# ANALYTICAL TOOLS FOR LOOP DETECTORS, TRAFFIC MONITORING, AND RAMP METERING SYSTEMS.

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## ABSTRACT

This paper presents three useful analytical tools developed in the course of evaluating the performance of a freeway management system (FMS). Each tool is applicable at a different level of a FMS. The first calibrates speed measurements from loop detectors using only data reported from a given detector. The approach finds a correction that sets the daily median speed to the expected free flow value, and it proved able to correct for changing performance over time even in the presence of noisy measurements. The results are evaluated using a GPS equipped probe vehicle. The second tool is conceptually similar to the first, using the weekday median value from each week to present clearly on a single plot the time-series evolution over several years of delay, volume, or other system performance measures. Without this weekly median, typical daily variability makes it difficult to present in a single plot the trends over more than a few weeks. Finally, this paper presents a straightforward means to evaluate ramp meter operation using a GPS equipped probe vehicle. The process builds off of the loop detector evaluation mentioned earlier.

## INTRODUCTION

The development and deployment of Intelligent Transportation System (ITS) technologies provide a wide variety of opportunities for local, regional and state agencies to improve the capacity, reliability, and efficiency of their transportation systems. A Freeway Management System (FMS) employs various ITS tools to improve safety, optimize the real capacity of the freeway, and provide a better level of service to motorists without the addition of more traffic lanes [1]. The FMS acquires data from the roadway and process these data to identify and respond to problems, notifying operators and motorists. Accurate traffic data acquisition is essential for effective traffic surveillance, the backbone of such ITS management applications. If the data are unreliable then the control decisions and the information given may be inappropriate.

The Ohio Department of Transportation (ODOT), in conjunction with the City of Columbus and the Federal Highway Administration, deployed the first phase of the Columbus Metropolitan FMS (CMFMS). This first phase runs along I-70 and I-71, covering approximately 14 miles of freeway with 45 detector stations every third of a mile (roughly 285 loop detectors on the mainline lanes) and it became operational at the end of 2001. The system includes dual loop detector stations every mile, spanned by two single loop detector stations in between. The authors undertook a detailed study of the CMFMS performance [2], which included the development of several calibration tools and performance measures that should prove useful for other freeway management systems (FMS), both for initial calibration and for ongoing operations. This paper presents three of the analytical tools developed in the course of the evaluation. Each tool is applicable at a different level of a FMS. The first calibrates speed measurements from loop detectors using only data reported from a given detector. The approach finds a correction that sets the daily median speed to the expected free flow value, and it proved able to correct for changing performance over time even in the presence of noisy measurements. The results are evaluated using a GPS equipped probe vehicle. The second tool is conceptually similar to the first, using the weekday median value from each week to present clearly on a single plot the time-series evolution over several years of delay, volume, or other system performance measures. Without this weekly median, typical daily variability makes it difficult to present in a single plot the trends over more than a few weeks. Finally, this paper presents a straightforward means to evaluate ramp meter operation using a GPS equipped probe vehicle. The process builds off of the loop detector evaluation mentioned earlier. The remainder of this paper presents the three analytical tools and then finishes with brief conclusions.

## EVALUATING THE LOOP DETECTORS

Loop detectors are the most common freeway vehicle detector and most other traffic detectors on the market employ similar principles, so this work should also be applicable to many other detectors as well. There are two types of loop detector stations in the CMFMS, single loop detectors and dual loop detectors, where the name denotes the number of loops in each mainline lane. Both types of stations can measure flow, the number of vehicles that pass per unit time, and occupancy, the percentage time that the detector is occupied. Dual loops allow for direct measurement of speed from the traversal time between the two loops of known spacing

(generally on the order of 20 ft), while speed can only be estimated at single loops, as presented below. Conventional speed estimates from single loop detectors are,

$$mean(speed) = \frac{\hat{L} \cdot q}{occupancy} = \frac{\hat{L}}{mean(on-time)} \tag{1}$$

where $\hat{L}$ is the assumed mean vehicle length. But some vehicles may be four times the length of the mean, their presence extends the mean on-time and thus reduces the estimated speed even though traffic is not actually moving slower. To reduce susceptibility to unusually long vehicles (as well as short actuation detector errors such as "flicker"), we calculate a more robust estimate of speed [3],

$$median(speed) = \frac{\hat{L}}{median(on-time)} \tag{2}$$

Loop detectors are not always calibrated correctly and may be completely non-operational, so it is necessary to identify non-performing and potentially inaccurate detectors. The first step in our work identifies any non-operational loops using a generous criterion, i.e., if no data were reported for a given detector in a given day it is labeled non-operational on that day and that day is excluded from further research.

### *Loop Detector Calibration*

It proved necessary to calibrate the operational loop detectors because many of them initially provided unreasonable speed measurements or estimates. Most of these errors arose from inaccurate dual loop separation or varying sensitivity leading to inaccurate assumptions of the effective length at the single loop detectors. Since a dual loop detector provides measured speed from the traversal time between two loops, scaling errors occur when inaccurate loop spacing is used. For this study we assume that any systemic errors in on-time arising from detector sensitivity at a single loop detector also lead to scaling errors in speed, i.e., an incorrect $\hat{L}$. We investigated the possibility that the error may be additive rather than multiplicative and at least for the CMFMS the fit was not as good with additive models.

## Single Loop Detectors

Typically speed at single loops is estimated via Equation 1, while this study uses Equation 2. In either case, the given detector's sensitivity biases the on-time measurements and errors in speed estimates arise. Starting with an initial assumption that $\hat{L}$=20 ft, estimated speeds are collected from all of the single loop detectors in the CMFMS over a month during a normally off-peak period. Namely, from 9am to 3pm every day the 5 min estimated speed is recorded using Equation 2 individually for each single loop detector. The period chosen for this experiment is April 1, 2005 through April 30, 2005 except for station 28 through station 34, which were not operational, so data for these stations were taken from April 1, 2003 to April 30, 2003. Using the fixed $\hat{L}$ many stations had free flow speeds below the posted speed limit. Some stations exhibited a large difference in speed across neighboring lanes during free flow conditions, at

many stations the range was in excess of 30 mph. In most cases the discrepancies arise due to variations in detector sensitivity, though some of the lower readings appear to be due to systematic variations in the vehicle fleet (more long vehicles in the particular lane). In any event, to correct for the speed estimation errors we calculated a multiplicative correction factor individually for each loop, as follows. First, the daily median of the 5 min speeds is taken from the off-peak time period, and this process is repeated for all weekdays in a month. Next, the median of these daily speeds is found. The correction factor is then defined as 5 mph above the posted speed limit divided by this daily median speed. For example, in this study the median speed in lane 2 at station 26 northbound is 81mph, so the correction factor is 0.86 (the quotient of 70 mph and 81 mph). Naturally one could use a radar gun or other measurement device to validate the speeds more accurately then simply guessing what the free flow speed should be, which is exactly what we do with probe vehicle data.

Specifically, the *travel time run* data were collected from a probe vehicle equipped with a GPS receiver to provide an independent measure of freeway operation. For each tour drivers take a vehicle on two round trips during the morning peak (7AM-9AM) or evening peak (4PM-6PM), Tuesday through Thursday. The run covers almost all of the detector stations on I-70/I-71, from the central business district (CBD) (station 102) to Polaris Parkway (station 33). The drivers were instructed to usually travel in lane 2, the second lane from the left, though they can pass slow vehicles if warranted. The GPS receiver records the location of the vehicle (longitude and latitude), and velocity every second. Roughly 355 round-trip probe vehicle runs through the corridor were then used in the validation.

The GPS velocity measurements from the probe vehicle are compared against the single loop speeds for the sample period in which it passed. Figure 1A shows a scatter plot of the uncorrected loop speed as the probe vehicle passed versus GPS velocity in lane 2 at station 26 northbound. It exhibits a systematic bias, with almost all estimates being too high. Figure 1B shows that this bias is removed after applying the correction factor calculated from the detector data. Figure 2 shows the comparison after the correction factor is applied at all of the single loop detectors in the southbound leg of the travel time run and the number of observations in the given plot. After applying the correction factors (implying that the true effective vehicle length differs from 20 ft) most of the single loop detectors report speeds close to the GPS velocity. Almost all of the loop detectors still showing a large discrepancy appear to be related to the sensitivity of the loop changing at some point during the four year study period and this point will be discussed shortly.

On a side note, even with the correct $\hat{L}$ the performance of Equations 1 and 2 degrade when flow is very low (e.g., between 1am and 5am) because the fixed $\hat{L}$ may not be representative of the few vehicles in a given sample. Fortunately, one can use an occupancy threshold to find such samples and correct the speed estimate [4].

## Dual Loop Detectors

Following the same process used with the single loop detectors and using the same month of data, about half of the dual loop detectors show that median speed in the off-peak time periods is outside the expected range of 60mph to 70mph. To correct the discrepancy of speed, multiplicative correction factors to the loop separation are once more found by the quotient of

the median and expected value, as detailed above. Figure 3 shows dual loop speed versus GPS velocity in lane 2 at station 22 southbound before and after applying the correction factor, notice how much of the systemic bias is removed. Figure 4 shows the comparison after the correction factors are applied at all of the dual loop detectors passed in the northbound leg of the travel time run and the number of observations in the given plot. ODOT has subsequently used a radar gun to independently correct the spacing at the dual loop detector stations and they found results close to our corrected spacing.

### *Changing Sensitivity of Loop Detectors*

Even after applying the correction factors many large discrepancies between loop speed and GPS speed remain because the sensitivity appears to change over time. Delving deeper into the issue, looking into the stability of the correction factor on a larger time scale, if the detector sensitivity changes then the correction factor should follow to keep the speed estimates accurate.

Extending the methodology used to establish the correction factors, using the same time period (9 am-3 pm) we calculate the median speed every weekday over four years. Rather than further processing these daily medians, the value for each day is plotted in a time series for each loop, e.g., Figure 5 shows the trend in daily median speed at loop station 17 northbound. The daily median speed in all three lanes for February 2002 through June 2002 is about 20 percent higher than for the rest of the time. The cause of this shift is unknown, though it is suspected that it arose due to adjustments in the filed. Such errors were observed at many other stations, almost all of which showed a similar piecewise stable trend. Since the correction factor at station 17 was calculated using data from April, 2005, the loop speed during February 2002 through June 2002 should be overestimated, as illustrated by the cluster of points with loop speed around 90 mph in Figure 6A. The unexpected trend in median speed shows the need to update the correction factor over time. In this case, two different correction factors are used, one during the first half of 2002 and the other applied for the rest of the data. Figure 6B repeats the comparison of loop speed to GPS velocity using the two correction factors. In general the correction factor could be calculated periodically to see if the sensitivity of any loop detectors have changed significantly. For example, the correction factor could be updated every week, with the correction factor calculated in one week applied to loop data for the following week.

Other examples in [2] illustrate how this approach caught a loop detector that was erroneously set to pulse mode (providing a fixed on-time per actuation) rather than presence mode (providing the true on-time per actuation). Another example in [2] shows that the approach was able to find problems arising from the detector inputs being incorrectly mapped to the lanes at a dual loop detector.

## SYSTEM PERFORMANCE

Many performance measures were developed in the course of this research, although often these measures are simply refinements on earlier techniques, there were several small but important advances. The most significant being filters to allow one to clearly view trends over several years of time series data. Many metrics are well suited to time series presentation (speed, flow, occupancy, travel time, delay, etc.). Other measures are well suited to averaging over time and

space (vehicle miles traveled- VMT, delay, amount of time delay is present, etc.). For some of the metrics it makes sense to aggregate by day in addition to other time periods (VMT, delay, amount of time delay is present, and average daily travel- ADT). When examining a time series of these daily values over an extended period it quickly becomes difficult to pull out meaningful trends in the presence of typical daily variability (e.g., incidents, weekends, and holidays). To overcome this problem we take the median of the weekday values for each week. This process of taking the weekly median allows one to review several years of data on a single plot and still extract useful information of how recurring conditions evolve. Similarly, one could easily use min, max or another statistic; restrict the analysis to a specific day of the week, or so forth.

Several performance measures were considered in the research, ultimately, ADT was chosen to measure throughput and vehicle delay was chosen to measure congestion. To estimate delay we used a matrix of 5 min sample speeds indexed by time and detector location, then assumed that conditions remain constant on a given link for the entire 5 min sample and distance spanned by the link. From this speed matrix we estimated delay, defined to be travel below 55 mph, for a given five minute sample and link:

$$\text{total vehicle delay} = \text{flow} \cdot \max\left(\frac{\text{link distance}}{\text{speed}} - \frac{\text{link distance}}{55\text{mph}}, 0\right) \tag{3}$$

resulting in a delay matrix of the same size as the speed matrix. One can then sum across rows (delay at a link over a day), columns (delay across the corridor at an instant) or any other region of the matrix, e.g., to find the total delay arising from an incident.

Figure 7 shows the weekly median ADT and delay at four directional stations over three years. In each of the plots the vertical axis shows weekly median ADT (10,000 vehicles per day) or weekly median delay (vehicle-hours per day). Vertical delineations show each month (abbreviated by the first letter) on the plots. The chevron on the map to the right of the plots shows the direction and approximate location of the given detector station. Of course if a detector goes down in one or more lanes the measures will no longer be valid and they are omitted from the plots, as evidenced by the gaps in the curves. The measures from the affected station could easily be presented during these periods with a different line style as they may still hold meaning.

The impacts of many major events are evident in Figure 7. The most significant of which was the closure and reconstruction of I-670 across the north side of the CBD, an alternative route for traffic on the southern portion of the instrumented corridor. At the start of data collection in December 2001, I-670 had a western terminus at SR-315 and I-670 traffic could only travel to/from the north on SR-315. Between March 2002 and September 2003 I-670 west of I-71 was completely closed for rehabilitation. After the reconstruction, I-670 connected with I-70 in the west and the new SR-315 interchange allowed for traffic from I-670 to also travel to/from the south. The plots indicate the period of the I-670 closure, both ADT and delay increased significantly on the parallel portion of the I-71 corridor. Thus, we see ADT drops from before closure to after the closure in the second row of plots. The impact of the closure on ADT is much smaller north of the junction of the two routes. For southbound traffic, the bottom row of plots suggests that after reopening I-670 southbound delay was alleviated around the I-71/I-670 junction. The plots also show that after I-670 reopened, a small increase in southbound I-71

ADT is seen north of the junction with I-670 and a larger drop in ADT is evident south of the junction (third row).

## EVALUATION OF THE RAMP METERING SYSTEM

Ramp metering is one of the most frequently used methods of urban freeway control. Ramp metering limits access to the freeway to avoid or reduce mainline congestion with the objective of improving the efficiency of the freeway itself. The actual meter is a set of traffic signals located on a freeway entrance ramp, usually about halfway down the ramp, cycling between red and green to allow vehicles on. Most of the ramp meter stations in the CMFMS are traffic responsive, with the metering rate set automatically depending on the mainline traffic conditions. The details of the traffic responsive ramp metering algorithms are proprietary to the contractor that deployed them, however, according to the ODOT engineers operating the system, the contractor has stated that the algorithms generally use conditions at the mainline loop detector station immediately downstream of the given ramp.

Once more using the GPS equipped probe vehicle, we evaluate the ramp meter system on I-71. Just over half of the probe vehicle tours were the so-called travel time runs described earlier, with the remaining tours following a different route to collect operational data of the ramp meters. As with the travel time runs, these *ramp run* data are collected during the morning peak (7AM-9AM) or evening peak (4PM-6PM), Tuesday through Thursday. The ramp run is shorter than the travel time run since the ramp meters are only on the southern half of the corridor. The run spans from the CBD (station 102) to Cooke Road (station 14). Drivers are instructed to normally travel in the outside lane, though they can pass slow vehicles if warranted, and they exit the freeway at specific locations so that they can re-enter it through a total of four ramp meters northbound and six ramp meters southbound. Figure 8 shows the data from one round trip superimposed on an aerial photograph, illustrating the path of a probe vehicle collecting ramp run data.

If the mainline is congested, then the ramp meter should be on. Hence, if the mainline travel time experienced by the probe vehicle were larger than measured under free flow conditions, one would expect the travel time on the ramp section should also be increased. Figure 9 shows velocity versus distance from four selected runs through the meter at Long St. As we did with each ramp, the analysis area is limited to the start of an on-ramp to the start of the following off-ramp, divided into three sections: on the ramp upstream of the meter, between the meter and end of ramp, and mainline between on and off ramp. Probe vehicles exhibit two patterns of velocity upstream of a ramp meter, either the vehicle stops several times if the meter is on, otherwise the driver gradually increases velocity as they pass the ramp meter if the meter is off. The probe vehicle drivers were instructed to record the status of all visible ramp meters as they passed them. The reports were then verified by checking the probe vehicle velocity upstream of ramp meters, looking for the presence or absence of stops on the ramp (indicating the meters were on or off, respectively). In principle one could simply use the presence or absence of such stops upstream of the meter as an indication of its status.

The mean probe vehicle velocity over the mainline section is used to determine the presence or absence of congestion, if it is less than 45 mph the mainline is taken to be congested, and free flowing otherwise. So four combinations are possible:

1) Meter off, Mainline free flow,

2) Meter on, Mainline free flow,

3) Meter off, Mainline congested,

4) Meter on, Mainline congested,

as illustrated in Figure 9. Both *Meter off, Mainline free flow* and *Meter on, Mainline congested* would be expected from normal ramp meter operation. *Meter on, Mainline free flow* could indicate a problem with the metering algorithm or it may simply show that the meters are successful in restricting flow enough to keep the mainline from becoming congested. In any event, *Meter off, Mainline congested* clearly indicates a fault in traffic responsive metering.

Figure 10 Tabulates the status of ramp metering and the corresponding mainline traffic conditions at Long St. for all of the ramp runs. Figure 10A shows a scatter plot of travel time upstream of the meter versus the mainline travel time. Each point on the plot is coded with one of four symbols to denote which of the four conditions observed on the given run. But this scatter plot lacks a temporal component. Using the same data, Figure 10B shows the status of the ramp meter and mainline traffic condition as a function of the time of day. The top plot shows that on all AM runs the meter was off and mainline free flow while the lower plot shows that this state is also dominant in the PM, though the other three states are also observed (the ramp leaves the CBD). Next, to see if the condition changed from month to month or year to year, Figure 10C-D show the number of times each state was observed on a given date (the horizontal axis spans two years). The analysis was repeated using speed data from the mainline loop detectors immediately downstream of the ramp rather than the probe vehicle mainline travel time, and then again using the mainline loop detectors immediately upstream of the ramp. The results using both conditions from the mainline loop speeds are similar to those presented using the probe vehicle travel time, and thus are not shown. The analysis was repeated at the other ramp meters in the tour (including the mainline loop detector speed analysis), as included in [2]. Summarizing the results, Table 1 shows the percentage of observations in each of the four conditions at each ramp meter.

## CLOSING AND CONCLUSIONS

This research examined the performance of a specific FMS, though many of the tools developed in this work are applicable to other traffic monitoring systems and this paper highlights three of them. We first examined the performance of the detectors to validate that they are operating correctly. Using just the data reported by the loop detectors, we corrected loop sensitivity errors at single loop detectors and spacing errors at dual loop detectors. The procedure is simple, effective, and beneficial. The paper then shifted attention to the operation of the FMS as a whole, using delay and ADT to evaluate the system at each detector station. Ordinarily one would expect to see variation from day to day as well as a difference between weekday and weekend conditions, making it difficult to interpret a time series plot of data more than a few weeks long. To address this problem we used the conceptually simple weekly median filter to clearly show conditions from each week over three years. Once more, care must be taken to differentiate between changes due to detectors being down and changes due to travel patterns, as

was done in the body of this work. These measures clearly reflected the impact of I-670 closing for rebuilding and then reopening over a year later. Finally, attention shifted to the operation of the ramp meters and a low cost evaluation method using probe vehicles to monitor metering performance. Several problems were identified, the largest being the presence of mainline congestion while the adjacent meter remains off.

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These evaluation tools reflect the efforts of a large team at the Ohio State University, as well as considerable help from the sponsor, ODOT, including: Farouk Aboukar, Matt Graf, Nick Hegemier, and George Saylor.

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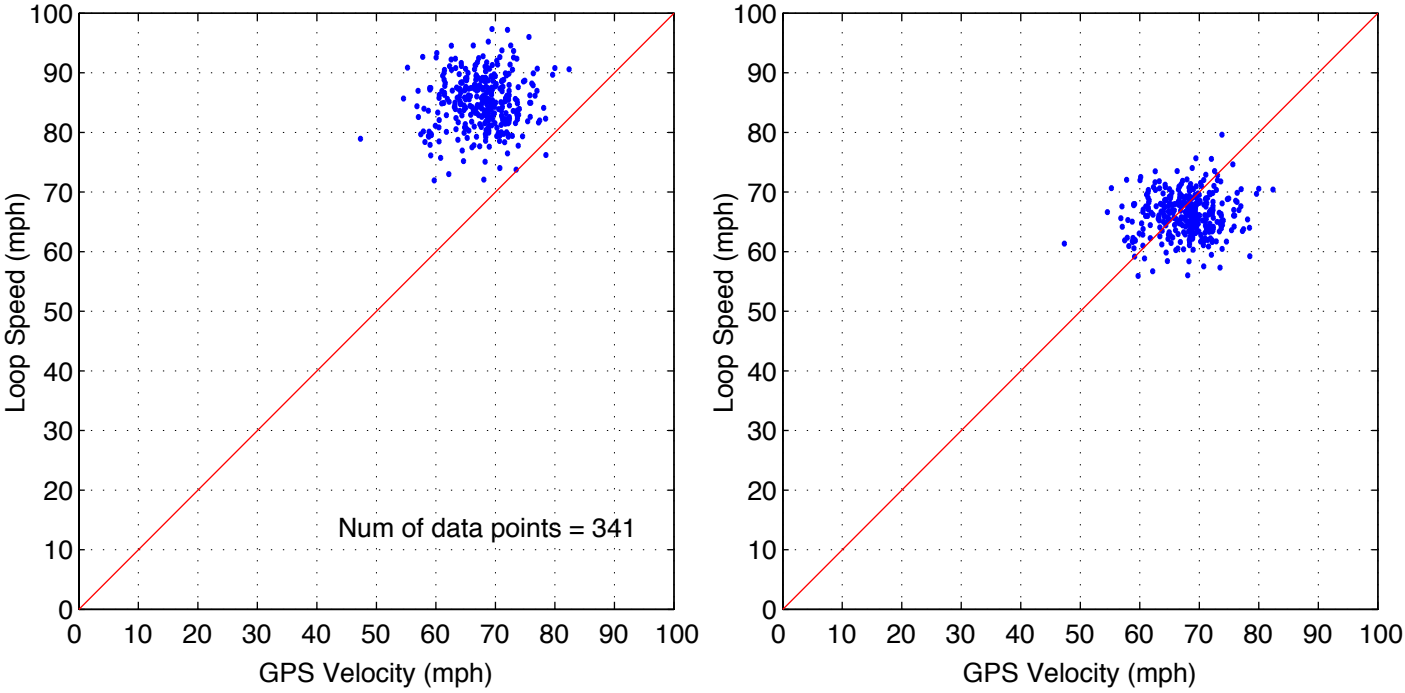


Figure 1, Comparison between loop speed and GPS velocity at station 26, lane 2 (A) shows that loop speed is higher than GPS velocity without correction, i.e., loop speed overestimated, (B) shows the difference between loop speed and GPS speed is within 10mph, and unbiased after applying the correction factor.

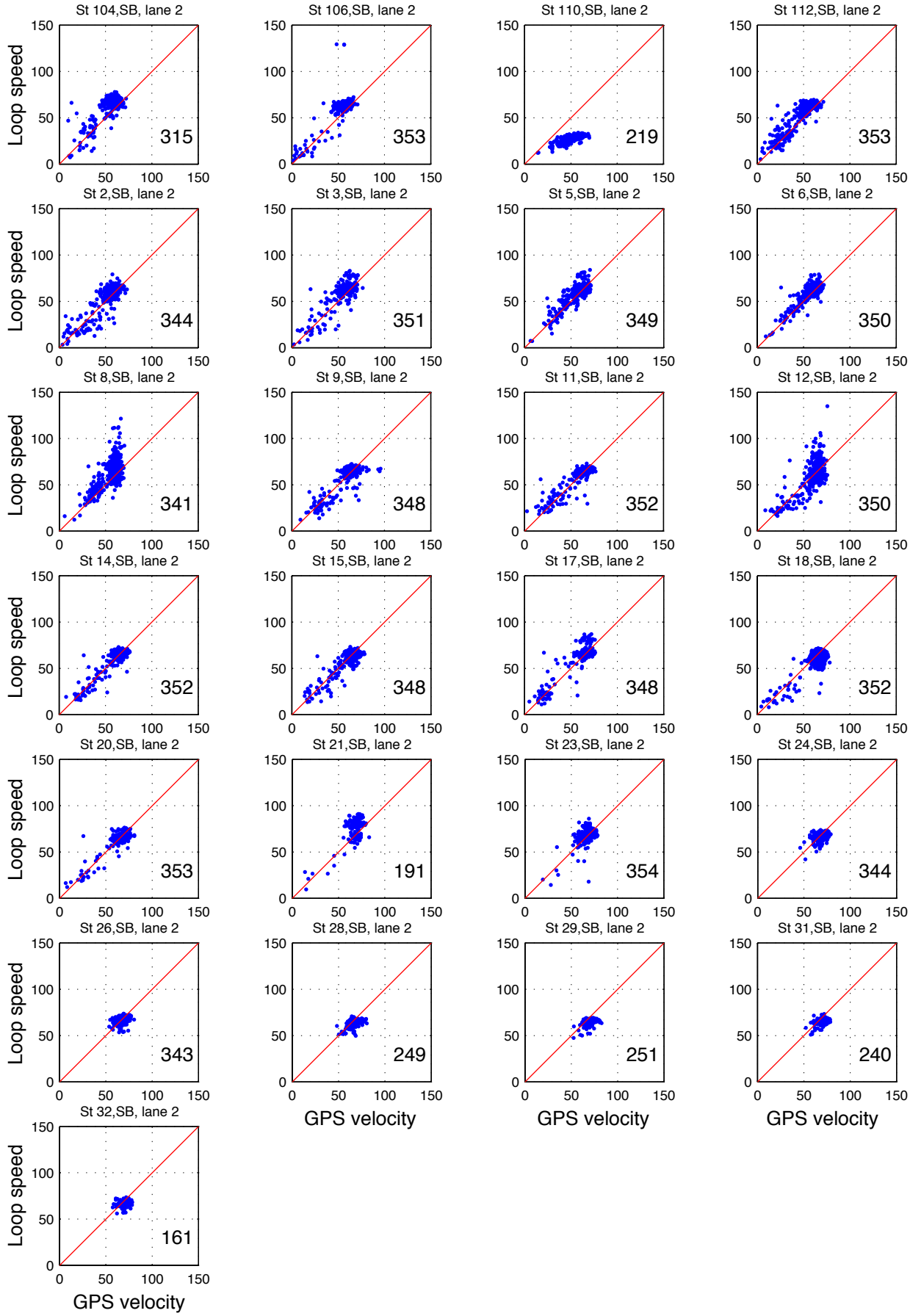


Figure 2, Comparison between single loop speed estimates incorporating correction factors and concurrent probe vehicle velocity measurements for southbound single loops (all mph). Each plot had a different number of observations, as indicated in the lower right corner.

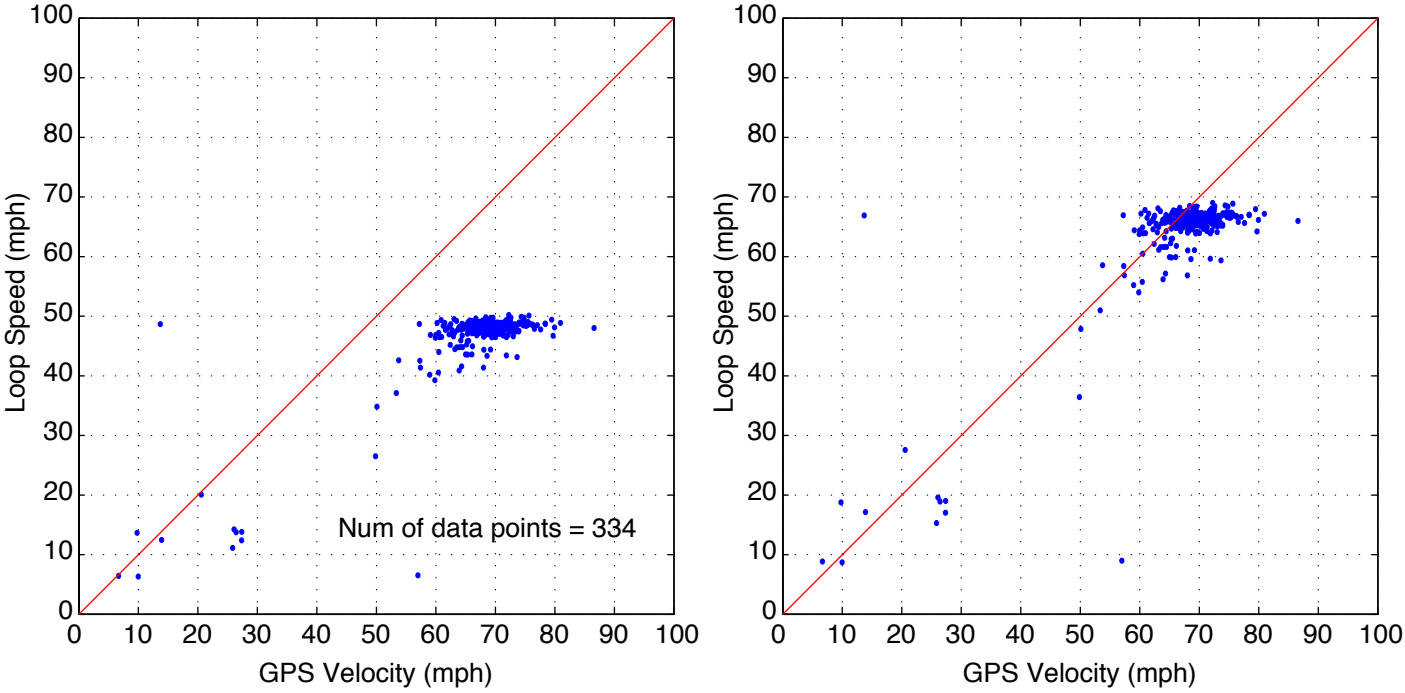


Figure 3, Comparison between loop speed and GPS velocity at station 22, lane 2 (A) shows that loop speed is lower than GPS velocity without correction, (B) shows the difference between loop speed and GPS speed is within 10mph after applying the correction factor.

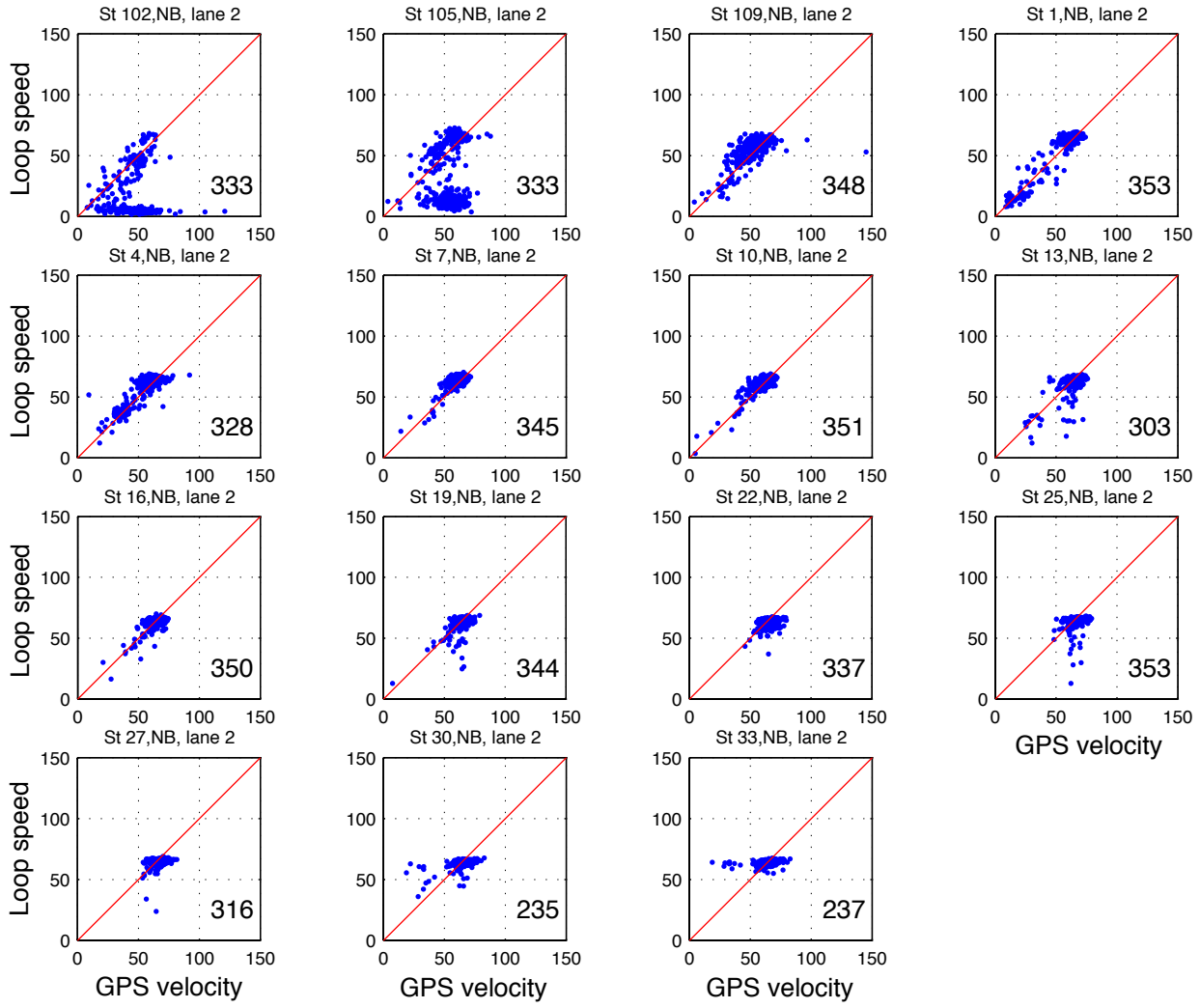


Figure 4, Comparison between dual loop speed measurements incorporating correction factors and concurrent probe vehicle velocity measurements for northbound dual loops (all mph). Each plot had a different number of observations, as indicated in the lower right corner.

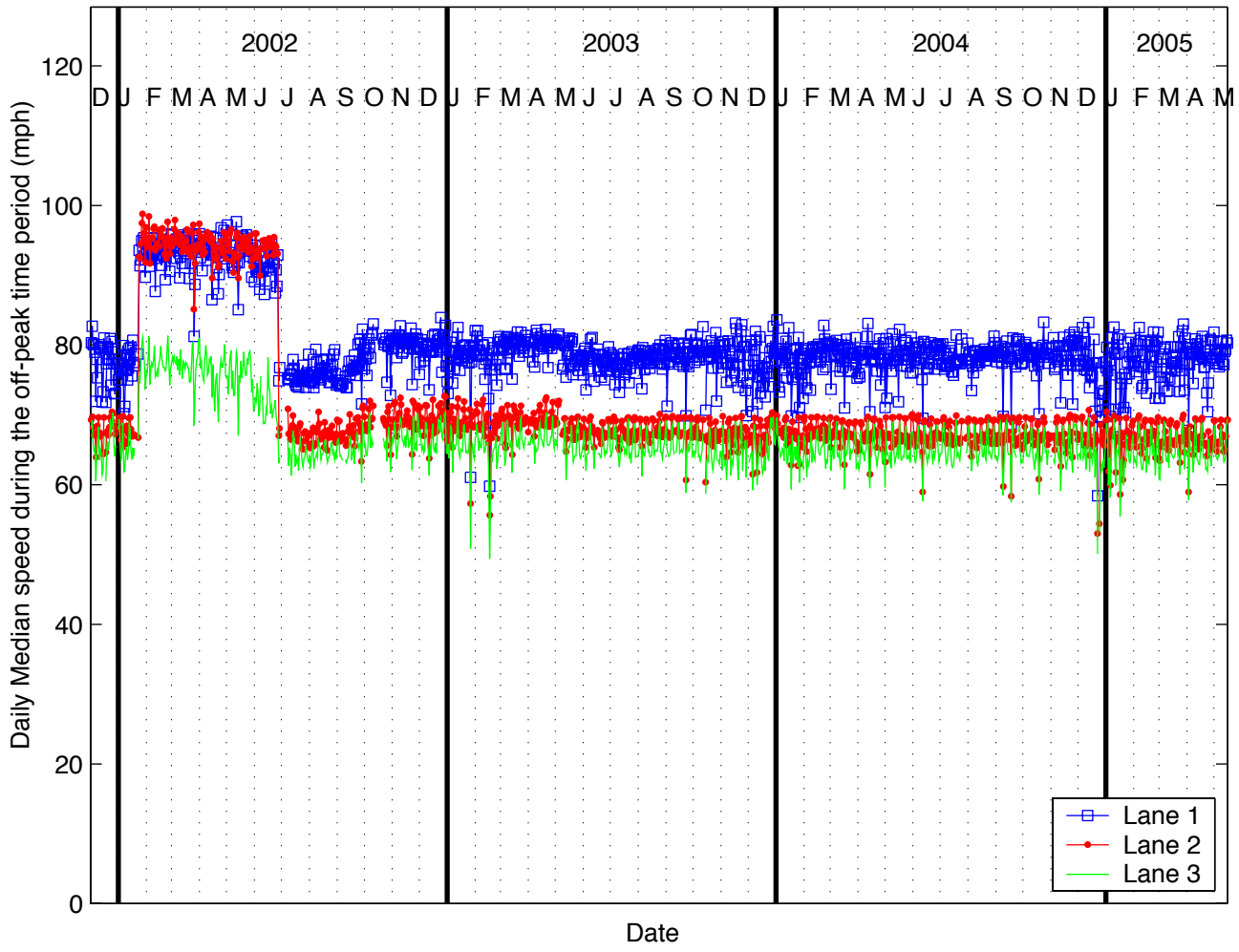


Figure 5, Daily median speed trends at loop station 17 northbound over four years.

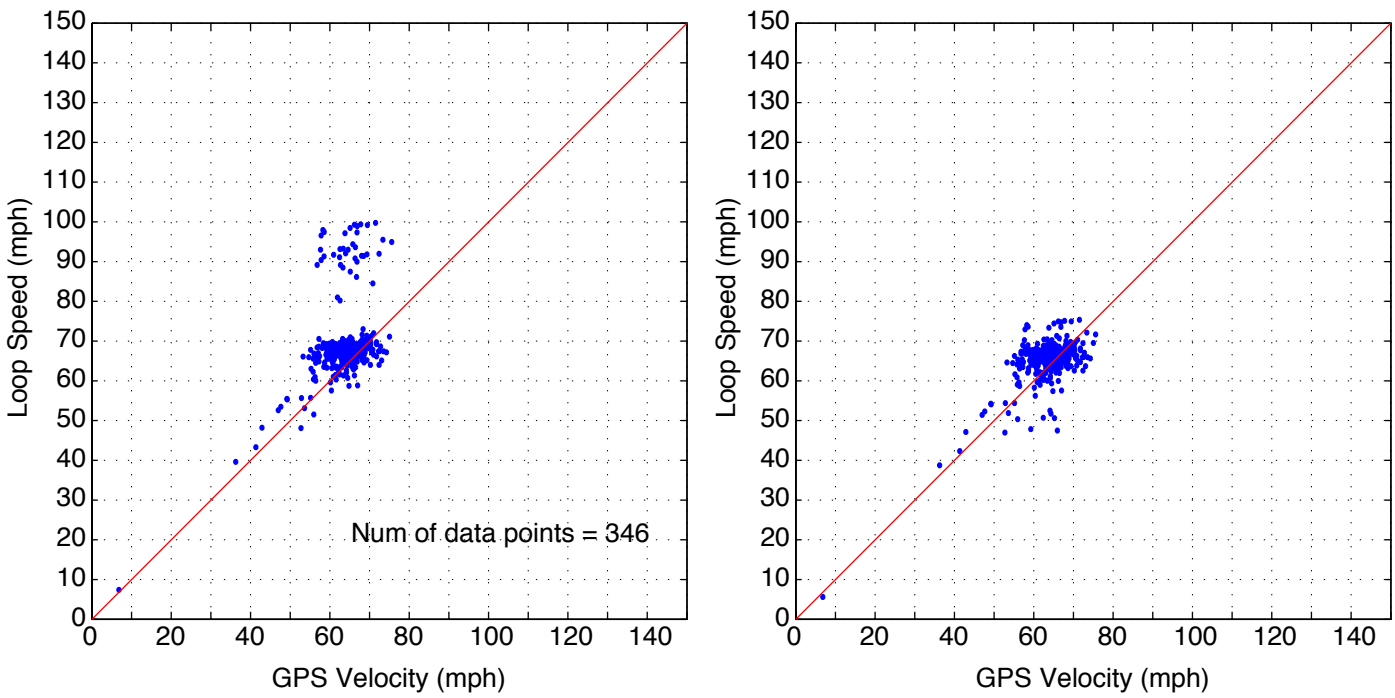


Figure 6, Comparison between loop speed and GPS velocity at station 17, lane 2 (A) after applying a single correction factor, (B) after applying two correction factors.

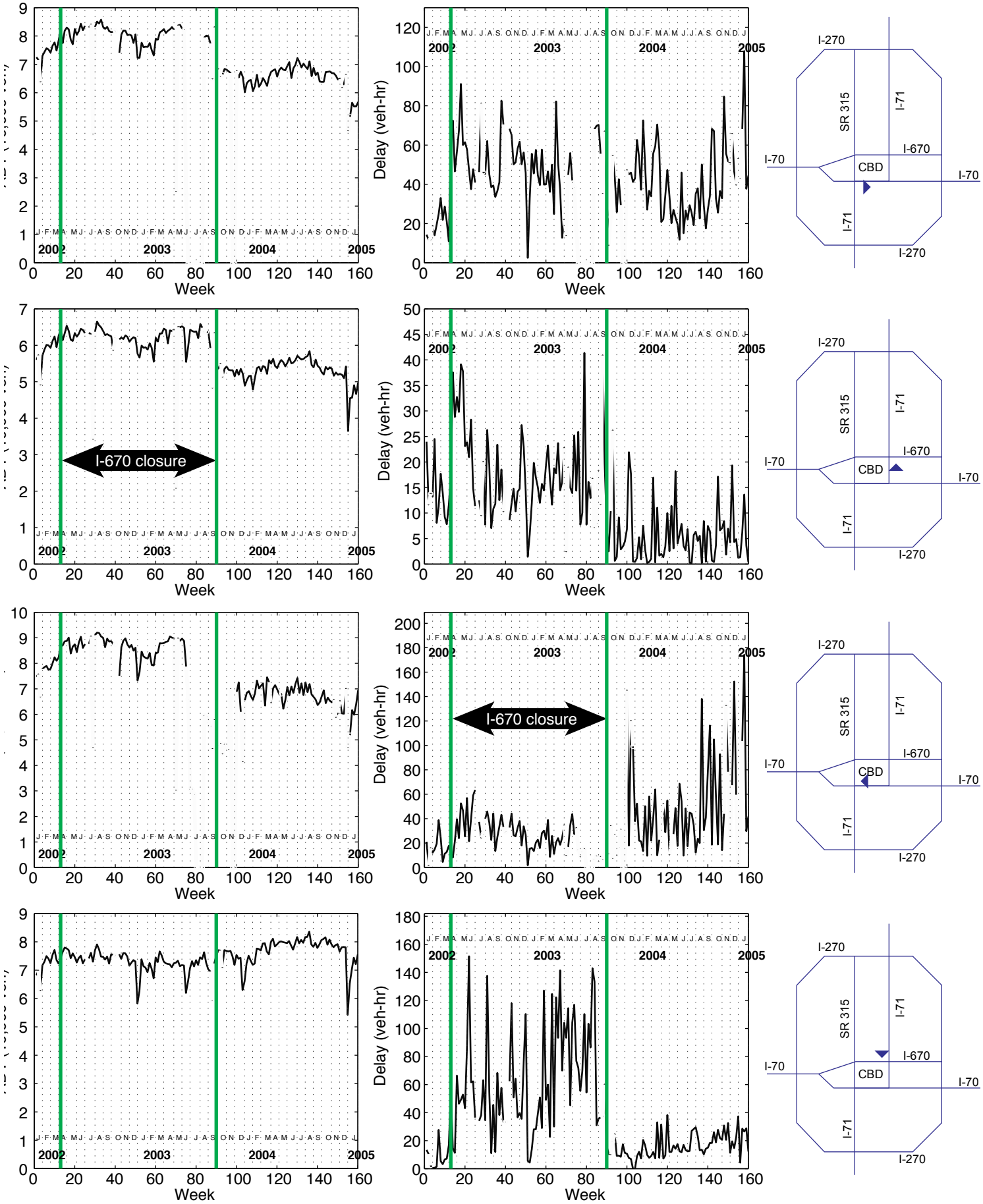


Figure 7, Weekly median ADT and delay at four directional stations over three years (one station per row). The maps at right show the freeway network and the chevron the direction and approximate location of the given detector station.

Figure 8, Path of a probe vehicle (white circles) superimposed on an aerial photo, showing the path through the I-71 ramps in both directions at 17th Ave.

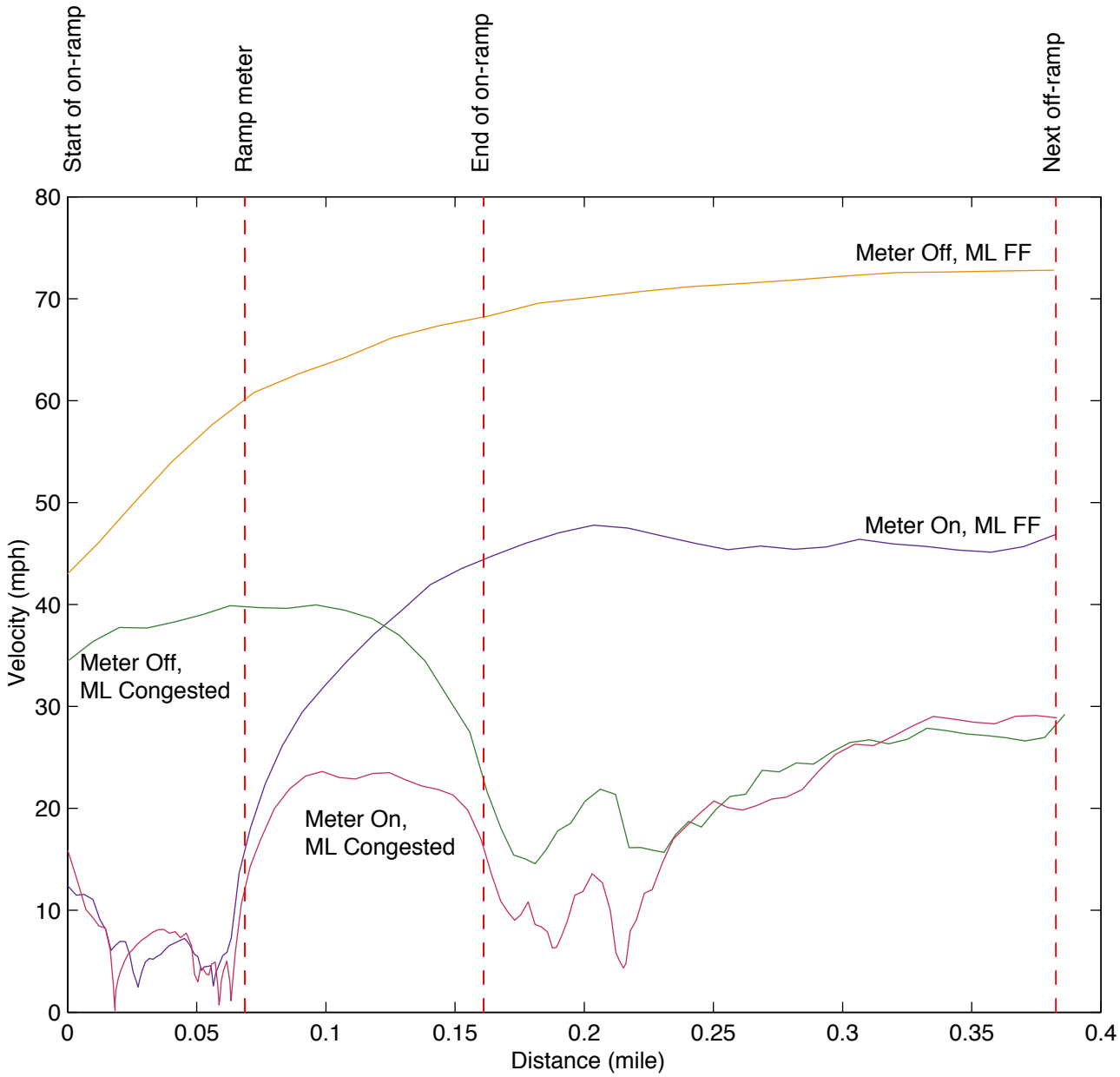


Figure 9, Velocity versus distance from four probe vehicle runs through the northbound I-71 on-ramp at Long St.

Table 1, the percentage of observations in each of the four conditions at the 10 ramp meters: just morning peak, just evening peak, and both combined

| | | Northbound (from CBD) | | | | Southbound (to CBD) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Long St | 11th Ave | 17th Ave | Hudson St | Cook Rd | E. North Bdy | Weber Rd | Hudson St | 17th Ave | 5th Ave |
| morning | Meter on, ML Cong. | 0% | 0% | 0% | 0% | 10% | 30% | 12% | 11% | 0% | 0% |
| | Meter off, ML FF | 100% | 99% | 99% | 99% | 69% | 68% | 80% | 68% | 80% | 96% |
| | **Meter off, ML Cong.** | **0%** | **1%** | **1%** | **1%** | **17%** | **2%** | **7%** | **13%** | **20%** | **4%** |
| | Meter on, ML FF | 0% | 0% | 0% | 0% | 4% | 0% | 1% | 8% | 0% | 0% |
| evening | Meter on, ML Cong. | 28% | 3% | 2% | 1% | 0% | 0% | 0% | 2% | 1% | 0% |
| | Meter off, ML FF | 62% | 86% | 85% | 76% | 98% | 99% | 99% | 96% | 92% | 90% |
| | **Meter off, ML Cong.** | **6%** | **11%** | **10%** | **22%** | **1%** | **1%** | **1%** | **2%** | **7%** | **10%** |
| | Meter on, ML FF | 4% | 0% | 3% | 2% | 1% | 1% | 0% | 0% | 0% | 0% |
| both combined | Meter on, ML Cong. | 18% | 2% | 1% | 1% | 3% | 10% | 4% | 5% | 0% | 0% |
| | Meter off, ML FF | 76% | 91% | 90% | 84% | 88% | 88% | 93% | 87% | 88% | 92% |
| | **Meter off, ML Cong.** | **4%** | **7%** | **7%** | **15%** | **7%** | **1%** | **3%** | **5%** | **12%** | **8%** |
| | Meter on, ML FF | 3% | 0% | 2% | 1% | 2% | 1% | 0% | 3% | 0% | 0% |