173) are more than 10 mph above or 10 mph below the limit.

To address the discrepancy of speed from a single loop detector, a multiplicative correction factor, ε_S, is applied to the short duration sample periods (subscript i) using the initially assumed $\tilde{L}$ via Equation 4 (as shown in Lee, 2007, the multiplicative correction factor is functionally equivalent to an additive correction factor). Assuming drivers usually keep the posted speed limit in free flow time periods, ε_S can be estimated via Equation 5, where the sample period in Equation 5 (i.e., the daily median on-time, denoted with subscript J) is much longer than the sample periods used in Equation 4. If more information about the free flow speed is available then a different value of the assumed free flow speed can be used in this equation. The correction factor typically remains stable for a long period (e.g., Fig. 2). Of course the errors that impact the speed estimate also impact on-time and occupancy. Assuming the speed variance over a given sample is negligible, occupancy can be corrected via Equation 6.

$$\hat{V}_i' = \hat{V}_i \times \varepsilon_s = \frac{\tilde{L}}{\text{median (on-time}_i)} \times \varepsilon_s \tag{4}$$

where,

$\tilde{L}$ = the assumed constant effective vehicle length for all samples,

median(on-time$_i$) = the median of all on-times observed in sample period i,

$\hat{V}_i$ = the uncorrected estimated speed in sample period i,

ε_s = a multiplicative correction factor for single loop detectors, and

$\hat{V}_i'$ = the new estimated speed corrected by the multiplicative correction factor.

$$\varepsilon_s = \frac{\text{assumed free flow speed}}{\dfrac{\tilde{L}}{\text{median (on-time}_J)}} = \frac{\text{speed limit}}{\hat{V}_J} \tag{5}$$

$$occ_i' = \frac{occ_i}{\varepsilon_s} \tag{6}$$

One can further improve the estimate by taking the median from many days. Specifically, we calculated a multiplicative correction factor individually for each loop as follows. First, the daily median on-time is found for all weekdays in a month. Next, the median of these daily median on-times (termed *the monthly median on-time*) is found, thereby reducing the impacts of transient events while still allowing the correction factor to adjust to evolving conditions at the detector station. Then, using Equation 5 the correction factor is estimated using the monthly median on-time and the posted speed limit.

Dual Loop Detector Spacing

Thus far the discussion has centered on correcting the sensitivity at a loop detector, whether it be a single loop or one of the paired loops in a dual loop detector. A very similar problem arises at dual loop detectors with regard to spacing. Ordinarily individual vehicle speed is measured directly from the difference in the vehicle's arrival times at the two loops (or the vehicle's departure times from the two loops), and the known loop spacing via Equation 7. Normally s_x is assumed to be the physical spacing whether using the arrival or departure times. However, this approach only works when the loop spacing is actually known. While detector plans specify the precise spacing between the pair of loops, as we have found, the crew installing the detectors sometimes does not follow the specifications. Even when the physical spacing between the two loops is known accurately, the effective spacing still depends on the size of the two detection zones. The impacts from a difference in sensitivity between the loop detectors are indistinguishable from the impacts of physical loop spacing on the computed speed, hence in this section, "loop spacing" is used to denote the effective loop spacing after accounting for both the physical spacing and any modification due to the sensitivity of the two detectors (either with or without the correction in the previous section). Clearly, if the two detection zones differ, then s_x should depend on whether Equation 7 is using the arrival or departure times since the distance traveled between the leading edges of the detection zones differs from that between the corresponding trailing edges. Without the on-time corrections from Equations 4-6, then the remainder of this section should be applied strictly to the arrival times, or strictly to the departure times, since the correction for one will not necessarily apply to the other.

$$v_x = \frac{s_x}{TT_x} \tag{7}$$

where,

the subscript, x, denotes whether the measurement is from the arrival times or departure times,

v_x = individual measured vehicle speed,

TT_x = vehicle traversal time, and

s_x = detector spacing.

To calibrate the loop spacing, we follow a process virtually identical to the one we used above for on-time. Once more a multiplicative correction factor, ε_d, is applied to the initially measured average V_i for sample i via Equation 8 (thus effectively modifying s_x from Equation 7). Assuming drivers usually keep the posted speed limit (or a target speed measured by radar, etc.) in free flow time periods ε_d can be estimated from the individual vehicle speed measurements, v, via Equation 9, where V_J is either the daily median(v) or preferably, as before, calculate ε_d over many days via the monthly median(v) to reduce the impact of transients.

$$V_i' = V_i \times \varepsilon_d \tag{8}$$

where,

V_i = the uncorrected average measured speed in sample period i, and

V_i' = the corrected average measured speed in sample period i.

$$\varepsilon_d = \frac{\text{assumed free flow speed}}{V_J} = \frac{\text{speed limit}}{V_J} \tag{9}$$

Other Detection Technologies

Many emerging vehicle detection technologies emulate the operation of single or dual loop detectors, e.g., side-fire microwave radar. With only minor modification the methodology should also be applicable to those emerging detector technologies as well. Each technology has its own unique characteristics, e.g., effective vehicle length or effective spacing, so it is impossible to present an exhaustive discussion, but the general process will be similar to the extension from the single loop detector sensitivity to dual loop detector spacing shown above. When applying this methodology to the emerging detector technologies, care must be taken to control for dynamic corrections by the sensor, e.g., a side-fire microwave radar may already automatically adjust its sensitivity throughout the day using a proprietary algorithm. If these adjustments are not accounted for they may undermine the assumptions of the present work. Furthermore, many of these emerging sensors incorporate the functionality of the loop detector controller and only report aggregate measures, in which case the present work would have to be employed by the sensor manufacturer rather than an operating agency.

VALIDATION OF THE CORRECTION FACTORS

In addition to the loop detector data collection, our group has collected many GPS equipped probe vehicle tours of the I-71 corridor. The tours come primarily from the peak periods and each tour passes almost all of the detector stations shown in Fig. 1. We can extract the time and velocity whenever the probe vehicle passes a detector station. The driver was instructed to drive in lane 2 (second from left) except when overtaking another vehicle. With 355 probe vehicle passes through the corridor between January 2002 and May 2005, we use these data as an independent measure of speed in lane 2 and then gather the concurrent 5 min loop detector data for the given pass. To verify the correction factors, the corrected single loop detector estimated speeds from Equation 4 and dual loop detector measured speeds from Equation 8 are compared against the corresponding GPS velocity measurements from the probe vehicle data. Fig. 4(a) shows a typical scatter plot comparing the uncorrected single loop detector estimated speed in lane 2 as the probe vehicle passed versus the corresponding GPS velocity at station 9 northbound. It exhibits a systematic bias, with almost all estimates being too high. After applying the correction factor from Equation 5, Fig. 4(b) shows that the bias is removed. Without the correction, only 46% of the samples have a loop detector speed within 10 mph of the probe vehicle velocity, but after the correction 98% of the samples do. This detector exhibited a very stable sensitivity level throughout the period with probe vehicle data, so in this case we would get similar results whether using a single month to calibrate via Equation 5 or the monthly median method described above.

To underscore the importance of using the monthly median method, consider the daily median on-time trend at station 21 northbound, as shown in Fig. 2(c). The daily median on-time at this single loop detector station changes several times over eight years, and in fact the loop detectors did not report any data between October 15, 2003 and November 15, 2004. Fig. 4(c) compares the uncorrected speed estimates against the probe vehicle velocity. The probe vehicle velocity shows that all of the observations at this station come from free flow conditions, yet clearly, no single multiplicative correction factor can bring all of the loop detector data in line with the probe vehicle data. Fig. 4(d) repeats the comparison after using Equations 4-5 and the monthly median method. Without the correction, only 54% of the samples have a loop detector speed within 10 mph of the probe vehicle velocity, but after the correction 97% of the samples do. Fig. 4(e-f) show examples after correction from a single loop detector and dual loop detector, respectively, that experienced more congestion. As before, the corrections using the posted speed limit bring most of the loop detector data in line with the probe vehicle data.

To quantify this process, we use the average error (AE), average absolute error (AAE), and average absolute relative error (AARE) between the GPS velocity and the loop detector's speed (estimated speed for single loop detectors and measured speed for dual loop detectors). The statistics are calculated both before and after applying the correction factors via Equation 10. A positive AE indicates that on average the loop detector speed is faster than the corresponding GPS velocity. For example, at station 9 northbound (Fig. 4 a-b), the AE before applying the correction factor is 10.8 mph and drops to 0.4 mph after. However, the AE allows positive errors to cancel negative errors since it simply reflects the bias, so we also calculate AAE and AARE. The AAE before and after applying the correction factor at this station is 10.8 mph and 2.2 mph, respectively. The AARE before and after applying correction factor is 17.4% and 3.6%, respectively.

$$AE = \frac{\sum_{n=1}^{N} V_n^{Loop} - v_n^{GPS}}{N}, \quad AAE = \frac{\sum_{n=1}^{N} \left| V_n^{Loop} - v_n^{GPS} \right|}{N}, \quad AARE = \frac{\sum_{n=1}^{N} \left| \frac{V_n^{Loop} - v_n^{GPS}}{v_n^{GPS}} \right|}{N} \tag{10}$$

where,

N = the total number of observations with both loop detector and GPS data,

v_n^{GPS} = the GPS velocity at n-th probe vehicle passage over the given loop detector, and

V_n^{Loop} = the loop speed for 5 min sample corresponding to the n-th probe vehicle passage.

Calculating these statistics at all of the detector stations, Fig. 5 shows the performance of the single loop detectors before and after applying the correction factor to the estimated speed ("without correction" and "with correction," respectively), thereby rectifying any mismatch between sensitivity and responsiveness. Again, these data come from lane 2, and in the case of dual loop detectors, only the upstream loop is shown. The plots show results for a total of 64 single loop detectors. For example, in lane 2 at station 2 northbound, the AE, AAE, and AARE before applying correction factors are 24.6 mph, 24.6 mph, and 47.4%, respectively. After applying correction factors, AE, AAE, and AARE drop to -0.2 mph, 2.4 mph, and 6.7%, respectively. In general Fig. 5 shows that by any of the metrics, the correction generally brings the error closer to zero when comparing the single loop estimated speeds against the concurrent GPS velocities. In many cases the improvement is by a factor of 10. Note that in this study the monthly median is calculated using all of the weekdays in the month in which the observation was made. Obviously this approach could not be implemented in real time. For real time applications, one could instead use the 20 preceding weekdays or the previous calendar month to generate the correction factor. Since the only differences would come near a discrete jump in detector sensitivity, and those are relatively rare (typically less than once per year) the results would be similar no matter how one would define the month of calibration.

As designed, the dual loop detectors were supposed to have 20 ft spacing between leading edges of the paired loops and we call this condition "original specification", but in some cases the installation contractor was very liberal in their interpretation of the specifications leading to large errors. As a result of this problem, the operating agency undertook the task of manually measuring the physical distance between the paired loops and we call this condition "manual calibration". Fig. 6 shows the performance of the dual loop detector measured speed compared to the GPS velocity via Equation 7 under these two before conditions. The figure also shows performance after applying the correction factor via Equation 8 to the measured speed (denoted "with correction"), thereby rectifying any remaining error in the paired detector spacing. The plots show results for a total of 26 dual loop detectors. For 10 of the 12 detectors with large errors in the *original specification* data, i.e., AAE >14 mph, the *manual calibration* made a significant improvement. Though there were a few cases where the manual calibration degraded performance. For example, station 13 southbound shows that AAE in the manual calibration is about three times larger than the AAE in the original specification data or in the with correction data. The AE of -9 mph at the station implies that the effective distance between the two detection zones is larger than assumed. In almost all cases our correction factor improved performance over both of the before conditions.

Table 1 summarizes the performance across all detectors, showing the results with and without our monthly median correction factors, sorted by free flow and congested conditions. The GPS velocity is used to differentiate between the two traffic conditions: a given sample is considered free flow if the GPS velocity is higher than 45mph, and congested otherwise. Roughly 10% of observations come from congestion. The right-most columns show the performance across all of the observations, both free flow and congested combined. With the small exception of the unbiased congested AE northbound for single loop detectors, the AE, AAE, and AARE after applying the correction factors are closer to zero than those before applying the correction factors. Across the different conditions the AARE in free flow are generally smaller than the corresponding AARE in congestion because in congestion the 5 min sample variance is larger and the denominator is smaller. On the other hand, the AAE is roughly consistent between free flow and congestion. In any case, the correction factors improve the loop detector speeds, as measured by the AE, AAE, and AARE.

CONCLUSIONS

This paper developed a means to quantify detector sensitivity using the daily median and showed how the sensitivity can change over time. It then developed a methodology to correct for unexpected sensitivity errors at a single loop detector by applying a multiplicative correction factor. Key to this work is the fact that for most detector locations, the dominant vehicle will be a free flowing passenger vehicle, and the daily median will usually be representative of such. In other words, the daily median on-time should fall into a small range. The methodology is simple enough that it could be implemented on a conventional model 170 controller.

While in an ideal world a technician would be dispatched to the field to correct the sensitivity errors, recognizing that such visits might not always be feasible, we develop a means to generate a correction factor that can be applied to all samples. To reduce sensitivity to transient events, the correction factor is determined by finding the value that brings the monthly median to the target value. This same approach is extended to also correct for errors in the assumed effective spacing at dual loop detectors. Ideally for dual loop detectors one would first individually correct the on-times in both loops via Equations 4 and 6, and then correct the spacing via Equations 8 and 9, but the methodology would also work without correcting the on-times. Both the single loop and dual loop detector methods are then validated against concurrent velocity measurements from a GPS equipped probe vehicle. As demonstrated in Figs. 5-6 and Table 1, the methodology showed good performance compared to the uncorrected data.

Finally, many emerging vehicle detection technologies emulate the operation of single or dual loop detectors, e.g., side-fire microwave radar. So although the focus of this paper is loop detectors, as discussed herein, with only minor modification the methodology should also be applicable to those emerging detector technologies as well.

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Table 1. Average Error (AE), Average Absolute Error (AAE), and Average Absolute Relative Error (AARE) before and after applying the monthly median correction factors, segregated by free flow and congestion across all observations at all detection stations

Types of loop detectors	Dire-ction	Application of correction factor	Free flow (GPS velocity > 45mph)				Congestion (GPS velocity ≤ 45mph)				Overall (all observations)			
			Number of observations	AE (mph)	AAE (mph)	AARE (%)	Number of observations	AE (mph)	AAE (mph)	AARE (%)	Number of observations	AE (mph)	AAE (mph)	AARE (%)
Single loop detectors	NB	without correction	9,101	-3.3	9.7	15.5	1,096	0.0	5.6	21.7	10,197	-3.0	9.3	16.2
		with correction		0.5	2.6	4.2		-1.0	3.3	14.4		0.3	2.7	5.3
	SB	without correction	8,783	-2.4	10.3	16.3	1,051	-2.1	6.5	26.8	9,834	-2.3	9.9	17.4
		with correction		0.5	2.7	4.3		-0.5	3.7	17.6		0.4	2.8	5.7
Dual loop detectors	NB	original specification	3,783	8.7	10.4	16.4	453	3.5	6.9	23.1	4,236	8.2	10.0	17.1
		manual calibration		2.9	4.6	7.5		2.2	4.4	15.3		2.8	4.6	8.4
		with correction		0.7	3.1	5.1		-1.8	3.4	13.1		0.5	3.1	5.9
	SB	original specification	3,544	9.8	10.7	16.7	409	3.1	5.0	19.1	3,953	9.1	10.1	17.0
		manual calibration		6.9	7.7	11.9		1.4	3.8	15.1		6.3	7.3	12.2
		with correction		0.6	2.6	4.2		-1.1	3.1	13.7		0.4	2.7	5.2

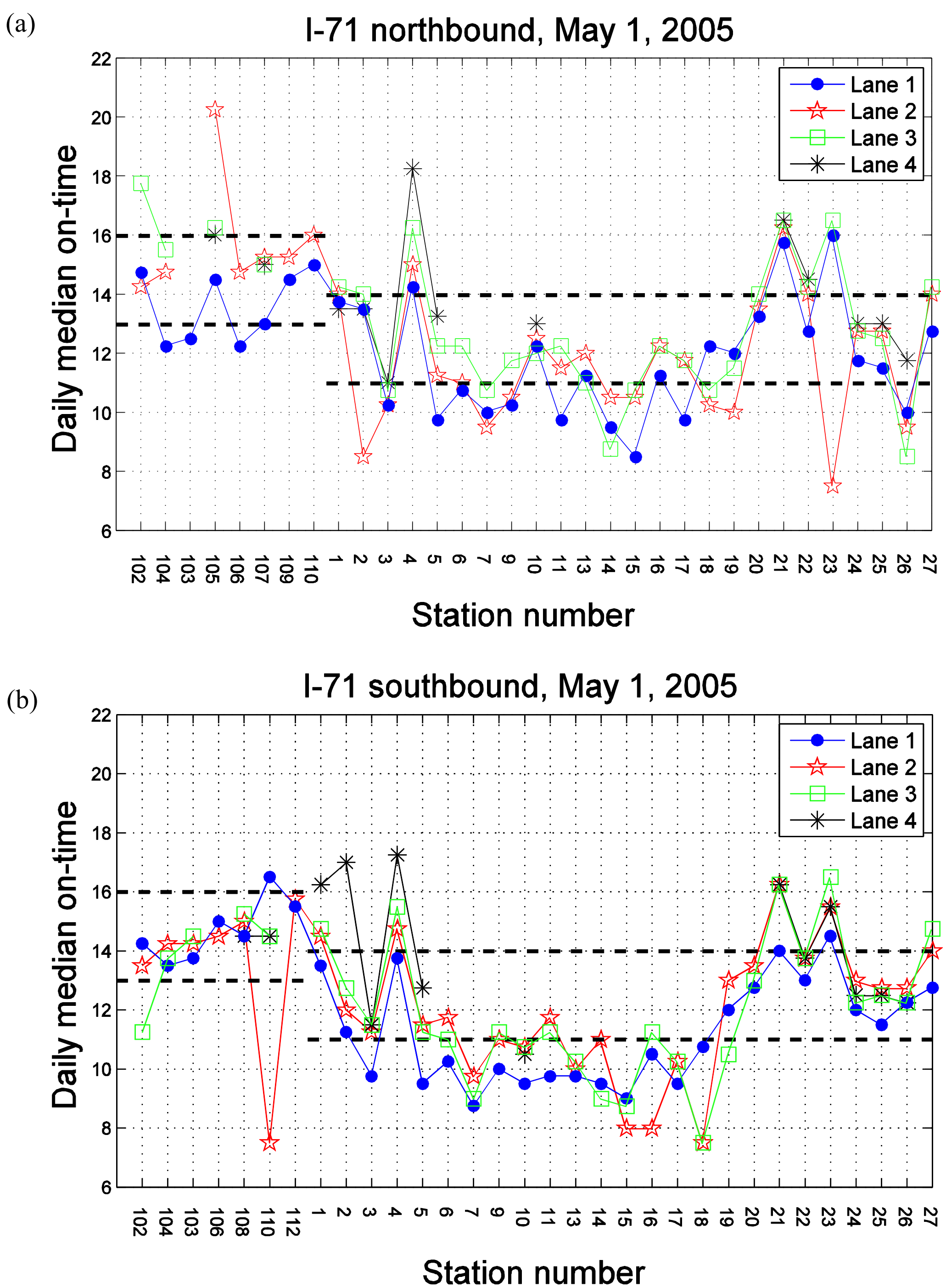

Fig. 1. Daily median on-times at each loop detector in the I-71 corridor on May 1, 2005: (a) 107 loop detectors over 33 stations northbound; and (b) 108 loop detectors over 32 stations southbound. The dashed horizontal lines bound the expected range of median on-time given the speed limit at the station. Note that at dual loop detector stations only the upstream detector is shown.

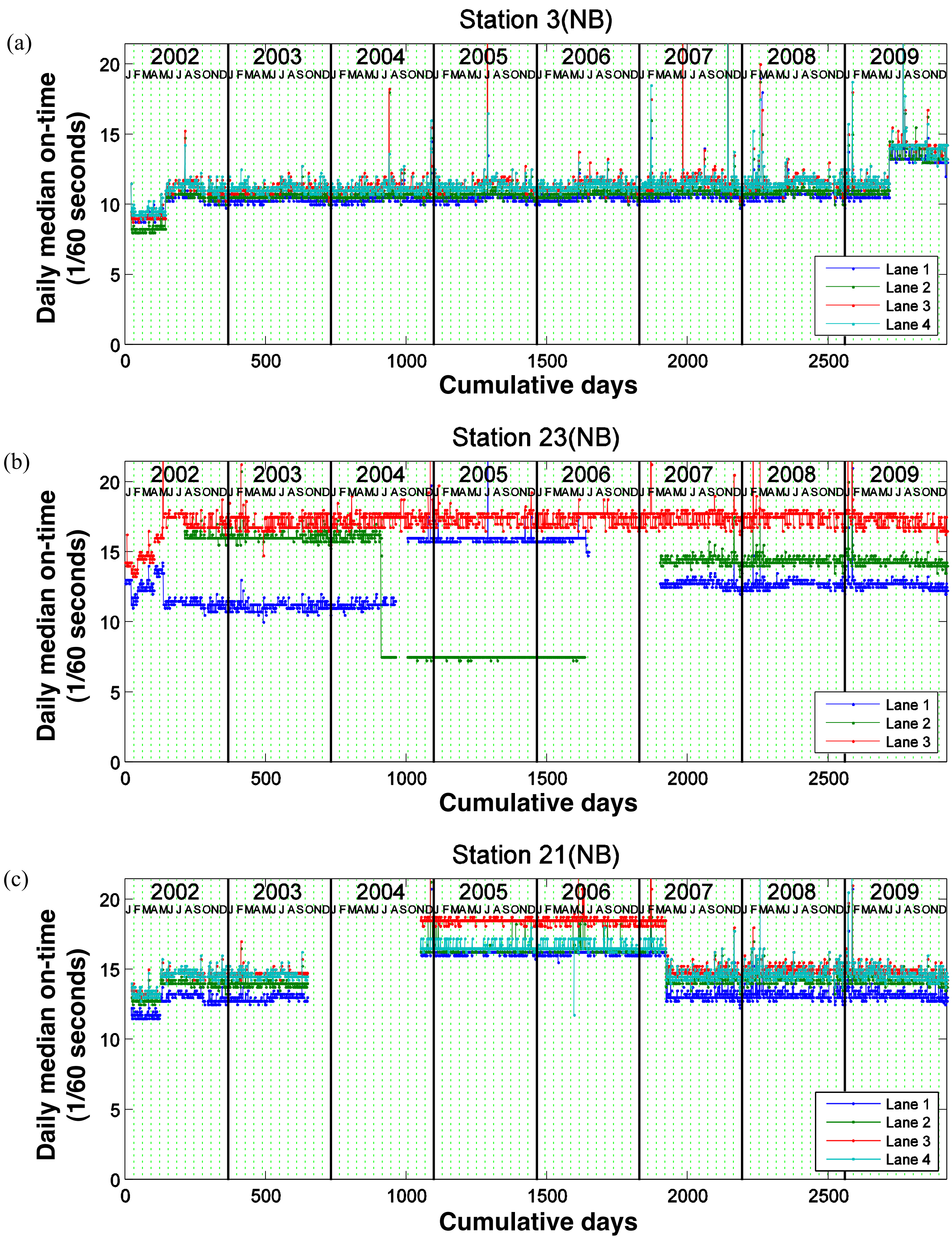

Fig. 2. The trend of daily median on-times by lane over eight years: (a) station 3 northbound; (b) station 23 northbound; and (c) station 21 northbound.

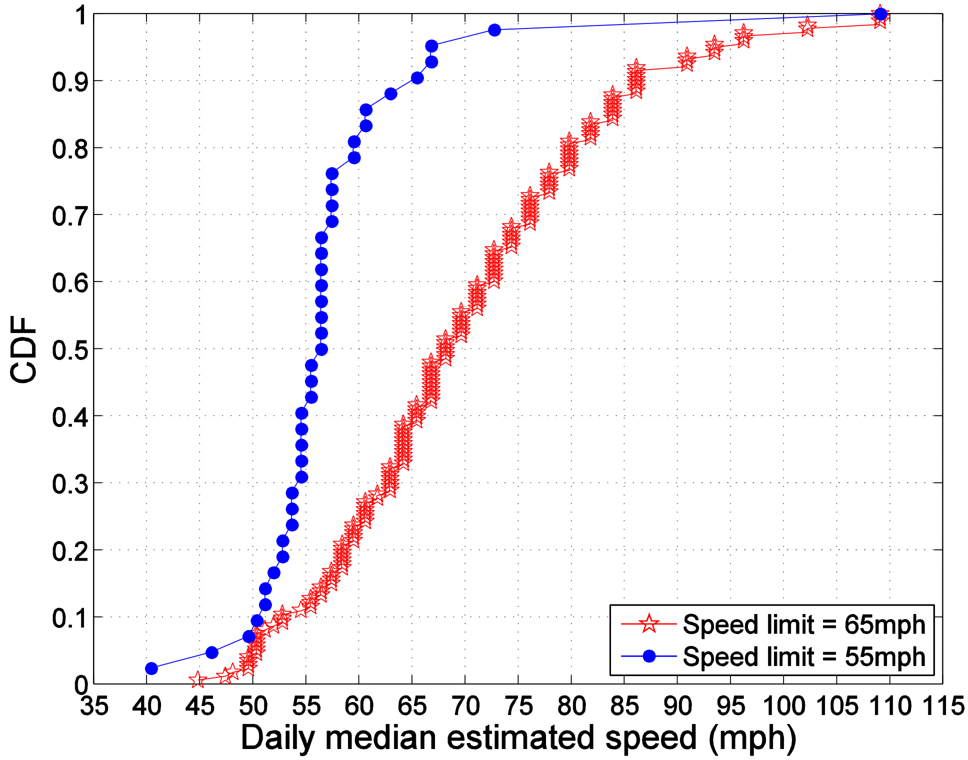

Fig. 3. CDF of daily median estimated speed over 215 loop detectors both directions (42 with a 55 mph speed limit and 173 with a 65 mph speed limit). Note that at dual loop detector stations only the upstream detector is shown.

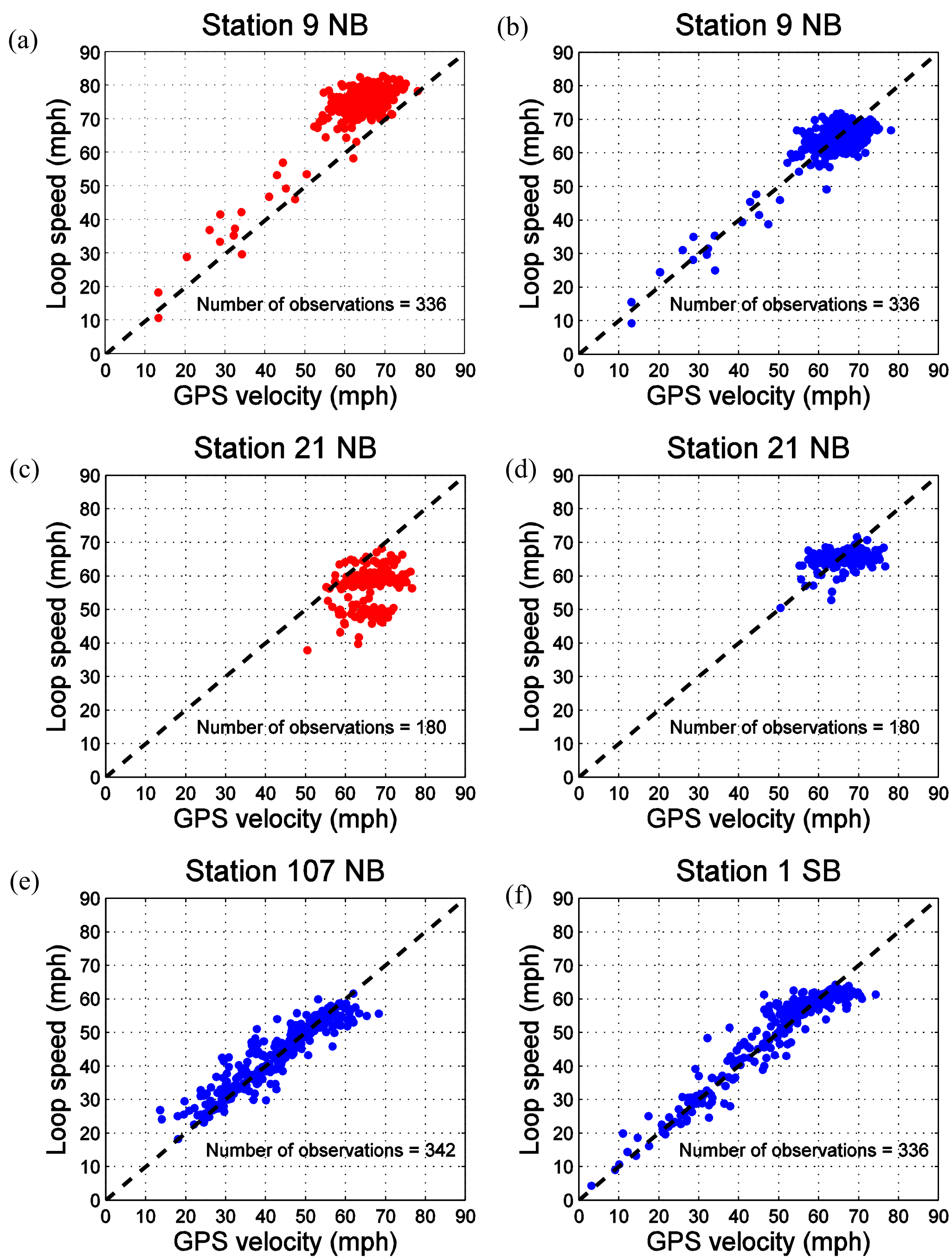

Fig. 4. Comparison of single loop detector estimated speed and GPS velocity: (a) from station 9 northbound (lane 2) before applying correction factors. The loop detector speed is systematically higher than the GPS velocity; (b) After applying the correction factors at station 9 northbound lane 2 the loop detector speed is unbiased relative to the GPS velocity; (c) Repeating the process at station 21 northbound (lane 2), first the raw data show the impact of the changes in the daily median on-time; (d) After applying the correction factors from the monthly median method to station 21 northbound the correction factors adjust to the changing detector sensitivity; (e) After applying the correction factors to station 107 northbound; and (f) Comparison of dual loop detector measured speed and GPS velocity from station 1 southbound after applying correction factors.

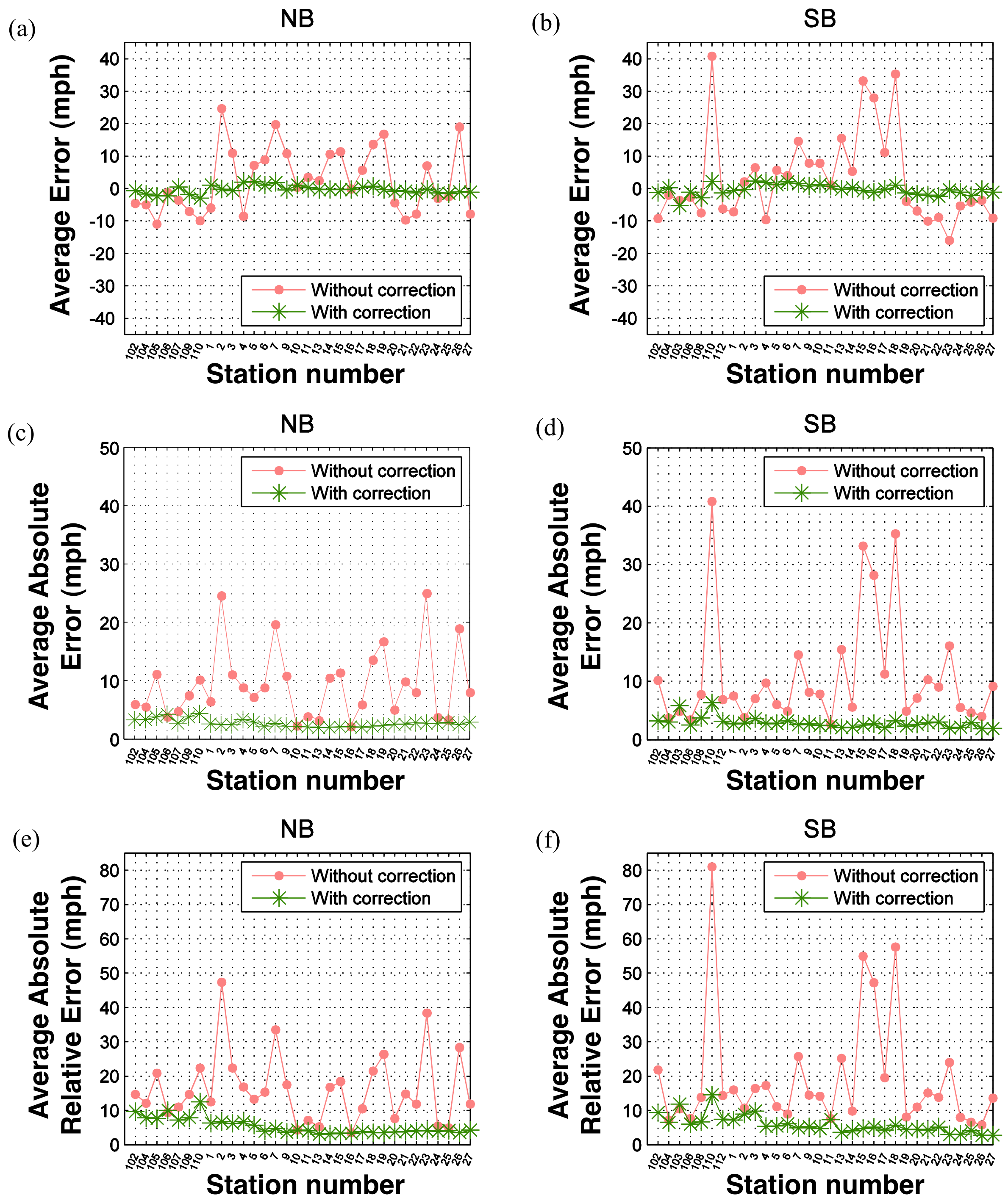

Fig. 5. AE between single loop detector estimated speed and GPS velocity with and without correction factors in lane 2 for (a) northbound and (b) southbound. Next, AAE between single loop detector estimated speed and GPS velocity with and without correction factors for (c) northbound and (d) southbound. Third, AARE between single loop detector estimated speed and GPS velocity with and without correction factors for (e) northbound and (f) southbound.

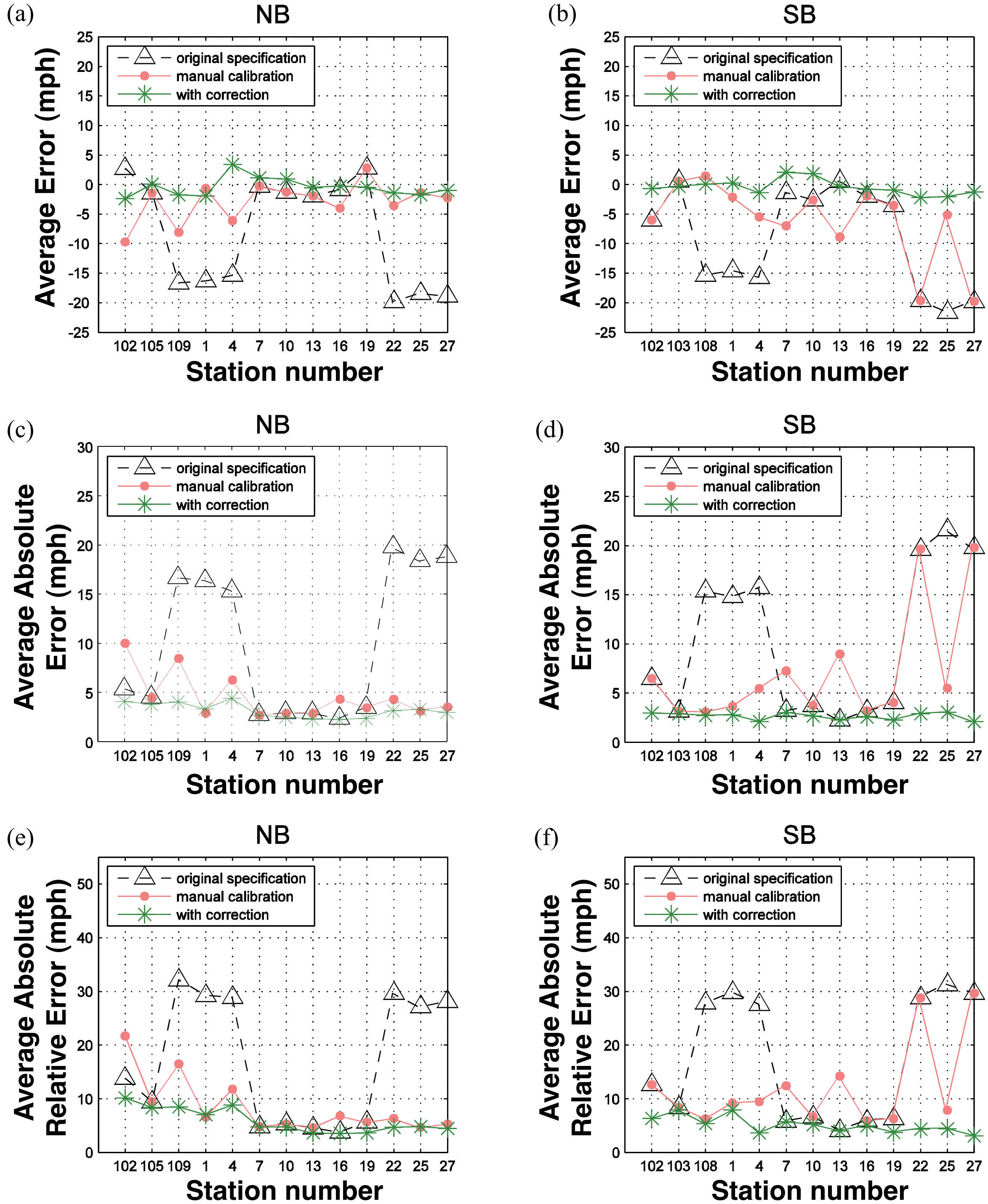

Fig. 6. AE between dual loop detector measured speed and GPS velocity with and without correction factors in lane 2 for (a) northbound and (b) southbound. Next AAE between dual loop detector measured speed and GPS velocity with and without correction factors for (c) northbound and (d) southbound. Third AARE between dual loop detector measured speed and GPS velocity with and without correction factors for (e) northbound and (f) southbound.