Using Transit Vehicles to Measure Freeway Traffic Conditions

Benjamin Coifman, PhD
Associate Professor
The Ohio State University
Joint appointment with the Department of Civil and Environmental Engineering and Geodetic Science, and the Department of Electrical and Computer Engineering
Hitchcock Hall 470
2070 Neil Ave, Columbus, OH 43210
Tel: (614) 292-4282
E-mail: Coifman.1@OSU.edu

SeoungBum Kim
Graduate Research Assistant
The Ohio State University
Department of Civil and Environmental Engineering and Geodetic Science,
Hitchcock Hall 470
2070 Neil Ave, Columbus, OH 43210
E-mail: kim.1936@OSU.edu

ABSTRACT

Many public transit agencies have equipped their fleet with automatic vehicle location (AVL) systems, which periodically provide the location of each vehicle in the fleet. Although the AVL is deployed for transit operations, the vehicles also provide valuable information about the traffic stream throughout the road network. In this study we develop a methodology to mine the transit AVL data and find all trips that use any portion of a pre-specified freeway segment. These trips are then used to measure travel time and average speed over the freeway, thereby quantifying conditions on the facility. The results are validated against concurrent loop detector data from a corridor. The greatest benefits, however, are in areas without fixed vehicle detection, so the methodology is also demonstrated on such a freeway corridor. The study corridors typically have fewer than 50 observations per day per km per direction, so this paper includes a process for selecting those segments with at least one observation per hour. Even with this low density of observations, the data are aggregated to clearly show the recurring congestion patterns. Non-recurring events are also evident, but they have a long time to detection. With a higher frequency of observations -- e.g., from other fleet AVL systems, cell phone tracking, or Vehicle-Infrastructure Integration (VII) probe data -- the methodology should also be effective for rapidly identifying non-recurring congestion.

Word count:

4489 + 12 figures = 7489 words

INTRODUCTION

Measuring and monitoring traffic conditions is important for freeway management. Performance measurements typically use various infrastructure based detection technologies for this purpose, e.g., inductive loop detectors. Alternatively, a floating car equipped with a global positioning system (GPS) receiver or an inertial navigation system can capture the vehicle's trajectory and by extension, the traffic conditions that gave rise to it. A floating car can measure conditions in areas that are not otherwise instrumented. However, traditional floating car studies are usually limited in scope and are costly to implement. As intelligent transportation systems (ITS) evolve, new information is becoming available for traffic monitoring. Automatic vehicle location (AVL) based on GPS is one such example, it is being deployed on various fleets to manage their operation. Like floating car trajectories, an AVL system can provide traffic conditions without wayside detectors.

For example, [1] studied the use of freeway service patrol (FSP) vehicles' AVL to monitor the freeway conditions in Los Angeles, CA. In that research performance measurements from FSP data were evaluated and compared against measurements from loop detectors. Bertini et al [2] looked at transit vehicle travel time and travel speed data in Portland, OR, to assess traffic conditions on arterials and [3] on freeways; while Cathey and Dailey [4-5] looked at many of the detailed issues involved in extracting meaningful information on various corridors from transit AVL data in Seattle, WA.

ANALYSIS

In Columbus, OH, the Central Ohio Transit Authority (COTA) operates 58 fixed routes and additional paratransit service with a fleet of 276 transit vehicles [6]. Almost all of these vehicles as well as many non-revenue vehicles are equipped with AVL. The AVL transmits position, heading, speed, observation time, vehicle number, and route number to the COTA operations center, usually once every minute. Our study corridors typically have fewer than 50 observations per day per km per direction, so this work addresses some of the challenges that arise in monitoring traffic conditions from transit vehicles with such infrequently reported data.

There is no universal standard for AVL systems, for example [2-3] employs an AVL system that reports position as vehicles approach and depart bus stops, while [4-5] employs a system that only reports the times that buses pass fixed "signpost" receivers. These earlier studies use AVL data reported at specific locations, which greatly simplifies the task of localizing traffic conditions. The present study uses AVL data reported strictly on elapsed time, necessitating an additional step of parsing the data to extract travel times on the segments of interest and eliminate any observations that are off of the facility, e.g., from overpasses. Another notable difference from [2-5] is the time scale of evaluation employed; the previous studies evaluated conditions over only a few days while the present work evaluates conditions over an entire month. At this larger time scale we develop a methodology to aggregate the data and clearly show recurring congestion patterns over time and space even with a low density of daily observations. Non-recurring events are also evident, but they have a long time to detection. With a higher frequency of observations -- e.g., from other fleet AVL systems, cell phone tracking, or Vehicle-Infrastructure Integration (VII) probe data -- the methodology should also be effective for rapidly identifying non-recurring congestion.

The scope of the present work is limited to freeways where the confounding problems arising from bus stops impacting the measured travel time are not an issue. The study employs the system-wide AVL data collected during the month of May 2003 (Figure 1A). At the time I71 (shown with a solid line) was the only freeway instrumented with vehicle detection, so this corridor was used for development and validation. The non-instrumented freeways (SR315, I70, I270, I670, and portions of I71) are shown with dashed lines. The study area along I71 begins in the central business district (CBD) at the interchange with SR315 and I70, extending to the northern suburbs, covering roughly 20 km in the shape of a "J", as illustrated in Figure 1A. About 100 transit vehicle trips are observed in each direction on some portion of this corridor in a typical weekday. Figure 2A-B show respectively a detail of the road network around I71 and the observed AVL data on one day. To find vehicles in the corridor a coarse filter area is defined around the freeway corridor to separate candidate points that may be on the freeway from the rest of the AVL data. The darker region in Figure 2C is an example of the coarse filtering region, with the candidate points shown as dark "o"'s and the excluded points lighter. These candidates are further culled by taking the shortest distance to the centerline, any points falling beyond a threshold are also discarded (Figure 2D). The remaining candidate points are considered to be within the freeway right-of-way. Since some of these points within the right-of-way come from vehicles crossing the freeway rather than traveling along it, several steps are taken to eliminate the crossing vehicles. The first step is to require the vehicle to be within the right-of-way for at least three minutes, i.e., if three or more consecutive data points from a given vehicle are found in the right-of-way those points are considered a trip on the freeway. The start and end points of each trip are extracted, as well as the travel time between the two points. Furthermore, within each trip, each pair of consecutive points is used to dynamically define a link. For each link the start and end points are recorded as well as the link travel time. Figure 1B shows an example of a vehicle trip with six links on I71. The first and last points in a trip are considered boundary points and they can only be identified by observing a consecutive point falling outside of the filtered area, denoted with "out of I71" in the figure. This process bypasses several potentially misleading features of the AVL data. For example the instantaneous speed is not of much use given the long delay between observations. The route data are also excluded for two reasons, first, many of the buses on the freeway are on positioning moves and might erroneously report the route either just completed or about to be begun. Secondly, even when accurate, the route number does not help differentiate between vehicles on the freeway and those just outside of the corridor. While the route number is redundant with the vehicle number in this freeway application, it would likely be useful in arterial applications to differentiate between express and local service.

The distance along the roadway must come from some other source because the straight-line distance between two points usually does not capture the actual distance traveled. For both trip and links, the distances come from a GIS database. For I71 we employ a reference run made by a probe vehicle sampling position every second while on the other freeways we use the centerline data provided by the Ohio Department of Transportation (ODOT). In either case, we snap the AVL coordinates to the GIS data and find the distance along the roadway between the first and last points for the trip and consecutive points for the links. Finally, average speed is calculated from the quotient of travel time and distance. Figure 3 shows an example of the time series speed measured from the southbound trips from a single day.

Calculating link-based speed and travel time from the loop detector data on I71

To independently validate the transit measurements, this study employs the concurrent loop detector data from I71. There are 40 detector stations collecting traffic data along the corridor at about 0.5km segment spacing. This study uses five-minute median speed from each station, measured across all lanes, representing traffic conditions at the given discrete point in space. To convert the point observations from the loop detectors to link and trip estimates that are comparable to the transit data, we use the matrix of speeds indexed by detector station (distance) and sample (time) and assume that conditions remain constant on a given loop detector segment for the entire 5 min sample and distance spanned by the segment (in this case the segments start and end at the mid-point between successive stations). Then we estimate vehicle trajectories assuming that vehicles traveled at these prevailing conditions. So trajectories change slope at the boundaries of the cells, either at the end of a segment or at the end of a 5 min sample. From the estimated trajectories one can estimate travel time directly, taking the difference in the times that a trajectory passes the chosen start and end points. In this case, every time a transit vehicle is observed in the corridor the start and end point of every transit trip is used as the start of a travel time estimate over the distance along the roadway spanned to the corresponding end point. The process is then repeated for all of the dynamic links extracted from the AVL data.

After applying the algorithms to generate link-based and trip-based measures independently from the concurrent loop data and transit data, Figures 4A and 5A respectively compare the resulting average trip speed and trip travel times from the two sources. The three different symbols used for the points will be discussed shortly, for now consider all three groups as a single ensemble. The figures show the results from the entire month, both directions, with the abscissa showing the loop detector estimates and the ordinate showing the transit measurements. If the two independent measures for a given trip have the same value the point will fall on the line at 45-degrees, which is shown with a dashed line in the figures. Indeed, most of the measurements fall close to this line, but many points are far away from it. Investigating the cause of the large deviations, most of them arose from errors in the data, specifically,

1. Extremely low (below 1mph) or high (e.g., infinite) speed reported in the loop detector speed matrix (45% of the errors),
2. Missing values in loop detector speed matrix causing erroneous travel time estimates (50% of the errors),
3. AVL appeared to report incorrect coordinates (2% of the errors),
4. Ambiguity about the location of a transit vehicle that is near the freeway but potentially not on it (3% of the errors).

Addressing the errors

In the case of the first error, the erroneous speed measurements in the loop detector data were usually observed to last only short time periods and at only one station a time. If those erroneous measurements are reported from a station included within a given segment, the travel time will be under-estimated or over-estimated and it will directly impact the average link speed calculation. In this case, the travel time estimation algorithm was modified to either not generate any travel time measurement or to replace the infeasible measurement with the current speed from the loop detector station most immediately upstream of the problematic station. Using the upstream station, rather than previous time period at the given station, avoids the propagation of errors when two successive samples at one station exhibit this problem (a few stations were more prone to errors than the others).

In the case of the second error, in the absence of any measurement at one station, the loop detector based travel time estimate cannot be made across that cell of the matrix. These errors appear to be due to communication faults or the field hardware "locking up". Since these errors typically lasted for many samples and/or impacted several adjacent loop detector stations, it was decided to simply identify the trips impacted by these missing loop detector measurements and exclude them from further analysis.

In the case of the third error, the AVL system would occasionally report the same coordinates for a vehicle in two or more successive samples with different time stamps. While it is possible for a vehicle to encounter stop and go traffic, it is not likely to remain completely stopped for one minute while on the freeway. It appears that this problem arises when the GPS receiver loses its fix for a long period while the reporting system continues to report the last valid GPS measurement with an updated time stamp. In any event, if two or more successive points in the AVL data from a transit vehicle have identical coordinates it is considered problematic in terms of calculating link travel time. If two consecutive points on the freeway have the same exact coordinates, then the latter point is deleted. If the deleted point is the "end point" of a trip, the end point is reset to its predecessor point and the process is iterated if necessary. The trip time will only be impacted by such errors in the start and end points, any such errors in the intervening points will only impact the link travel times.

In the case of the fourth error, the first or last point may be recorded off the freeway on a ramp, overpass, or underpass. Provided the point is close enough to the centerline and an interchange, it is impossible to tell from that single point whether it is on the freeway or off. So a vehicle that just exited via an off-ramp and was in the process of crossing over the freeway when it reported its position would lead to an erroneously large travel time if this fact goes undetected since some of this time includes travel on the ramp and arterial. To capture these ambiguous points, "H" shaped regions are used to identify points that may be on the ramps or any over/under pass, e.g., Figure 2E. To this end, it is necessary to define such a region for all of the interchanges along the subject corridor, e.g., as highlighted by the squares in Figure 1C. Figure 2F shows an example of the candidate points caught in the trap, but the fact remains that these ambiguous points may or may not be from the freeway. To differentiate between the two possibilities, if the first or last point in a trip is close enough to an interchange to fall within one of these "H" shaped regions, it is discarded and the next point on the freeway is used in its place, this process is iterated until no end points fall in the given "H" shaped region. If an intermediate point is close enough to an interchange to fall within the "H" shaped region, the point is retained since the transit vehicles generally do not exit and immediately reenter the freeway.

After applying these filtering methods, the link-based and the trip-based measurements were regenerated from both the loop detector and transit data. The combined results for both southbound and northbound directions from the entire month are presented in Figures 4B and 5B, for average trip speed and travel time, respectively. Compared to Figures 4A and 5A showing the unfiltered case, the majority of the points do not change going from the unfiltered to the filtered plots, as indicated with dots. A "+" in Figures 4A and 5A indicates a point that was eliminated due to the filtering steps and is not included in Figures 4B and 5B. Finally the square markers denote points that changed position as a result of the filtering, and in general they moved closer to the line at 45-degrees.

As evident in Figures 4 and 5, many erroneous measurements have improved as a result of the filtering, addressing errors in both data sets. Some errors remain after filtering. Figure 6 shows the cumulative distribution function (CDF) quantifying the difference between the before and after data from Figure 4. About 90% of the measurements after filtering fall within 16 km/h of one another. Still, some large errors remain in Figure 4B, with roughly 10% of the differences exceeding the 16 km/h threshold. Some of these arise due to the fact that (i) the loop detector speeds are based on conditions in all lanes while the transit vehicle only traveled in a single lane, (ii) the assumption that median conditions at the loop detectors represented an extended time and distance, and of course (iii) the fact that the AVL system was not deployed with the intention of monitoring the evolution of traffic conditions.

Creating transit-based summary plots of traffic conditions

Through proper aggregation, the loop detector data can yield a comprehensive picture of the traffic state evolution along the freeway. Figure 7A shows the matrix of 5 min median loop detector speeds along the northbound I71 corridor on one day (May 1, 2003). In this time-space plane the lighter the color in a cell the higher the speed, with the exception that white denotes no data. So each row of this plot contains the time-series speed at the given station, while the barely noticeable change in "height" from one row to the next reflects the segment length as defined above. A queue arising from an incident starts around 14.5 hrs at 9.6 km, grows upstream and is ultimately manifest as an obtuse triangle of lower speeds in the time-space plane.

Next the AVL data are summarized over the same region of the time-space plane, as follows. First all of the observed transit links are projected into the plane assuming the vehicle traveled at a constant speed for a given link, i.e., the average link speed (recall that each transit trip consists of multiple links, bounded by the AVL data points). Since the transit links are dynamic while the loop detector boundaries are fixed, to facilitate comparison between the two data sources and aggregation of the transit data, the plane of transit data is then discretized using the same cell boundaries from the loop detector matrix, i.e., the segment boundaries and five-minute sample period. All transit links passing through a given cell are found and the average speed across these transit links is assigned to the cell, or the cell is left blank if no transit links passed through it. Two details of the process are worth elaboration, first, since most of the transit links span multiple cells, we include a given link speed in the speed distribution for each of the cells spanned by the link. Second, since most transit trips include multiple links, when an endpoint between two links falls in a cell, we include the speeds from both links in the cell's speed distribution. Figure 7B shows the resulting transit-based speed matrix corresponding to Figure 7A, and Figure 7C shows the absolute difference between the two. While the impact of the incident queue is evident in Figure 7B and one can even identify the bottleneck location, with only about 100 transit trips through the corridor per day, the transit-based observations are infrequent enough that the time to detection is large.

With so few observations per day, the transit-based data have limited value to real time traffic management. But even with the infrequent trips, aggregating the data over longer periods can reveal the recurring conditions and be used to calculate "typical" speeds or travel times. Figure 8 repeats the above exercise using all weekdays over the entire month of May 2003, separately in each direction. Figure 8A&D show the monthly median speed across the daily loop detector matrix for each cell and Figure 8B&E show the monthly median across the non-blank cells of the daily average transit link speed matrices. In other words, the value of a given cell comes from the median of the corresponding cell in all of the daily matrices, e.g., Figure 7A-B. If a 5 min long cell has only one non-blank day in the transit matrices, that cell is suppressed in Figure 8 to reduce the impact of non-recurring events. The time-space plane of Figure 8B&E is much more densely populated with transit data compared to the typical single day in Figure 7B. For the southbound data, both loop detector and transit-based plots clearly show the morning and evening queues extending several kilometers upstream from the CBD and the I70 interchange. Figure 8C&F show the absolute difference between the transit and loop detector data. Some of the difference between the two matrices is simply due to the fact that the transit-based data come from a subset of the days used to generate the loop detector matrix. Figure 9 shows the CDF of the difference between loop detector and transit-based speeds from Figure 8C&F. The distribution exhibits a bias because the majority of vehicles passing the loop detectors are passenger vehicles and they travel a little faster than the buses. Even with this bias, over 95% of the transit-based observations are within 16 km/h of the loop detector observations.

<u>Extending monthly summary plots to a non-instrumented freeway</u>

Next, this study examined the four non-instrumented freeway corridors in Columbus: SR315 (including I71 south of the CBD), I70, I270, I670, as shown in Figure 1A. The centerline coordinates are used in each corridor to identify AVL data points along the given freeway and as before, any ambiguous endpoints at interchanges are excluded. Because some buses dwell on overpasses away from interchanges, and report many successive points that are off of the freeway but within the right-of-way, one additional filtering constraint is employed, namely that any valid trip has to travel further along the freeway than it does across the freeway. While the time-space plane was segmented by the detector locations on I71, the non-instrumented freeways are simply segmented every 1.6 km. First, for reference, Figure 10A shows the total number of AVL data points reported per 1.6 km segment on I71, both directions, from each of nine successive days (including two weekend days). The curve for each day is shown with a thin line, the seven weekdays are clustered together above the two weekend days. The median across the nine days is shown with a thick line and falls in the cluster of weekday data. The remainder of Figure 10 repeats this tabulation for each of the four non-instrumented freeways. The instrumented portion of I71 has the most data points per km, I70 and I670 have sections that approach the number of data points seen on I71, and I270 and SR315 peak at about a quarter of the number seen on I71.

While the following analysis was repeated on all four non-instrumented freeway corridors, only I70 is shown here because it had a higher density of observations and the heaviest recurring congestion in the observed portion. Looking closer at the data, Figure 11 tabulates the frequency of link observations over the time-space plane by hour and segment for the average weekday in the month of May 2003 for I71 and I70. Both freeways have a large stretch with an average of at least one observation every 30 min for most of the day.

Following the same process used to generate Figure 8B&E, Figure 12 shows the directional summary of weekday median link speed from transit vehicles on I70 for May 2003. Recurring congestion is evident in the morning and evening peaks in both directions, extending upstream from the CBD (20-25 km). In fact 21-25 km on I70 in Figure 12 is coincident with 0-4 km in Figure 8, where I70 east/west shares the right-of-way with I71 north/south. The queues evident in the bottom of Figure 8A during the two peak periods can be seen extending upstream of the CBD in Figure 12A. A recurring evening queue is also evident at the top of Figure 12A, at the interchange with I270.

CONCLUSIONS

Many conventional traffic management systems are limited in coverage due to the high cost to deploy the fixed detection infrastructure. Often times AVL data from vehicle fleets are available from roadways that are not instrumented, providing traffic conditions that would otherwise be difficult to collect. In short, AVL systems already deployed on vehicle fleets promise an inexpensive means to extend traffic monitoring to new roadways that may not otherwise be observed. To this end, this paper developed a methodology to monitor freeway traffic conditions from transit vehicle AVL with infrequently reported data. It used a rudimentary travel time estimation algorithm to estimate measures from loop detector data and validate the transit measurements. The scatter plots in Figures 4-6 show that the trip-based travel speeds from transit data are generally consistent with the concurrent estimates from loop detector data. Several errors were found in both data sets and filters were developed to reduce their impact. Figure 7 shows that the link-based speeds capture the general trend of the traffic state over the time-space plane, but the small number of transit trips in a day yield a large time to detection. On the other hand, aggregating over longer periods, Figures 8-9 show that the transit data capture the recurring conditions over the month. Although the non-recurring events have a long time to detection, they are evident in the daily plots, e.g., by taking the difference between Figures 7B and 8B. With a higher frequency of observations -- e.g., from other fleet AVL systems, cell phone tracking, or Vehicle-Infrastructure Integration (VII) probe data -- the methodology should also be effective for rapidly identifying non-recurring congestion. Although the transit-based speed matrices are not as dense as those from the loop detectors, the transit data offer an opportunity to collect valuable information on non-instrumented corridors that would otherwise go unobserved. To this end, the methodology was extended to the non-instrumented freeways in Columbus, one of which is presented in Figure 12. The queuing seen on I70 is consistent with the loop detector data from the section where I70 shares the right-of-way with I71.

This methodology can be used for a wide range of applications, including direct traffic monitoring for control and planning applications, prioritizing which corridors would benefit most from deploying fixed detector infrastructure, and as illustrated in this study, even extracting the traffic conditions long after the AVL data were recorded for other purposes. While the results on freeways are encouraging, more research is needed on arterials to differentiate between increased travel time due to general traffic delay and increased travel time due to transit operations, e.g., bus stops and time points.

REFERENCES

[1] J. Moore, II, S. Cho, A. Basu, D. Mezger (2001). "Use of Los Angeles Freeway Service Patrol Vehicles as Probe Vehicles," *California PATH Res. Program*, Berkeley, CA, Rep. UCB-ITS-PRR-2001-5.

[2] R. Bertini and S. Tantiyanugulchai (2004). "Transit Buses as Traffic Probes: Use of Geolocation Data for Empirical Evaluation," *Transportation Research Record 1870*, TRB, pp 35-45.

[3] R. Bertini, M. Leal, D. Lovell (2002). "Generating Performance Measures for Portland's Archived Advanced Traffic Management System Data," *Proc. of the 81st Transportation Research Board Meeting*.

[4] F. Cathey, D. Dailey. (2002). "Transit Vehicles as Traffic Probe Sensors," *Transportation Research Record 1804*, TRB, pp 23-30.

[5] F. Cathey, D. Dailey. (2003). "Estimating Corridor Travel Time by Using Transit Vehicles as Probes," *Transportation Research Record 1855*, TRB, pp 60-65.

[6] COTA (2005). "Central Ohio Transit Authority," http://www.cota.com/cota/cotaweb/main.xml, accessed on December 15, 2005.

FIGURES

Figure 1, (A) Map of the study area showing the freeways superimposed on a week of transit AVL data, (B) a sample points from a southbound trip on I71, adjacent points just before and just after shown with triangles, (C) regions along I71 with uncertainty and errors due to interchanges and other road crossings.

Figure 2, (A) Sample of the road network, I-71 sweeps an S-curve from top to bottom, (B) reported AVL data on one day, (C) coarse bounding region around I-71 to select candidate points (darker) from off freeway points (lighter), (D) further narrowing the candidate points using distance to the center line, (E) "H" shaped region of ambiguity at an interchange, (F) selected ambiguous points (darker) and those deemed to definitely be on the freeway (lighter).

Figure 3, Time series of the average speed for each transit trip from southbound I71 on Monday, May 5, 2003.

Figure 4, Using one month of data, measured transit trip average speed versus estimated loop detector average speed for the same trip (A) before filtering, (B) the same data after filtering.

Figure 5, The travel times corresponding to the trips shown in Figure 4, (A) before filtering, (B) the same data after filtering.

Figure 6, CDF of the differences between estimated loop detector speed and measured transit average speeds for the trips in Figure 4.

Figure 7, (A) Matrix of 5 min median loop detector speeds along the northbound I71 corridor on one day, (B) corresponding transit-based average link speed matrix, (C) absolute difference between A and B.

Figure 8, (A&D) Matrix of 5 min median loop detector speeds along the I71 corridor over one month, (B&E) corresponding transit-based average link speed matrix, (C&F) absolute difference between directional loop detector and transit speeds, (A-C) northbound, (D-F) southbound.

Figure 9, CDF of the differences between loop detector speed and transit speed for the data in Figure 8.

Figure 10, Number of AVL points per km per day for nine days and the median across days along, (A) I71, (B) I70, (C) I670, (D) SR315, including the southern portion of I71, (E) I270. Interchanges are shown vertically, and for freeway corridors that change names, the different names are shown horizontally.

Figure 11, Median number of daily AVL points per 5 min per segment (detector spacing on I71 and 1.6 km on I70) for the month along, (A) I71 northbound, (B) I71 southbound, (C) I70 eastbound, (D) I70 westbound.

Figure 12, Matrix of 5 min monthly median of daily transit-based average link speed along the I70 corridor over one month, (A) eastbound, (B) westbound.

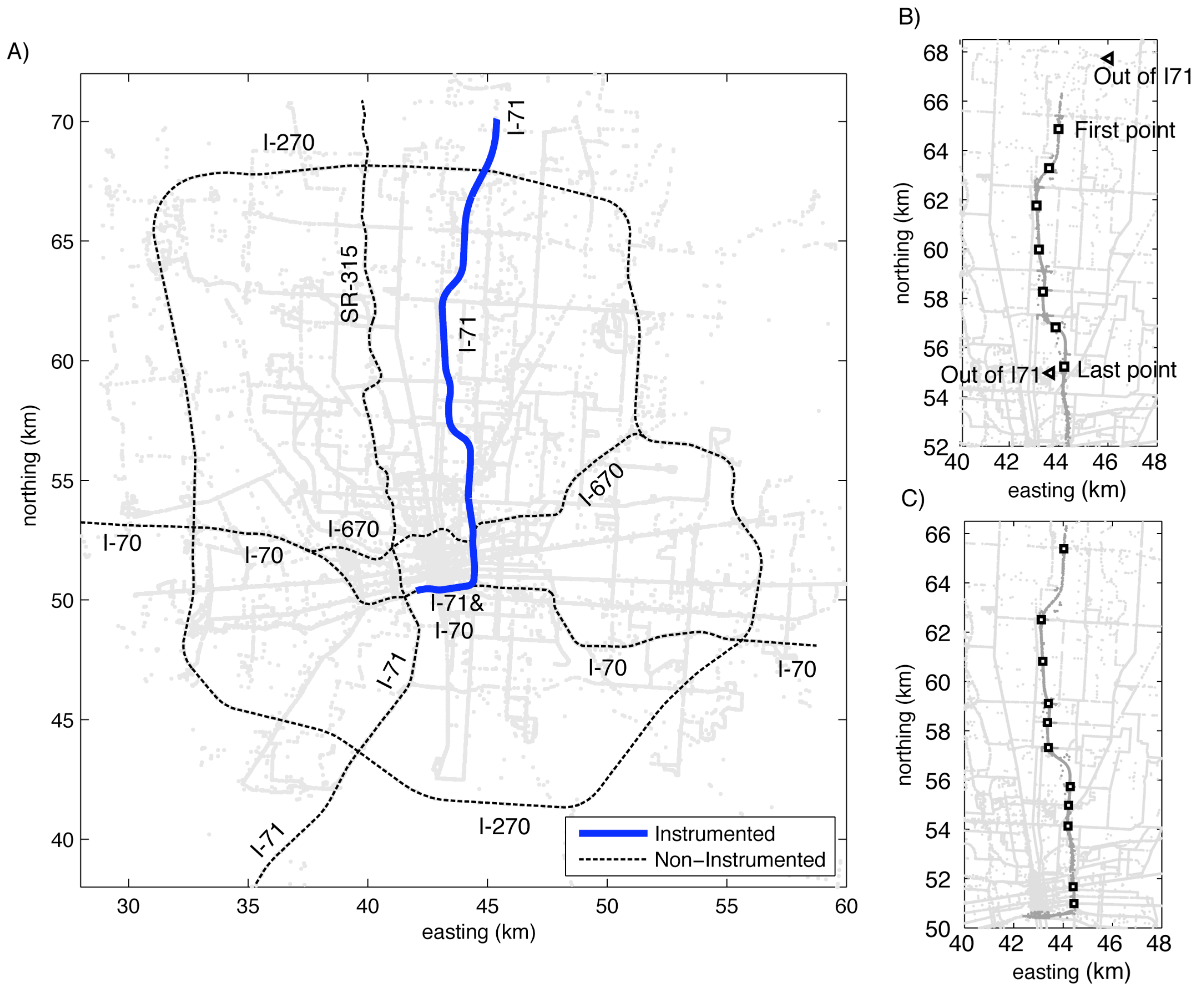

Figure 1, (A) Map of the study area showing the freeways superimposed on a week of transit AVL data, (B) a sample points from a southbound trip on I71, adjacent points just before and just after shown with triangles, (C) regions along I71 with uncertainty and errors due to interchanges and other road crossings.

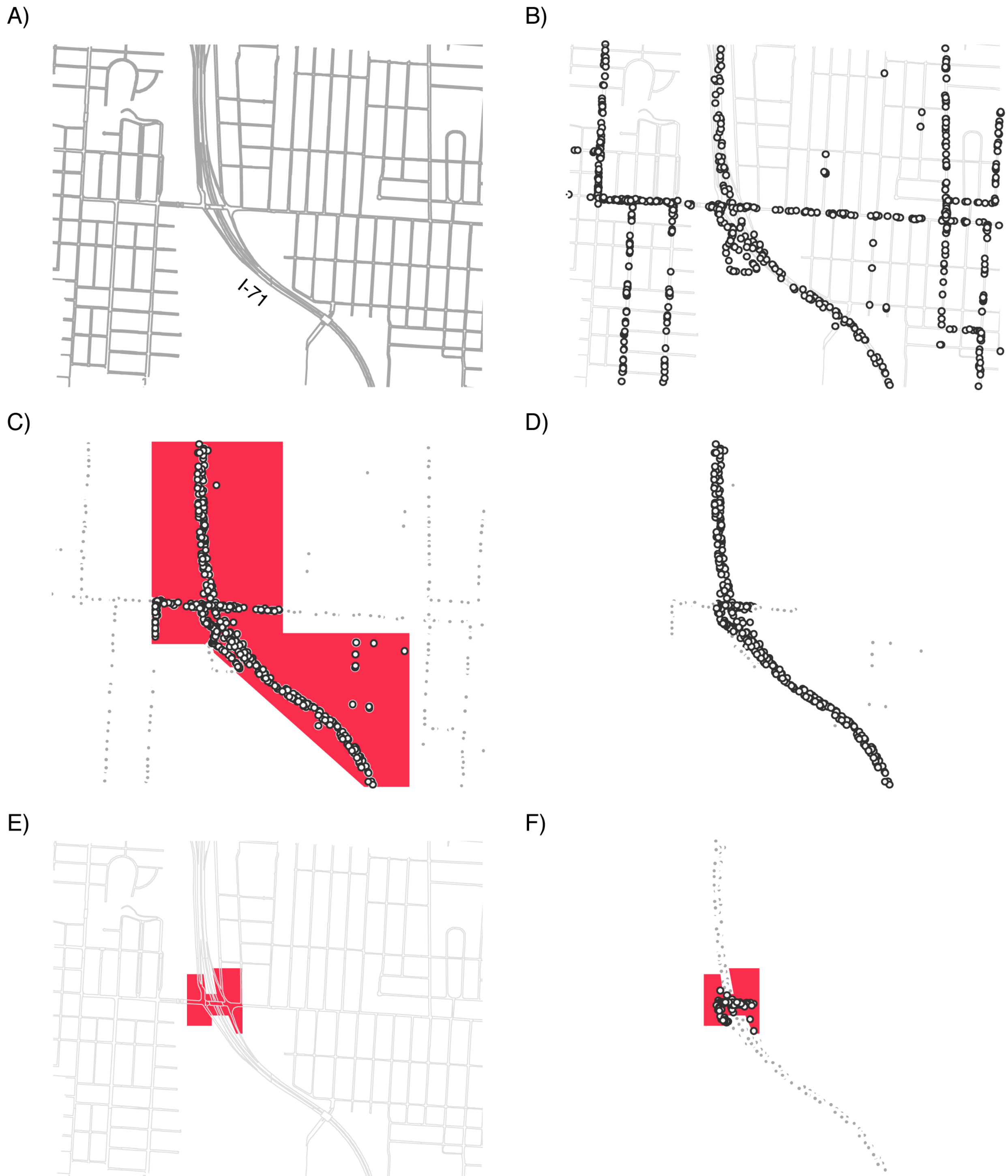

Figure 2, (A) Sample of the road network, I-71 sweeps an S-curve from top to bottom, (B) reported AVL data on one day, (C) coarse bounding region around I-71 to select candidate points (darker) from off freeway points (lighter), (D) further narrowing the candidate points using distance to the center line, (E) "H" shaped region of ambiguity at an interchange, (F) selected ambiguous points (darker) and those deemed to definitely be on the freeway (lighter).

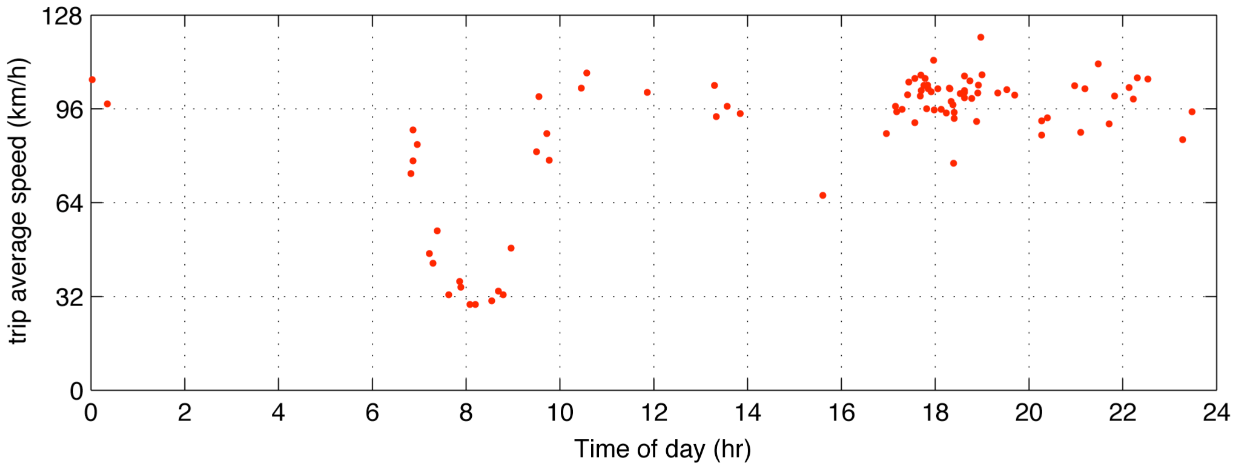

Figure 3, Time series of the average speed for each transit trip from southbound I71 on Monday, May 5, 2003.

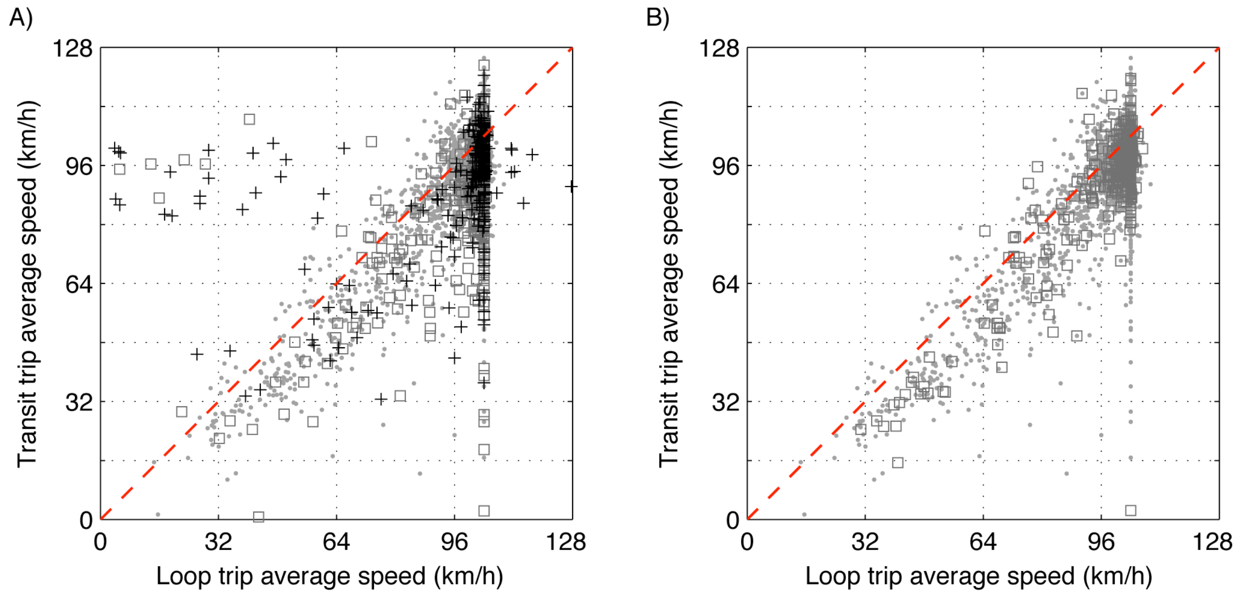

Figure 4, Using one month of data, measured transit trip average speed versus estimated loop detector average speed for the same trip (A) before filtering, (B) the same data after filtering.

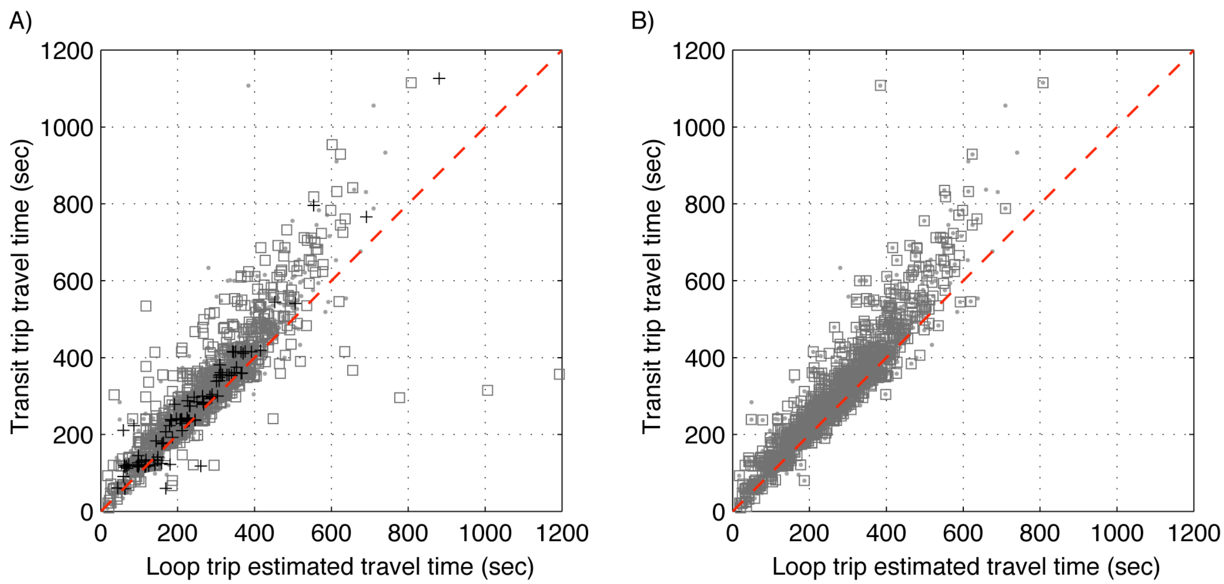

Figure 5, The travel times corresponding to the trips shown in Figure 4, (A) before filtering, (B) the same data after filtering.

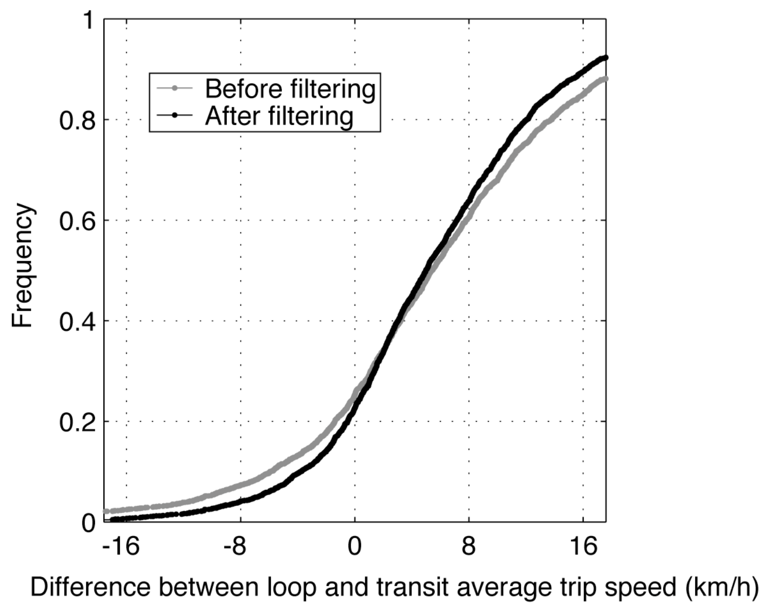

Figure 6, CDF of the differences between estimated loop detector speed and measured transit average speeds for the trips in Figure 4.

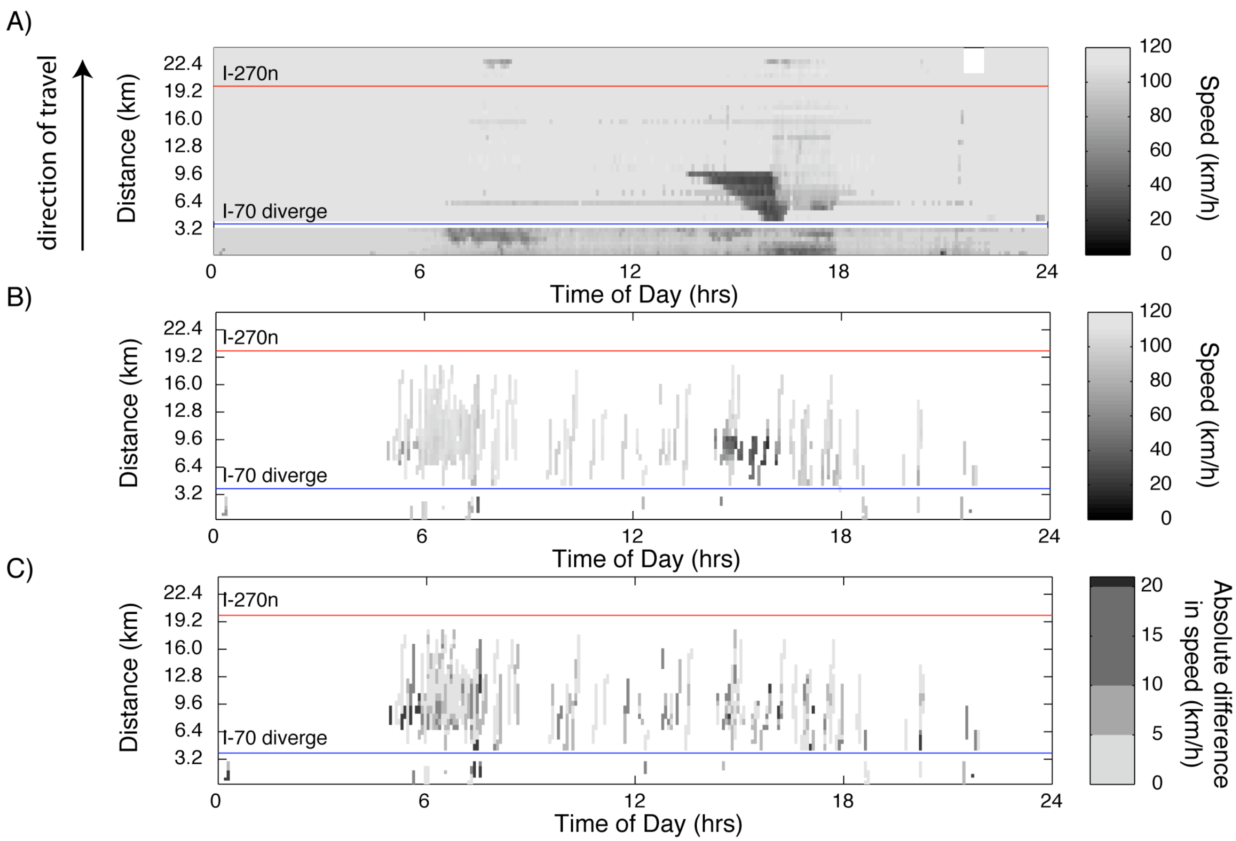

Figure 7, (A) Matrix of 5 min median loop detector speeds along the northbound I71 corridor on one day, (B) corresponding transit-based average link speed matrix, (C) absolute difference between A and B.

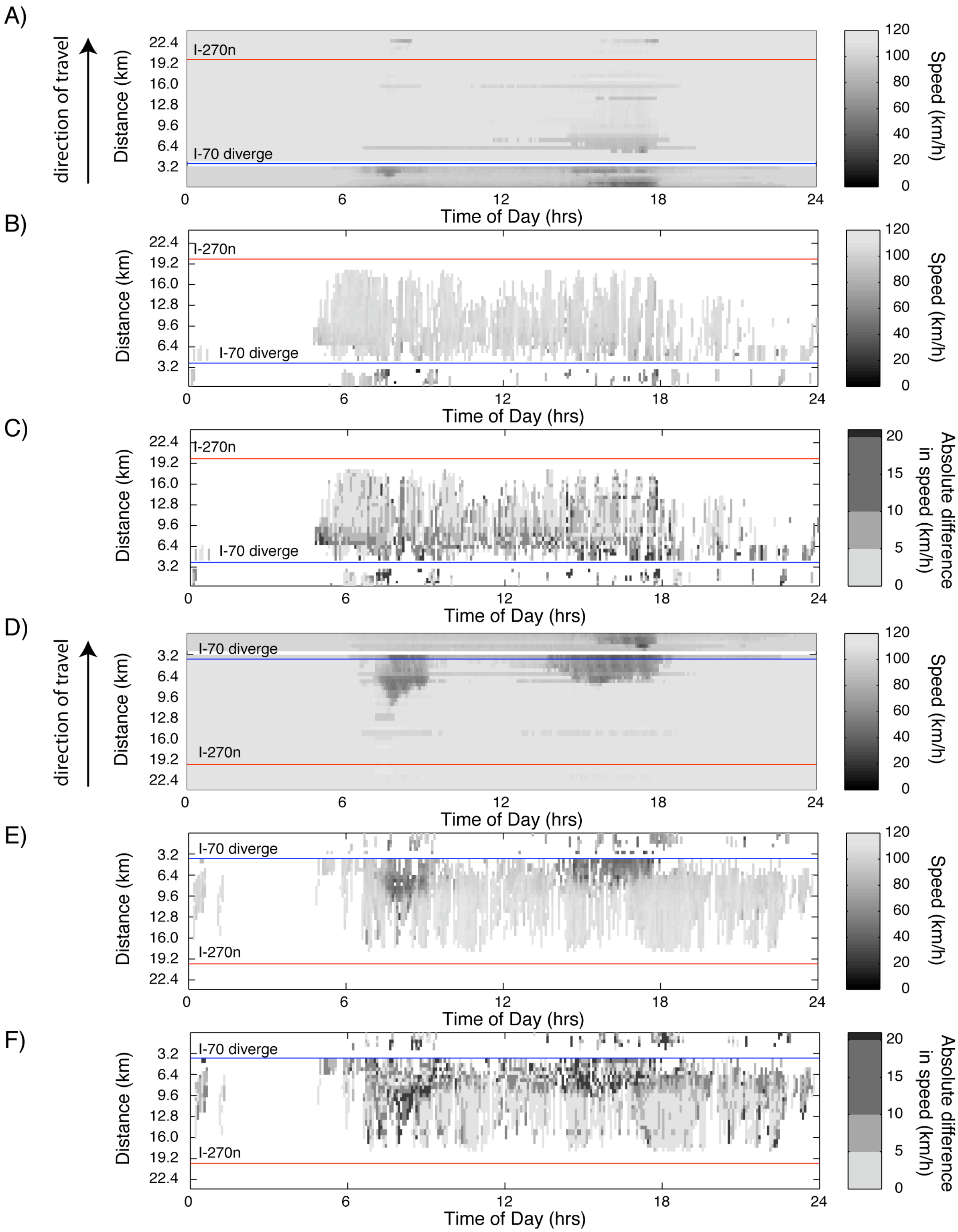

Figure 8, (A&D) Matrix of 5 min median loop detector speeds along the I71 corridor over one month, (B&E) corresponding transit-based average link speed matrix, (C&F) absolute difference between directional loop detector and transit speeds, (A-C) northbound, (D-F) southbound.

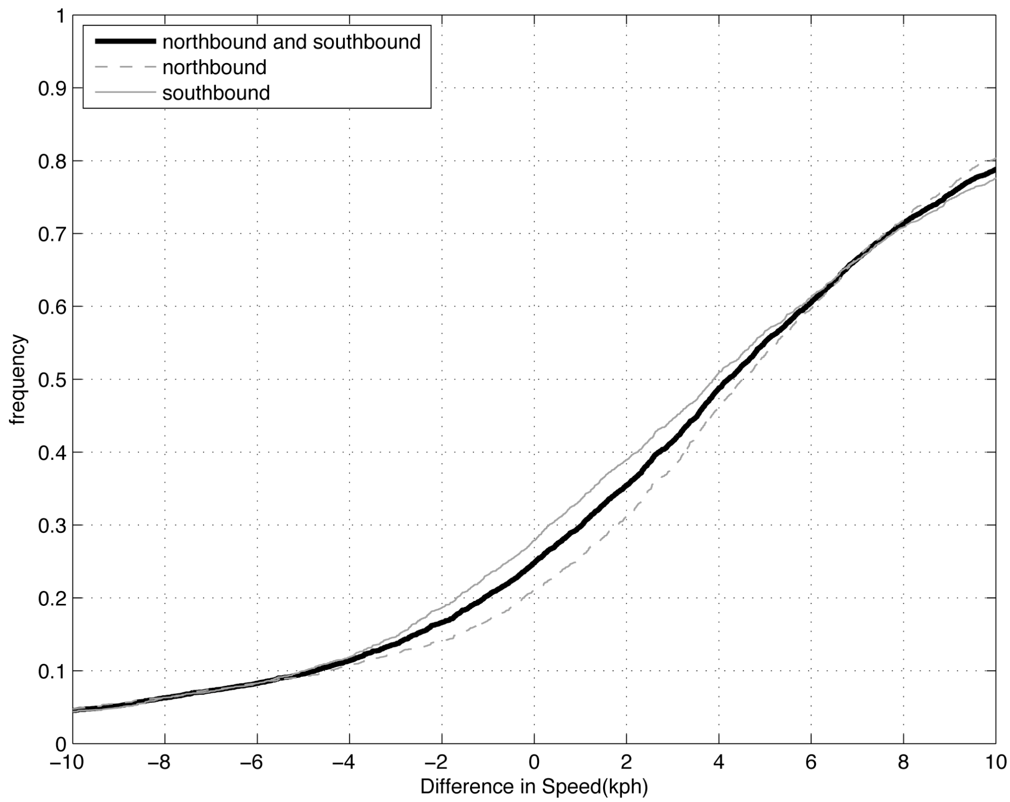

Figure 9, CDF of the differences between loop detector speed and transit speed for the data in Figure 8.

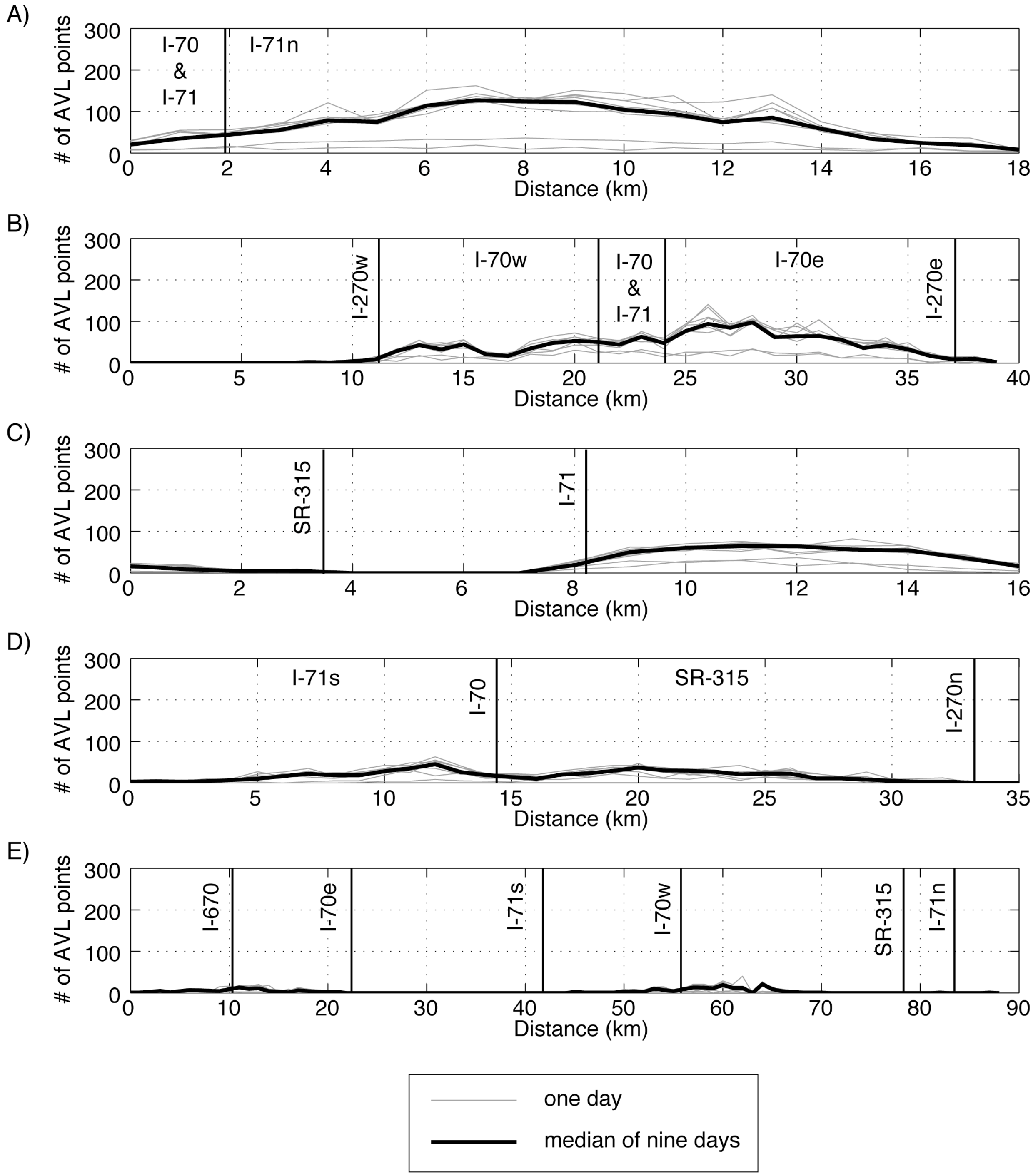

Figure 10, Number of AVL points per km per day for nine days and the median across days along, (A) I71, (B) I70, (C) I670, (D) SR315, including the southern portion of I71, (E) I270. Interchanges are shown vertically, and for freeway corridors that change names, the different names are shown horizontally.

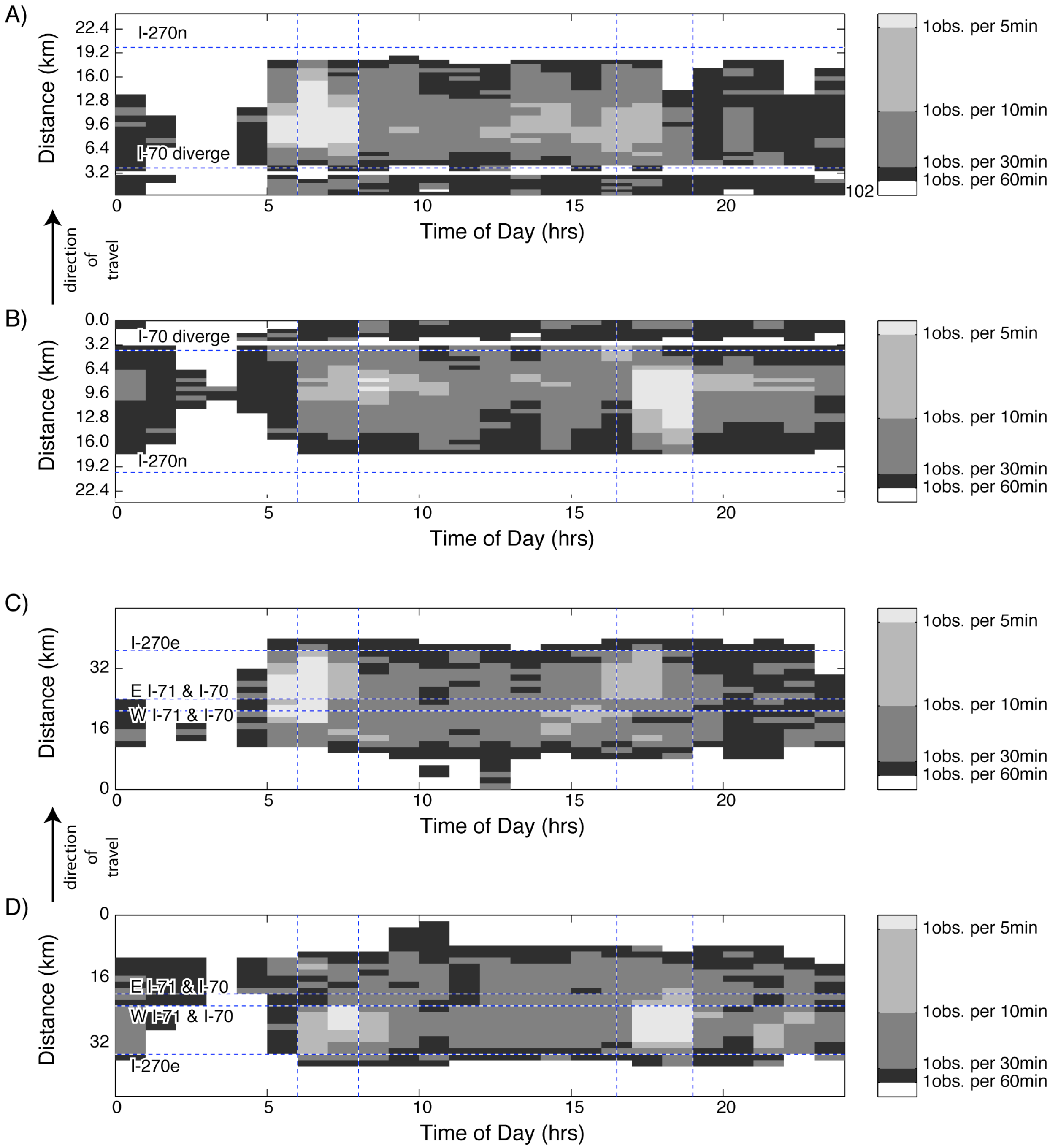

Figure 11, Median number of daily AVL points per 5 min per segment (detector spacing on I71 and 1.6 km on I70) for the month along, (A) I71 northbound, (B) I71 southbound, (C) I70 eastbound, (D) I70 westbound.

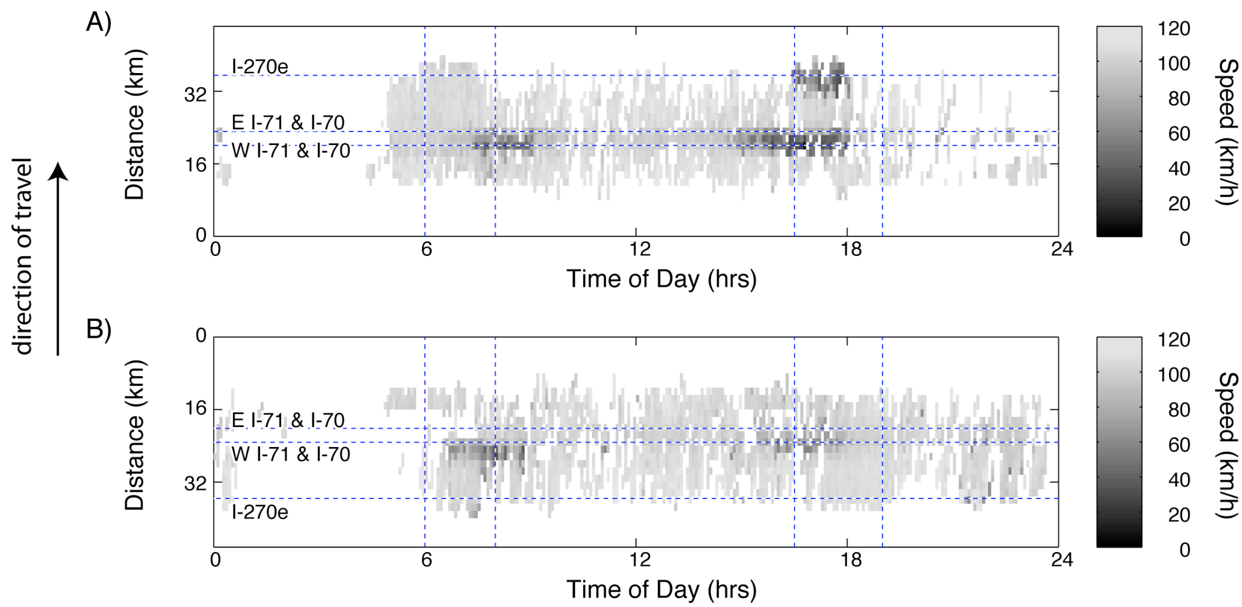

Figure 12, Matrix of 5 min monthly median of daily transit-based average link speed along the I70 corridor over one month, (A) eastbound, (B) westbound.