Mining vehicle classifications from the Columbus Metropolitan Freeway Management System

Prepared by:
Benjamin Coifman, Bo Huang, Keith Redmill, Mo Wu

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16. Abstract

Vehicle classification data are used in many transportation applications, including: pavement design, environmental impact studies, traffic control, and traffic safety. Ohio has over 200 permanent count stations, supplemented by many more short-term count locations. Due to the high costs involved, the density of monitoring stations is still very low given the lane miles that are covered. This study leveraged the deployed detectors in the Columbus Metropolitan Freeway Management System (CMFMS) to collect and analyze classification data from critical freeways where the Traffic Monitoring Section has not been able to collect much classification data in the past due to site limitations. The CMFMS was deployed in an unconventional manner because it included an extensive fiber optic network, frontloading most of the communications costs, and rather than aggregating the data in the field, the detector stations sent all of the individual per-vehicle actuations (i.e., PVR data) to the traffic management center (TMC). The PVR data include the turn-on and turn-off time for every actuation at each detector at the given station. Our group has collected and archived all of the PVR data from the CMFMS for roughly a decade. The PVR data allows us to reprocess the original actuations retroactively. As described in this report, the research undertook extensive diagnostics and cleaning to extract the vehicle classification data from detectors originally deployed for traffic operations.

The work yielded length based vehicle classification data from roughly 40 bi-directional miles of urban freeways in Columbus, Ohio over a continuous monitoring period of up to 10 years. The facilities span I-70, I-71, I-270, I-670, and SR-315, including the heavily congested inner-belt. Prior to this study, these facilities previously had either gone completely unmonitored or were only subject to infrequent, short-term counts.

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Prepared by:

Benjamin Coifman,[a,b,c] Bo Huang,[b] Keith Redmill,[b] Mo Wu[b]

The Ohio State University

a: The Department of Civil, Environmental, and Geodetic Engineering
b: The Department of Electrical and Computer Engineering

c: Hitchcock Hall 470
2070 Neil Ave, Columbus, OH 43210
Phone: (614) 292-4282
E-mail: Coifman.1@OSU.edu

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1 Introduction

Roadway usage, particularly by large vehicles, is one of the fundamental factors determining the lifespan of highway infrastructure. To forecast infrastructure health, state departments of transportation typically employ expensive vehicle classification stations to monitor vehicle usage, e.g., as evidenced by the federally mandated Highway Performance Monitoring System (HPMS). Vehicle classification data are used in many transportation applications, including: pavement design, environmental impact studies, traffic control, and traffic safety [1]. Each state typically has several dozen Weigh in Motion (WIM) stations, supplemented with many more vehicle classification stations. Some of the classification stations employ axle counters, but the least expensive of these stations use dual loop detectors to measure vehicle length and classify vehicles based on this measurement (e.g., the state of Ohio currently has over 200 permanent count stations, roughly half of which provide WIM or axle based classification, one quarter provide length based classification from dual loop detectors and one quarter only provide volume data from single loop detectors). These permanent classification and count stations are supplemented by many more short-term count locations (typically each is sampled for 48 hr, once per multi-year cycle). Needless to say, due to the high costs involved, the density of monitoring stations is still very low given the lane miles that are covered. As discussed below, this study sought to leverage the deployed detectors in the Columbus Metropolitan Freeway Management System to collect and analyze classification data from critical freeways where the Traffic Monitoring Section has not been able to collect much classification data in the past due to site limitations.

1.1 Background

Starting in 2001, the Ohio Department of Transportation (ODOT) deployed almost 70 loop detector stations in the Columbus Metropolitan Freeway Management System (CMFMS) over two phases [2]. The CMFMS covers most of the freeways inside the I-270 beltway (Figure 1). Roughly half of the stations are equipped with dual loop detectors while the remainder has single loop detectors. Conventional single loop detectors can count vehicle passages and measure the amount of time a vehicle is over the detector (the on-time), but because the vehicle length is unknown, they can only estimate vehicle speed. With two loops per lane, in addition to the single loop metrics, dual loop detectors can measure speed from the quotient of the known distance between the loops and the difference in arrival times; as well as length from the product of speed and on-time. Schematics for the 46 stations deployed in Phase I can be found in [2], while the coordinates, mile marker and lane mapping for the 23 Phase II stations were compiled by ODOT traffic operations in an unpublished spreadsheet.

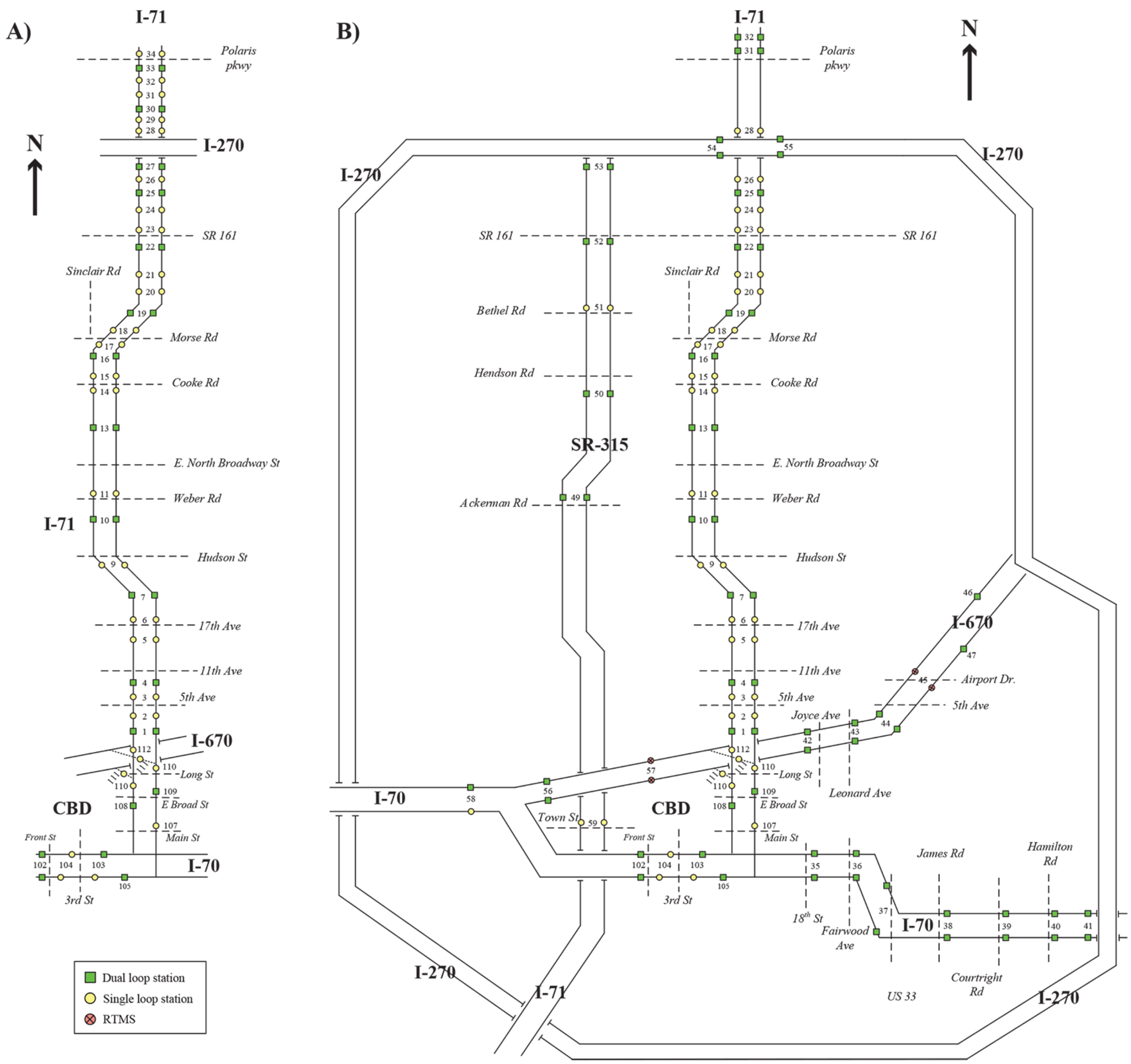


Figure 1 Approximate location of the CMFMS loop detector stations (A) Phase I, before February 2007, and (B) Phase I and II after February 2007.

The CMFMS was deployed in an unconventional manner because it included an extensive fiber optic network, frontloading most of the communications costs, and rather than aggregating the data in the field, the detector stations sent all of the individual per-vehicle actuations (i.e., PVR data) to the traffic management center (TMC). The PVR data include the turn-on and turn-off time for every actuation at each detector at the given station. Our group has collected and archived all of the PVR data from the CMFMS, and we now have roughly a decade of PVR data in our archives. The PVR data allows us to reprocess the original actuations. So rather than reporting aggregated speed, flow and occupancy (as was the original intent of the CMFMS deployment), we can quickly update our analysis at all stations without any field visit and with the data archive, do so retroactively. Our work over the last decade has shown that the collected PVR data contain a lot more information beyond conventional aggregate speed, flow, and occupancy. We have developed numerous tools to identify and correct detection errors using the PVR data, including tools to catch cross-talk errors [3], diagnose suspect detectors [4], automatically identify lane mapping errors in the configuration file or cabinet wiring [5], use the sensor data to correct for sensitivity setting errors and dual loop spacing errors [6], catch splashover errors [7], as well as catch and correct pulse breakup errors [8]. In most cases we can also correct for these problems in post-processing. Thereby allowing us to extract data with accuracy comparable to the length based classification stations deployed by the Traffic Monitoring Section (see, e.g., Chapter 6 in [9]). With all of this cleaning, we can measure individual vehicle lengths from dual loop detectors and classify vehicles based on these lengths with high accuracy. Furthermore, we have developed tools to estimate individual vehicle speeds and lengths from conventional single loop detectors with an accuracy that approaches the performance of measured speed and length from conventional dual loop detectors [9-15].

1.2 Objectives and Goals of the Study

Urban freeway traffic counts and classifications are inherently difficult to collect and typically most cities in the US have few classification stations even though AADT can change dramatically over a short distance, e.g., depending on which side of an interchange the station is located. The situation is exasperated by the fact that high volumes of urban freeway traffic preclude the use of pneumatic tubes or most other temporary detector deployments. Columbus is a typical city in this regard: the ODOT Traffic Monitoring Section has not collected much classification data on the Columbus freeways in the past due to the challenging site limitations. Although the ODOT Traffic Monitoring Section has only a few classification stations over the Columbus freeways, the CMFMS loop detectors are numerous. Unfortunately the CMFMS detectors were deployed for real time speed measurement, without concern about accuracy of counting, so the Traffic Monitoring Section has not used these loop detectors for counts or classification. As discussed above, Columbus is unique because the CMFMS was deployed in an unconventional manner that allows this research project to reprocess the data to extract individual vehicle lengths.

This work sought to leverage the existing real-time traffic monitoring infrastructure of the CMFMS to collect length based, vehicle classification data. The individual vehicle actuation data were collected from the 69 detector stations in the CMFMS, sampled at 240 Hz [2]. The approximate locations of the stations are shown in Figure 1 and include 330 loop detectors on the northbound/eastbound freeway mainline lanes and 328 loop detectors on the southbound/westbound freeway mainline lanes. In detail, the 46 detector stations on I-70/I-71 were installed during the first phase of the CMFMS, completed in 2001. These stations include 196 loop detectors on the northbound/eastbound freeway mainline lanes and 194 loop detectors on the southbound/westbound freeway mainline lanes. Another 23 detector stations were installed on SR-315 / I-270 / I-70 / I-670 during the second phase of the CMFMS, completed in 2006. These stations include 134 loop detectors on each of direction freeway mainline lanes. Roughly 90% of the Phase II detector stations have dual loop detectors, while only 35% of the Phase I detector stations have dual loop detectors. For most of the Phase I corridor there is one dual loop detector station every mile, with two single loop detector stations between dual loop stations.

The primary thrust of this work was extracting classification data for the previous ten years from the archived PVR data. While length based classification from dual loop detectors is common (see, e.g., [1]), it relies in finely tuned detectors. The focus of this task was on the details of extracting the classifications, establishing and implementing the desired level of confidence, developing approaches to handle data outages, establishing links with multiple stations and fusing data from those stations, developing tools to aggregate and report the data in the format(s) desired by ODOT, and several other related implementation tasks. The CMFMS detectors are not finely tuned, but we have developed tools using the PVR data to identify problems and in most cases correct for them. Our PVR work is also the first to push accurate length based vehicle classification to conventional single loop detectors. Since most researchers use aggregate data, the literature on PVR analysis is scant. Beyond our group's publications cited above, the only other significant publications have been from a research group at the University of Washington. They have examined a subset of the problems addressed by our group, e.g., [16-17]. There have also been a couple of classification evaluations that used PVR records from a few hundred vehicles for evaluation, e.g., [18-19].

The second thrust of this work sought to develop an on-going process collect these data into the future. The real-time aspect of the CMFMS was decommissioned in 2011 with the statewide move to vendor collected traffic speed and travel time data for real-time operations. Many of the CMFMS loop detector stations, however, remained functional and with the advances from the first thrust, it was hoped that a portion of the CMFMS could be reactivated to continue classifying vehicles. As discussed herein, although preliminary work was positive, unfortunately we were not able to realize this second thrust due to restricted access to the necessary ODOT communication links, several resurfacing projects that disrupted the loops, and the unanticipated need for frequent visits to the roadside controller cabinets.

The specific objectives as proposed were:

1) Work with ODOT and MORPC to establish the sampling criteria, e.g., minimum acceptable level of confidence, segment length versus number of stations per segment, minimum number of days with complete data coverage, how to address periods without data, etc.

2) Pre-filter our CMFMS database of past PVR data using the criteria from (1) and our existing diagnostic tools (i.e., [3-8] discussed in the Background section, above) to find the days when a given station provides sufficient data availability and quality. Report any minor faults that could be easily corrected (e.g., the detector sensitivity setting).

3) Develop tools to exploit the redundancy of multiple detector stations within a link for vehicle classification and efficient strategies to resolve discrepancies if two (or more) such stations disagree.

4) Work with ODOT and MORPC to establish reporting format(s), final set of links subject to (1), and identify any short term or long term counts or classifications along the freeways and dates covered by the CMFMS that could be used for validation (e.g., the former classification station at Miller-Kelton on I-70).

5) Extract length-based classification on the links from (4) for the entire period of available data from (2), and compare the results against the concurrent counts from (4).

6) Assess the status of the current CMFMS server for ongoing data collection, replace if necessary, and work with ODOT to establish the location of the server.

7) Extend the work from (2) and (5) to automatically run on any subsequently collected data from the CMFMS. Monitor the performance over time. Work with ODOT and MORPC to ensure the on-going monitoring is best suited for their needs, e.g., scheduling the data extraction- daily, monthly, or annually.

8) Since we do not know which stations will still be operational five or ten years in the future, we will collect data from as many stations as possible and develop a strategy to gracefully accommodate detector failure and detector station failure as the CMFMS ages.

9) Evaluate the performance of the on-going monitoring system against ground truth classifications from video and/or LIDAR.

10) Quarterly reports and final report

1.3 Overview

The remainder of this report goes into the details of the research. Sections 2-4 discuss low level processing necessary to extract the vehicle level data, starting with Detector Mapping at the given stations, proceeding through Raw Data Extraction from the archived data, and finishing with Pulse Matching at Dual Loop Detectors. All of these sections include extensive work to find and address detection errors at the various levels. Section 5 presents the process of Selection of Links and Representative Stations. Section 6 explains the details of our Vehicle Length Calculation and Length-based Classification. Section 7 discusses our Investigation of Continued Real-Time Operations. Finally, Section 8 presents the Closing and Discussion.

2 Detector Mapping

Figure 1 shows the approximate location of the CMFMS loop detector stations. Each loop detector station has either one or two physical loops (single or dual loops, respectively) in each lane of the roadway. These loops consist of several turns of wire embedded in the pavement, with lead-in wires that might span several hundred feet to connect to the sensor electronics in the controller cabinet. All of the loops come into the cabinet through a single conduit, often passing through various pull-boxes between the pavement and the cabinet. Needless to say, across all of the loops there are several dozen hand-wired connections between the lanes and the traffic controller. Each loop detector input is assigned a unique ID number between 0 and 31. The controller then uses a configuration file to map these loop IDs from the inputs to specific lanes and locations (e.g., detector 20 might be northbound lane 3 upstream). With all of the manual connections, it is very easy for a pair of wires to be swapped, resulting in one or more loops feeding the wrong input. Since the detector mapping changes from station to station, it is equally easy for a data entry error in the configuration files to result in one or more loops feeding the wrong input. The data archival process completely bypasses the controller processing (storing the detector numbers rather than the detector location) but the data extraction still requires a map from detector ID to specific lane and location.

Any mapping errors need to be found and corrected before the detectors can be used for classification. This work starts with the original configuration specified for Phase I and II. As discussed in this section, some stations had an incorrect mapping for some or all of the detectors. Some of these mapping errors were present from the first operational day of the given station, while others arose later (presumably due to a technician making adjustments in the field). In either case, some of the errors were subsequently caught and corrected by ODOT while the stations were operational, while others persisted to the end of operations. Meanwhile, in many locations the physical alignment of the lanes changed over time, usually due to temporary construction or permanent added capacity. Many of these changes were made to the CMFMS in 2007 when the north end of I-71 (from northern I-270 to Polaris Pkwy) was rebuilt, which affected Stations 27, 29 - 34. Stations 27, 29, 30 and 34 were eliminated while Stations 31 - 33 were rebuilt at new locations with completely different detector mapping relations. In conjunction with this work an extra lane was added to several adjacent stations (Stations 24 - 26 southbound and Station 28 northbound). In addition, CMFMS expanded its coverage to I-70, I-670, SR-315 and I-270 with newly added Phase II stations (Station 35-61) later in the year.

As a result of the Phase II revisions this work uses one base configuration from the start of operations to January 31, 2007, and a different base configuration from then onward. In either case, the configuration files are modified to address lane mapping errors, as discussed in Section 2.1. For the most part the detector mapping based on the original configuration files is correct. However, wiring mistakes or maintenance activity, such as reinstallation of loop detectors after pavement rehabilitation, can lead to mapping errors. The remainder of this chapter presents different types of detector mapping errors found in the CMFMS data together with how to detect and then fix them.

2.1 Lane Mapping Errors

Before discussing the lane mapping errors, it is important to note that in the configuration of the CMFMS the lanes are numbered from the inside (left lane) out to the shoulder.

2.1.1 Station 51

Station 51 is one of the few single loop detector stations deployed in Phase II. It is located on SR-315 and throughout its entire operational period it exhibited unusual patterns suggesting that at least one loop detector was inoperable and another lane provided garbled data. Using a technique similar to [5] to group lanes, the adjacent stations on the same freeway were used to identify periods where one direction was congested and the other free flowing. The time series pulse train was plotted for all of the detectors to manually determine which direction a given detector was in (the congested direction being characterized by much longer pulses than the free flow direction). This analysis revealed that the detector assigned to Lane 1 southbound actually came from a northbound lane, no data was reported by the detector assigned to northbound Lane 3, and the unassigned detector with Loop ID: 3 actually came from a southbound lane, as illustrated in Figure 2. Meanwhile, the daily travel volumes remained inconsistent with the adjacent stations.

Next, to verify the directional lane mapping, this work examined the early morning hours at this station as well as the stations immediately upstream and downstream. Borrowing ideas from [20], while passenger vehicles are indistinguishable from one another, the long vehicles are distinct and should be easily recognizable at adjacent stations. If traffic is free flowing, their arrival times will be offset by a free flow travel time. Figure 3A shows the results in lane 2 northbound from the original lane mapping using the individual vehicle lengths at the three stations after shifting vehicle arrivals by free flow travel times. While Figure 3B shows the corresponding results for the exact same time period with the revised lane mapping at station 51. The red circles highlight the fact that many more long vehicles at Station 51 match across the three stations when using the revised lane mapping. The other five lanes were verified in a similar manner. The final lane mapping for Station 51 is shown in Table 1.

The fact that a miss-calibrated single loop detector went undetected by ODOT operations is not surprising. Reportedly after the detector stations came on line the operators found that the estimated speeds from the single loop detector stations were too noisy to be beneficial and they already had sufficient information from the measured speeds from the dual loop detector stations. This finding is not surprising since they were relying on conventional aggregated estimates of speed from the single loop detectors, which indeed are very noisy due to the unknown effective vehicle length in a given sample [11-15]. So the single loop detector stations received little attention.

Table 1 Original and revised lane mapping for Station 51 indicating the Loop ID's, changes in the revision are highlighted with a bold font and shaded background.

	Ln 1 NB	Ln 2 NB	Ln 3 NB	Ln 1 SB	Ln 2 SB	Ln 3 SB
Original Lane Mapping	21	23	15	19	13	17
Revised Lane Mapping	21	**19**	**23**	**3**	13	17

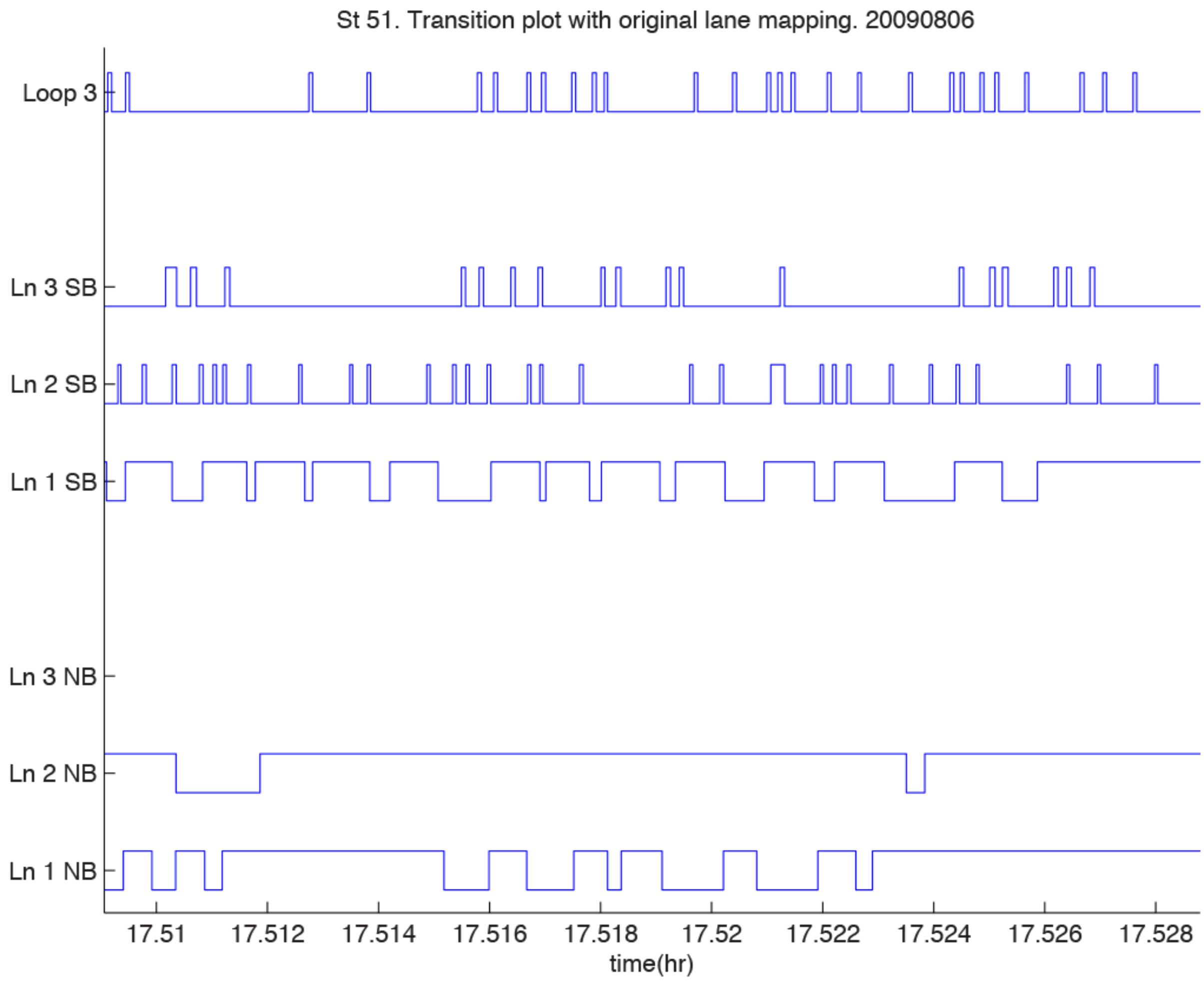


Figure 2 Transition using the original detector mapping for all detectors at Station 51 on August 6, 2009 during a period with congestion in one direction and free flow in the other. This example shows that northbound is congested as expected due to the evening peak hour while southbound is free flowing.

2.1.2 Stations 102 - 105

Previous research identified and diagnosed a lane mapping error at Stations 102 and 105 from August 2003 and Station 104 from October 2003. The lane mapping at Station 102 eastbound was fixed in March 2005 and 105 in October 2004, both by ODOT rewiring the connections. However, the lane mapping error at Station 102 westbound and Station 104 persisted to the end of service without being fixed. [2] These lane mapping errors can also be verified by methods described in Section 2.1.1. Table 2 shows the updated lane mapping revisions for these periods at these stations.

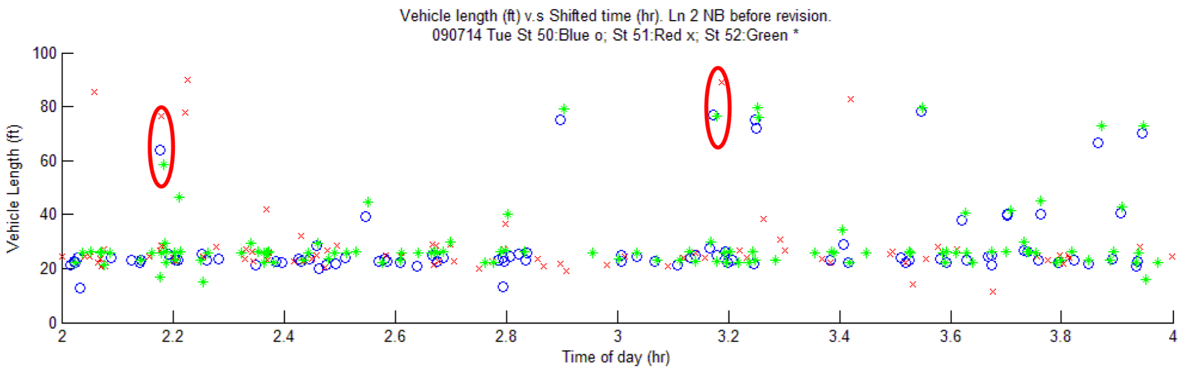
Note that the analysis in this section (Section 2.1) was based strictly on the observed behavior recorded in the data archive and comparisons were made without any ground truth reference. Where successive detector stations show divergent results, there could be three possibilities:

a) The majority has the correct lane mapping and the minority is wrong.

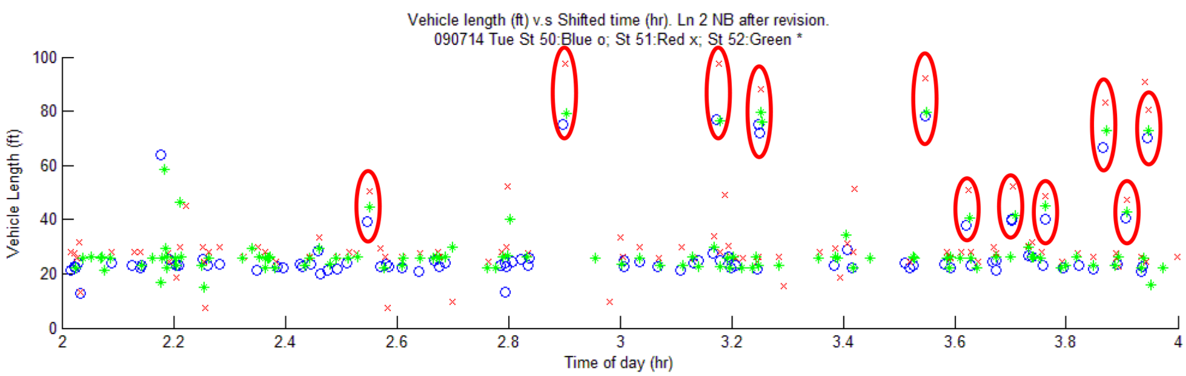
b) The minority has the correct lane mapping and the majority is wrong.

c) All detector stations have wrong lane mapping.

Without further validation, none of the three possibilities can be eliminated. The only certain thing is that something is wrong with lane mapping. Without additional information the current method will follow the majority (option a) for lane mapping correction since it has the highest possibility. However, there is no guarantee that it is correct. As discussed in Appendix B, subsequent work using probe vehicles found that in one occasion it was actually the majority that was incorrect.



(A)



(B)

Figure 3 Time series vehicle lengths at three consecutive stations on SR-315 in lane 2 northbound, early morning on July 14, 2009, (A) with the original lane mapping at Station 51- note that long vehicles at Stations 50 and 52 overlap, and (B) after revising the lane mapping at Station 51 now the long vehicles at Station 51 correspond with the other two stations.

Table 2 Original and revised lane mapping for Stations 102 - 105 during the periods noted in the text; where Ln 2 upst and Ln 2 dnst denote the lane 2 upstream and lane 2 downstream loops, respectively. The cells show the Loop ID's or "-" for no such loop. Station 103 eastbound and 104 only have single loop detectors, which are all shown as upst in this table. Changes in the revision are highlighted with a bold font and shaded background.

		Ln1 upst	Ln1 dnst	Ln2 upst	Ln2 dnst	Ln3 upst	Ln3 dnst	Ln4 upst	Ln4 dnst
St 102 EB	original	13	14	19	20	21	22	-	-
	revised	**14**	**13**	**20**	**19**	21	22	-	-
St 102 WB	original	23	24	15	16	27	28	-	-
	revised	**15**	**16**	**23**	**24**	27	28	-	-
St 103 EB	original	15	-	16	-	17	-	-	-
	revised	15	-	16	-	17	-	-	-
St 103 WB	original	22	21	20	19	14	13	-	-
	revised	22	21	20	19	14	13	-	-
St 104 EB	original	13	-	14	-	19	-	-	-
	revised	**14**	-	**13**	-	19	-	-	-
St 104 WB	original	21	-	22	-	23	-	-	-
	revised	21	-	22	-	23	-	-	-
St 105 EB	original	14	13	20	19	22	21	24	23
	revised	14	13	20	19	22	**23**	**21**	**24**

2.2 Swapped Upstream and Downstream Detectors

To measure speed and length correctly, the paired loops in a dual loop detector must be mapped correctly. Figure 4A shows the time series speed by lane at dual loop detector Station 44 on a typical day using the original lane mapping. The westbound lanes show a reasonable trend: most speeds are around the posted speed limit, with all lanes showing a drop in speeds over approximately the same time period. The eastbound lanes, however, yield speeds that are all over the place, with most below the posted speed limit. This trend of low speeds alone suggests that the detectors in a given lane are reversed since under normal conditions the arrival time gap between vehicles at a certain detector should be larger than the arrival time gap between upstream and downstream loops for a certain vehicle. So the observed trend suggests that the downstream detector pulse from one vehicle is erroneously being matched to the upstream detector pulse from the following vehicle, thus, giving rise to the observed trends in the eastbound lanes. Furthermore, the time of day trends show lower speeds (i.e., larger traversal times) during the early morning, which is consistent with the larger headways due to the lower flow during this time of the day. Testing this hypothesis, Figure 4B shows the time series speeds for the same day at the same detectors after swapping the upstream and downstream detectors in the lane mapping. Indeed, now the eastbound lanes show a reasonable trend while the westbound lanes now exhibit the patterns seen at the eastbound lanes in Figure 4A. As such, the lane mapping for the eastbound lanes at Station 44 was revised accordingly. Fortunately, northbound Station 44 is the only place in the CMFMS where we found such an error.

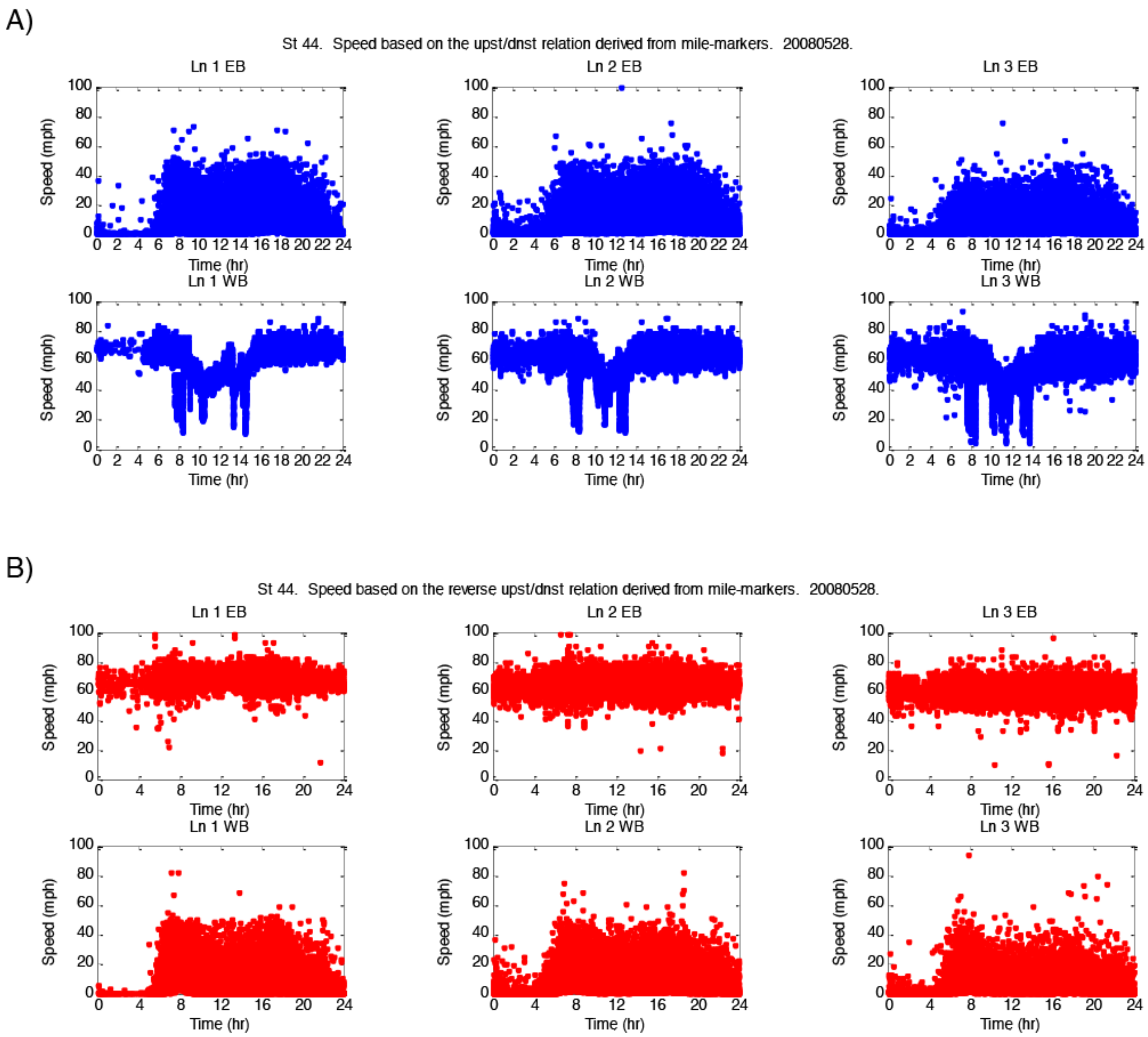


Figure 4 (A) Time series of individual vehicle speeds using the original lane mapping upstream/downstream relationship at Station 44 on May 28, 2008 (blue), and (B) the same data swapping upstream and downstream (red).

2.3 Temporary Lane Shift

There have been several major construction projects on the Columbus freeways over the years of data collection. The rebuilding of a portion of SR-315 employed routing all of the traffic to one side or the other of the freeway. From June 22 to September 25, 2009 the northbound lanes were closed to construction and the northbound traffic was rerouted to the eastern half of the southbound lanes between Goodale Blvd. and Ackerman Rd. The speed limit was reduced from 65 mph to 45 mph. The lane shift impacted Station 49, which was located just north of the construction zone, and south of the lane diversion. Obviously, this lane shift impacted the lane mapping at the station. The detectors remained operational throughout the reconstruction and it is possible to recover speeds and vehicle lengths for some lanes. The effective lane mapping during the northbound construction is shown in Table 3.

Since the temporary realignment made no account for the physical location of the loop detectors and a few lanes were unmonitored, it was decided to exclude the data from Station 49 during this period.

The process was reversed the following year, between June 17 and September 22, 2010 the southbound lanes were rebuilt and the southbound traffic was rerouted to the western half of the northbound lanes. The effective lane mapping during the southbound construction is shown in Table 3 and again, it was decided to exclude the data from Station 49 during this period.

Table 3 Original and temporary lane mappings for Station 49 during periods with nearby construction on SR-315. The cells show the Loop ID's or "-" for no such loop, changes in the revision are highlighted with a bold font and shaded background.

		Ln 1 NB	Ln 2 NB	Ln 3 NB	Ln 1 SB	Ln 2 SB	Ln 3 SB
Original	upst	22	24	16	19	13	17
	dnst	21	23	15	20	14	18
2009 construction	upst	**14**	**20**	**-**	**17**	**shoulder**	**-**
	dnst	**13**	**19**	**-**	**18**	**shoulder**	**-**
2010 construction	upst	**24**	**16**	**-**	**21**	**median**	**-**
	dnst	**23**	**15**	**-**	**22**	**median**	**-**

2.4 Lane Numbering Convention

The CMFMS was deployed for traffic management with the convention of numbering lanes from the inside to out (lane 1 on the left and increasing numbers to the shoulder). Whereas the Traffic Monitoring Section follows the opposite convention, numbering from the outside to in (lane 1 on the right and increasing numbers to the median). Since all of the raw data use the original *inside-out lane numbering convention*, this report also follows that convention. However, when extracting the final data in this study all lanes were aggregated together, so the two conventions are equivalent for the final vehicle classification data.

3 Raw Data Extraction

To understand the raw data extraction, it is best to first understand the data collection process. The raw data have to pass through several processors before being written to the archives. The leaves of this network are the traffic controllers, with one controller at each detector station. The controllers monitor the state of all of the loop detector at the station, sampling at 240 Hz. Whenever the state at a detector changes from empty to occupied (turning-on, resulting in a rising edge), or vice versa (turning-off, resulting in a falling edge), the controller notes the detector id, time in 240th of a second after midnight, and transition. The controller collects all of the transitions and then every few seconds the controller sends a new transmission to the TMC containing all of the transitions since the last transmission. The transmission rate is irregular, but it is usually between 3 and 8 seconds for a given station.

The ODOT server at the TMC catches all of the transmissions sent from all of the controllers. These data are quickly aggregated and used for real time operations. However, before aggregation, the raw PVR data are passed to the OSU archival server. The OSU server stores all of the transitions reported in one second in a single packet. All of these packets from a given day are written to an ASCII text file. Each packet consists of a header line (which includes both the ODOT server time and OSU server time in integers for that second), and one line per transition (including: station id, detector id, time, and type of transition). All of the transitions received from a given station in that second are recorded together, in temporal order, before the data from the next station is recorded. Thus, typically only a fraction of stations are recorded in a given packet, and each of those stations report the transition data from the previous few seconds.

As noted above, the archived raw data files are written on a FIFO basis of transition records per day. All transitions from different stations and loop detectors are mixed together throughout the whole raw data file for a given day. These text files are fairly large (on the order of 500 Mb), making them cumbersome to work with. Since most of the analysis is performed on transitions from a specific station or a specific loop detector, the data extraction takes a given daily raw data file and converts the essential information to a numerical format. These data are then split into separate files by station, sorted by loop and time. The data extraction includes detection processes for several errors and whenever possible correction processes for the given error. As described in the remainder of this chapter, these processes include: unmatched transitions, time stamp issues, checking for chronic pulse breakup/splashover problems, and deriving the correction factors. In many cases the additional information in the raw data is helpful for catching and correcting these problems (particularly the time stamp issues), e.g., the concurrent time stamps from the ODOT and OSU server in the packet headers or the range of time stamps from each station in a given packet. So these comparisons are done before the data are split into separate files. The error detection results are stored for each loop so that subsequent processing can use the findings.

There is at least one other chronic error in the CMFMS, namely that Stations 8 and 12 exhibit an unreasonably high rate of "zero on-time" errors, where the detector turns on and off in the same time step. This error was noted on p.9 of [2] and there is insufficient data in the archive to fix these pulses. So these two stations remain problematic and are largely excluded from the analysis.

3.1 Unmatched Transitions

The data extraction process takes all of the transitions from a given detector on a given day and sorts them by time to match turn-on and turn-off transitions into pulses, where each pulse represents a single vehicle passage at the given detector. The transitions should alternate turn-on, turn-off within a given detector, but occasionally transitions are lost between the detector and the archival process. So either the turn-on time or turn-off time for the pulse is recorded but the other transition is missing. When an unmatched transition occurs there will be two or more successive transitions of the same type. Taken pairwise, the first of two successive turn-on's or the second of two successive turn-off's is marked as an unmatched transition. These unmatched transitions are set aside, to potentially be used to recover unmatched transitions at dual loop detectors (rather than discarding the corresponding pulse at the other detector). The remaining transitions are grouped into pulses to be used in subsequent analysis. Fortunately, the rate of unmatched transitions is small, typically on the order of 0.1% of all transitions at a given detector.

3.1.1 Possible causes

One thing is certain about unmatched transitions, and that is the fact that they should not occur. Each transition represents the detector transitioning between two states. There are only two possible transitions: turning-on, representing the rising edge of a pulse, and turning-off, representing the falling edge of a pulse. These transitions are recorded in the archive as "1" and "0", respectively. Clearly, once on, a given detector should not be able to turn-on a second time unless between two turn-on transitions in the archive there was an unrecorded turn-off. This loss could happen anywhere between the controller and the OSU archival server.

While it is impossible to retrieve the unrecorded pulses, this section seeks to diagnose where the error occurs most frequently. The leading suspects are: the reporting process at the controller, the collection process on the ODOT server, or the archiving process on the OSU server.

If the error occurs in the reporting process at the controller, e.g., because the controller fails to record a transition at a detector while the controller is in the process of sending a report to the ODOT server, then the errors should manifest as most unmatched turn-on transitions falling at the end of the given cluster of transitions received from the station; and similarly most unmatched turn-off transitions falling at the start of the given cluster of transitions from the station. Thus, in the archive the errors would be distributed randomly within the packet for each second since the order the stations are recorded and number of transitions per station varies from packet to packet. With the 240 Hz scanning frequency, most time steps will not have a transition. The missing transitions would have to fall in the range of time between the last transition time from the station in one packet and the first transition time from the station in the next packet with data from that station, which is typically a small but non-zero range.

If for some reason the ODOT server discarded a portion of the packet, e.g., the first or last transition from a given report. The trend would look similar to the reporting process at the controller (the missing transitions falling at the start and end of clusters), but it would impact all clusters. Whereas, if the problem were with the controller reporting, it would only impact some packets since it also requires a vehicle arriving at the wrong time.

Alternatively, if the transitions went missing in the archival process (either as they are being reported by the ODOT server or being recorded by the OSU server), the missing transitions would most likely fall at the start or end of a data packet.

To differentiate between these possibilities, a typical day was selected (July 6, 2009) and the location of the unmatched transitions found in the raw data file. Each unmatched transition was sorted into start/middle/end of the respective packet, and then sorted into the percent distance into the respective cluster of data from the given station. Figure 5 shows the results from a typical station. The distributions appear to be independent of where the unmatched transition falls in the packet (all three rows show similar distributions), but depend greatly on where the unmatched transition falls in the given cluster. Thus, the results are consistent with the error falling either at the controller reporting or the ODOT server receiving. Next, the numbers show only 6,442 unmatched transitions out of 16,756 clusters from the station over the day. Thus, most clusters do not have unmatched transitions, suggesting that the error occurs at the controllers. Which makes sense, since the CMFMS used Model 170 controllers, whose processors are ca. 1980, i.e., they are likely the slowest processor in the communication chain.

3.2 Transition Time Issues

This section reviews several issues concerning the time stamps of the transitions.

3.2.1 Time jumps

As noted in the beginning of this chapter, each station reports each transition with the (local controller clock) time. These transitions are reported in temporal order and then recorded in the archive in this same order. Therefore, the sequential time stamps for the transitions recorded in the archive from a given station should be strictly non-decreasing throughout the day. Figure 6A plots the sequential time stamps on a typical day for a typical station, and indeed, the sequence is monotonically increasing (as an aside, the slope of the curve is inversely proportional to the volume, with the steepest slope during the early morning hours and shallowest sustained slopes during the peak periods).

While the trend in Figure 6A is the most common, there are exceptions. The sequential time stamp can abruptly jump forward (Figure 6B) or backwards (Figure 6C) and then after a while the time stamps jump back to the correct time. During the time jump the time stamps progress at seemingly the correct rate (as per the slope and difference between start and end times) with a vertical offset from the points immediately before the jump and after the recovery. Reviewing the raw data file, the jumps of a few hours shown in this figure are also consistent with the difference between the transition time stamp and the packet time stamp, i.e., the data were written to the archive with transition times a few hours different from the packet time stamp. In short, it looks like the controller clock jumps to a random set point, then progresses at the correct rate, only later to be reset to the correct offset. If this time jump error goes uncorrected, there will be no data with time stamps from the period corresponding to the jump, whereas there will be two sets of data with time stamps corresponding to the times when the transitions jumped to. Thus, disrupting the true measurements during both of the periods.

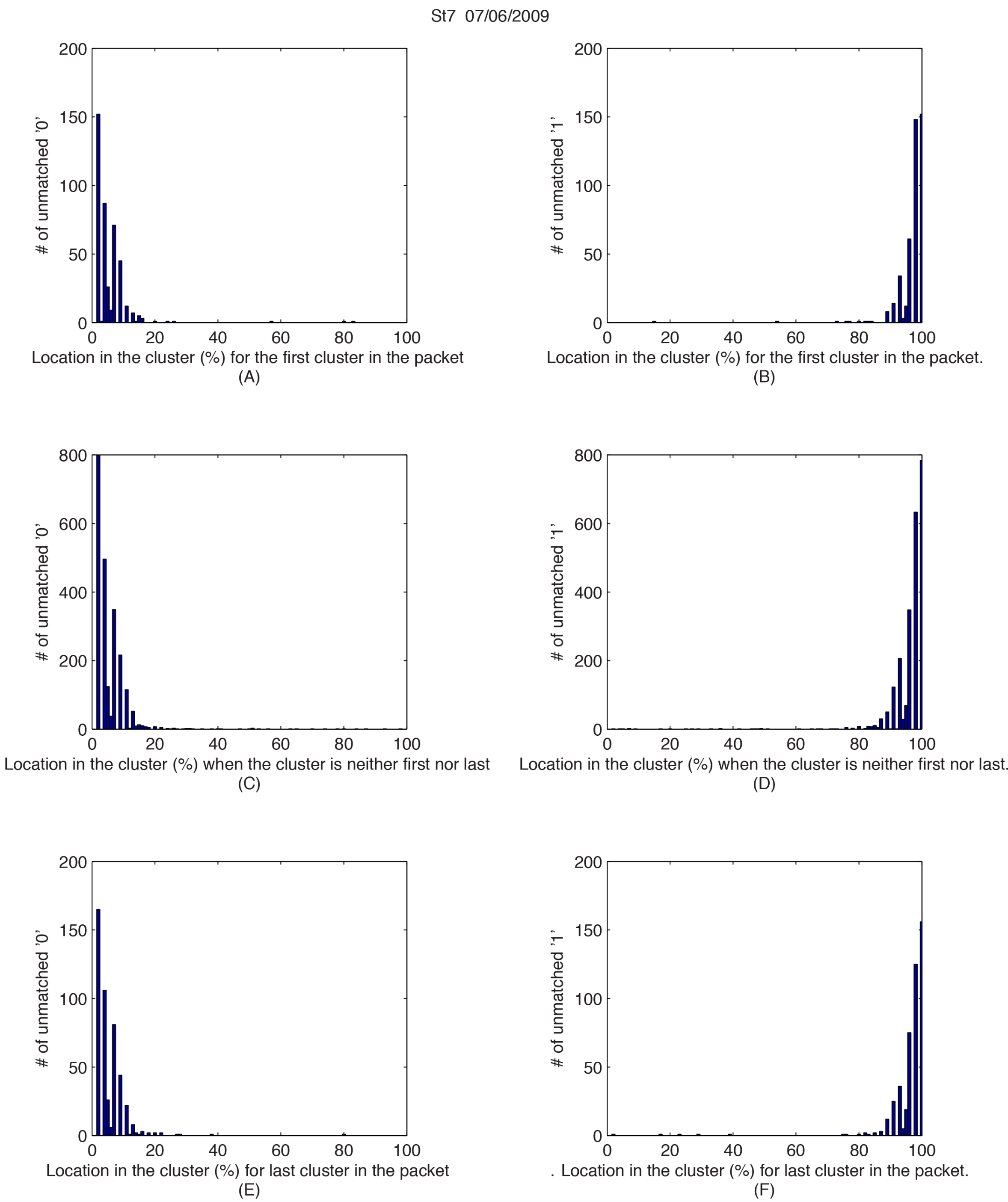


Figure 5 Distribution of unmatched transitions at Station 7 on July 6, 2009. The left-hand column shows the distribution for unmatched turn-off transitions (0's) within the given cluster of data from the station, the right-hand column shows the distribution for the unmatched turn-on transitions (1's) within the given cluster. Each row shows the distributions for unmatched transitions when the cluster from a station is (A)-(B) the first cluster in the packet, (C)-(D) neither first nor last in the packet, and (E)-(F) the last cluster in the given packet.

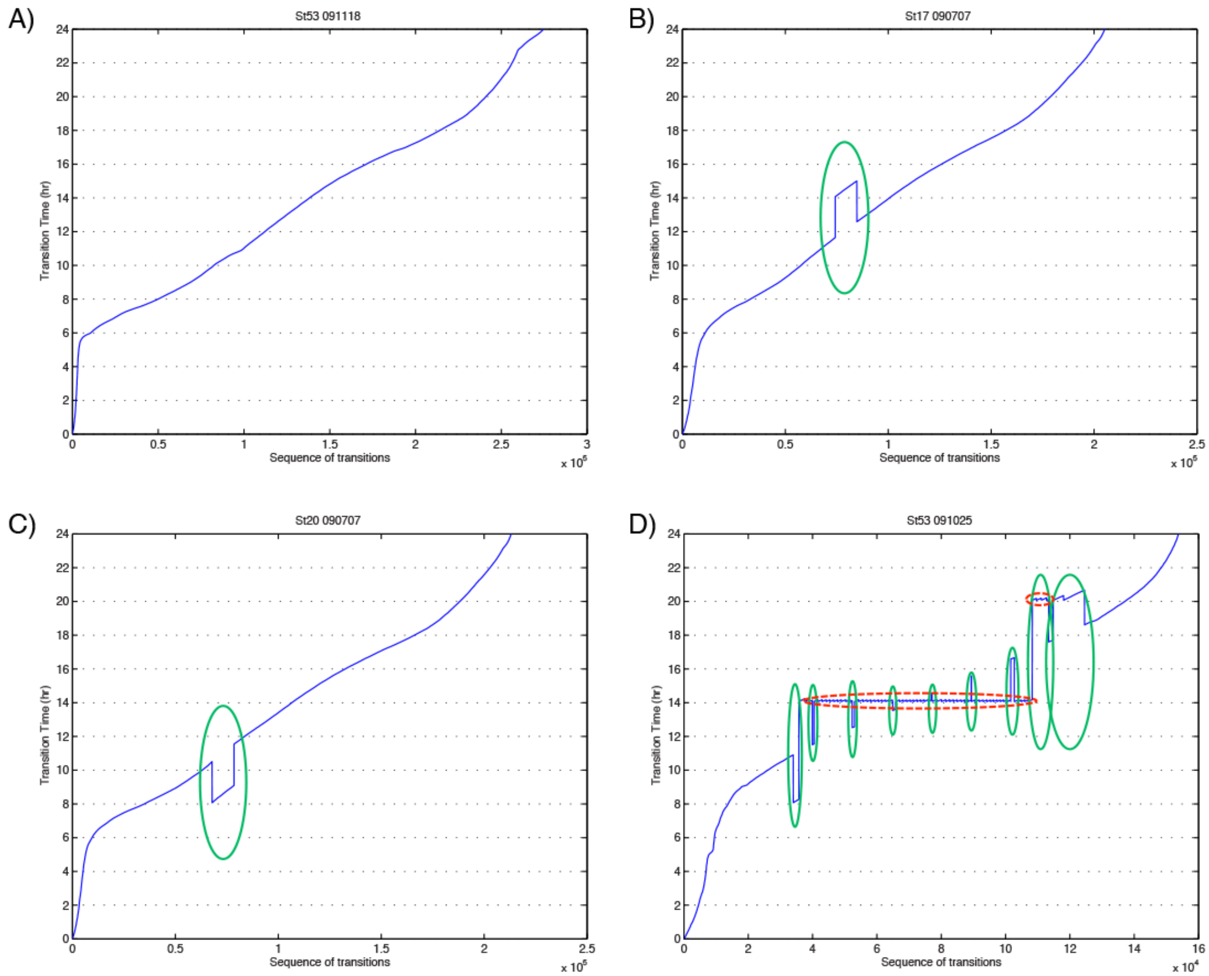


Figure 6 Transition time versus the arrival sequence for the transitions in the raw data file (A) for a normal station on a normal day, (B) a station exhibiting a single forward time jump just before 12:00, (C) a station exhibiting a single backward time jump just after 10:00, and (D) the only station with stagnancy and it also exhibits time jumps. Throughout this figure the time jump events are enclosed in vertically aligned eclipses in green solid lines, while the stagnancy events are enclosed in horizontally aligned eclipses in red dashed lines.

The time jump error impacts roughly 5% of the station days in the archive. All of the stations exhibit this error at some point. Often multiple stations are impacted with a time jump, but rarely are all stations impacted at the same time. When the time jumps occur, it is frequently the case that multiple stations all start the time jump at the same time, however, each affected station will jump to a different time.

Fortunately most time jumps can be detected and fixed based on the time stamps of data packets in the raw data. In the packets with the data of a given station, i.e., the cluster of transitions, all of the transitions are within a few seconds of the given packet time from the ODOT central server. Almost all of the transition time stamps are before the packet time, but occasionally there will be cases where the transition time is a fraction of a second later than the recorded packet time stamp, because server times are only reported in integer seconds.

In general the exact time that a station reports its data is unknown; but provided that there is no time jump, it cannot be any earlier than the last received transition time stamp in the report from that station. So we take the difference between the last transition time in a packet from a given station and the packet header time stamp from the ODOT central server, *Tdiff*, via Equation 1. In so doing, Tdiff effectively removes the trend due to the time of day. To illustrate this process, consider the sequential time stamps from Station 1 on July 18, 2002 in Figure 7A. Figure 7B shows the Tdiff versus the sequential packet number (excluding packets with no transitions from this station), corresponding to Figure 7A. Indeed, most of the packets are without a time jump, with Tdiff very close to zero, but the two periods with time jumps are now plainly evident. Thus, time jumps can be identified by $|Tdiff| \geq T_{jump}$, where T_{jump} is a threshold to define time jumps, and chosen to be 60 sec in this work. Then for successive time jump packets, compare the Tdiff value of adjacent packets, and sub-jumps can be identified by $|\Delta Tdiff| \geq \Delta T_{jump}$, where $\Delta Tdiff$ is difference between Tdiff of the ith packet and the i+1th packet, and ΔT_{jump} is the threshold to define sub time jumps, chosen to be 50 sec in this work.

$$Tdiff = T_{packet} - T_{last\_transition} \tag{1}$$

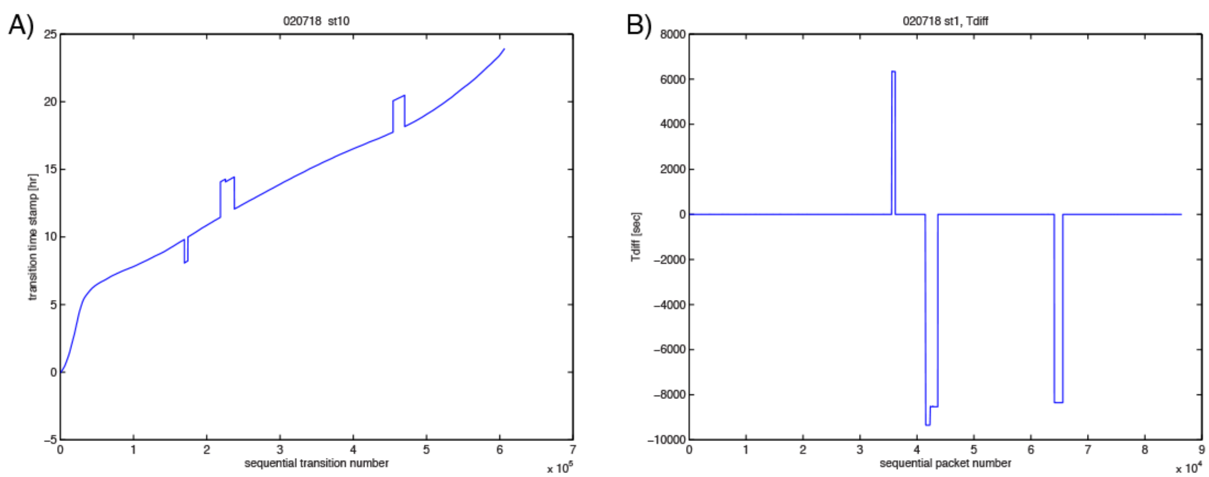


Figure 7 (A) Sequential transition time stamps in one day at a station with two time jumps; (B) The two time jumps in part A stand out in the sequential Tdiff.

For the purpose of time jump correction, we need a detailed examination of the Tdiff pattern. At a lower frequency Tdiff shows a slow steady drift over time even in the absence of time jumps, as evident in the saw tooth pattern across the bottom envelope of the points in Figure 8 (showing a detail from Figure 7B). This slow drift indicates that the controller clock is drifting slowly relative to the ODOT central server clock and is then reset by 1 sec at the start of each new "tooth". Each successive saw tooth does not necessarily have the same slope or duration as the tooth that came before or comes after it. On the other hand, Figure 9A shows that on the same day used in Figure 7 the concurrent Tdiff from the 45 different Phase I stations (Stations 1 - 34, and 102 - 112) exhibit almost the same shape between the successive 1 sec corrections (one saw tooth), with approximately the same slope and magnitude. Figure 9B shows the envelope of Tdiff from all stations, after applying a low pass filter to the data to remove transient large Tdiff. In general, this saw tooth pattern appears to be consistent across stations, even at stations that exhibit a time jump, as shown in Figure 10.

To correct for the time jumps, within each saw tooth the jump offset is found by taking the distance between the filtered envelope Tdiff for the station with the jump and the median envelope for all of the other stations that are not currently experiencing a jump. The time jump offset is then subtracted from the time stamp for all of the offsets within this saw tooth at the station with the jump, as illustrated in Figure 11 for the example started in Figure 7.

Occasionally a station will exhibit a different trend, e.g., the jump offset varies too much. These time jumps are unfixable at present and so the station is marked as bad for the given day.

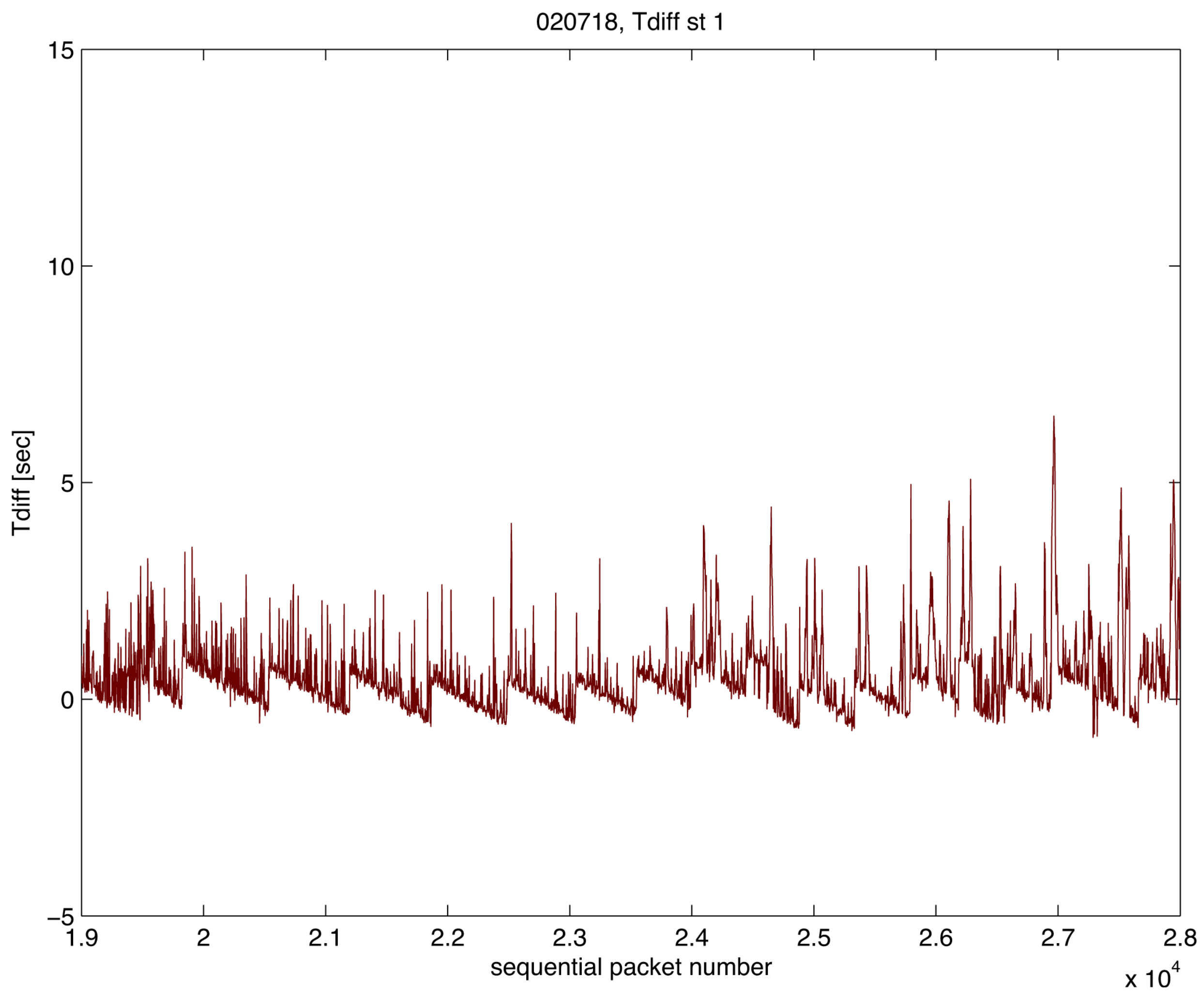
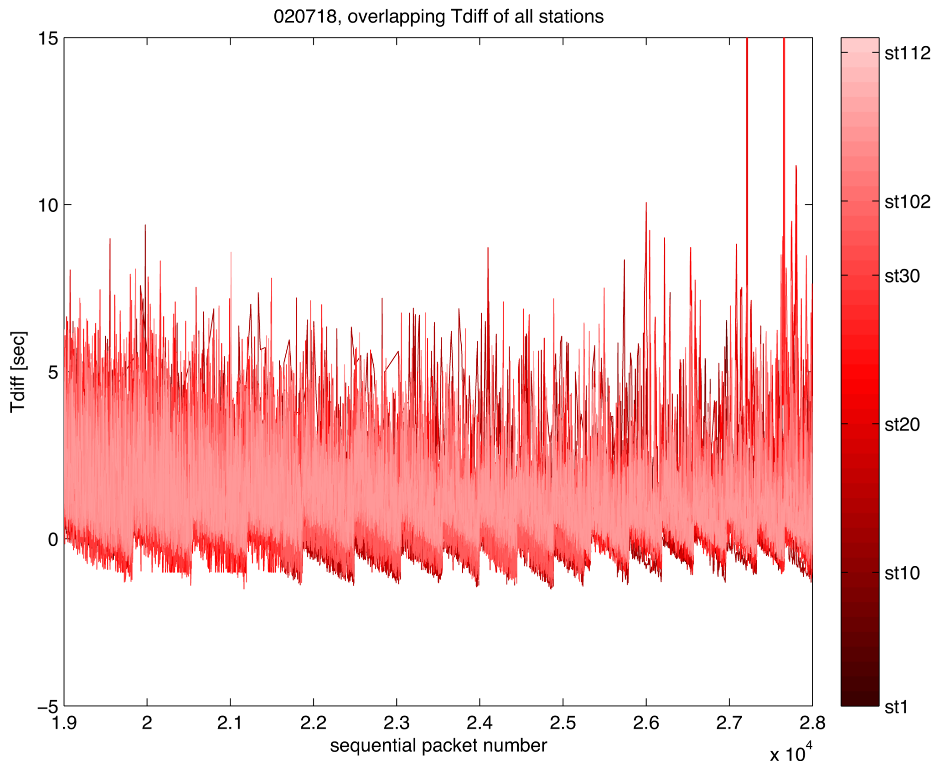
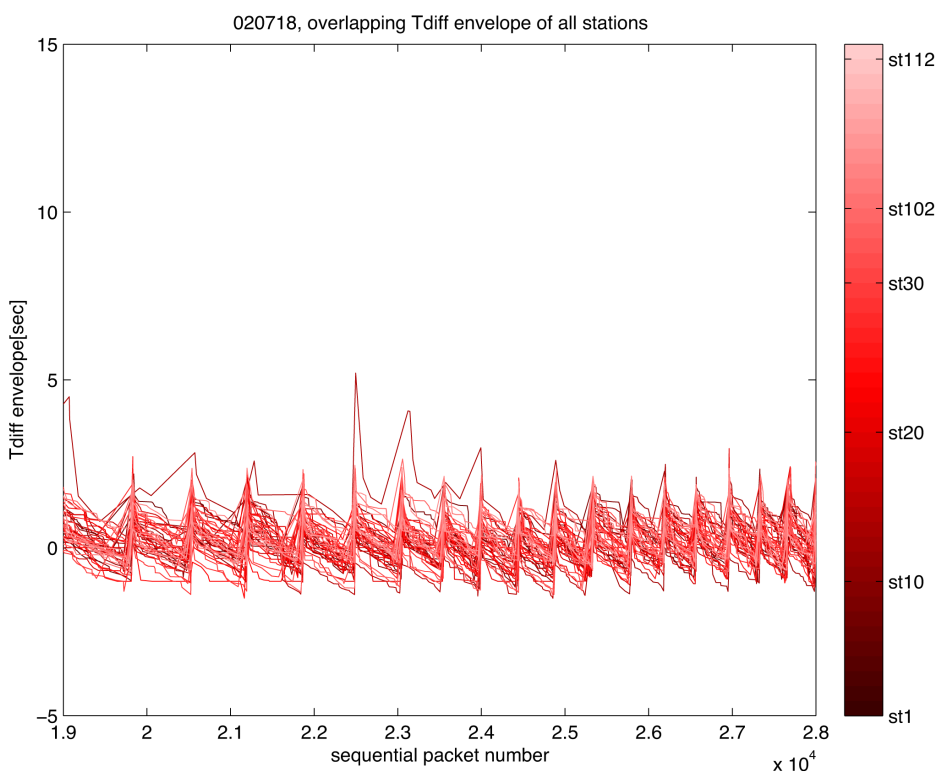


Figure 8 Detail of Tdiff from sequential packets, the bottom envelope shows a ‘saw tooth’ shape.



(A)



(B)

Figure 9 Overlapping (A) Tdiff and (B) Tdiff envelop for all Phase I stations.

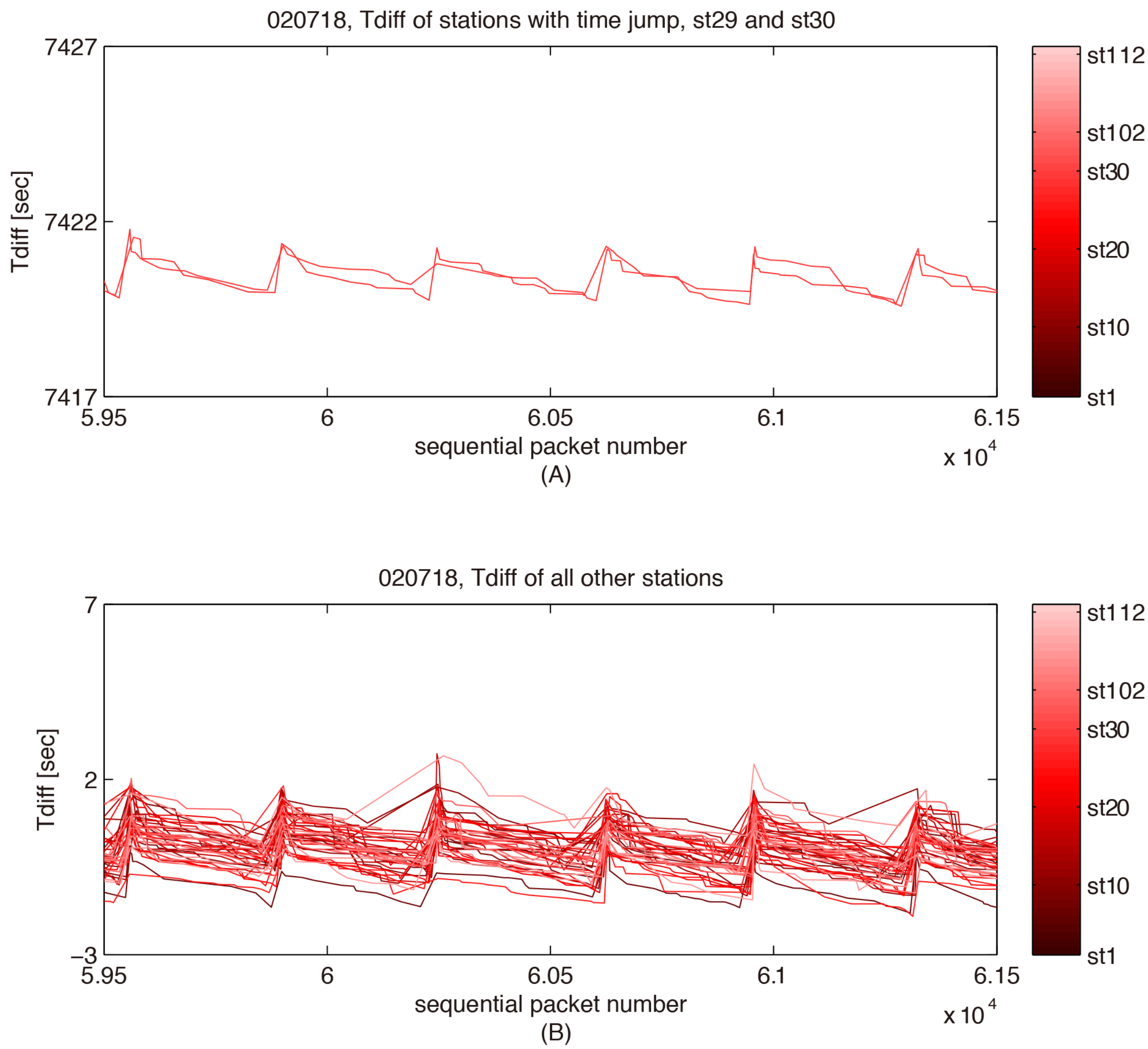


Figure 10 Detail of the low pass filtered envelope Tdiff (A) at two stations exhibiting a time jump- notice Tdiff is around 7420 sec, and (B) the remaining stations that are not currently exhibiting a time jump- notice that Tdiff is around 0 sec, as should be the case. Although there is a time offset between parts A and B, the general trend in the saw teeth remains similar between the stations with and without time jumps.

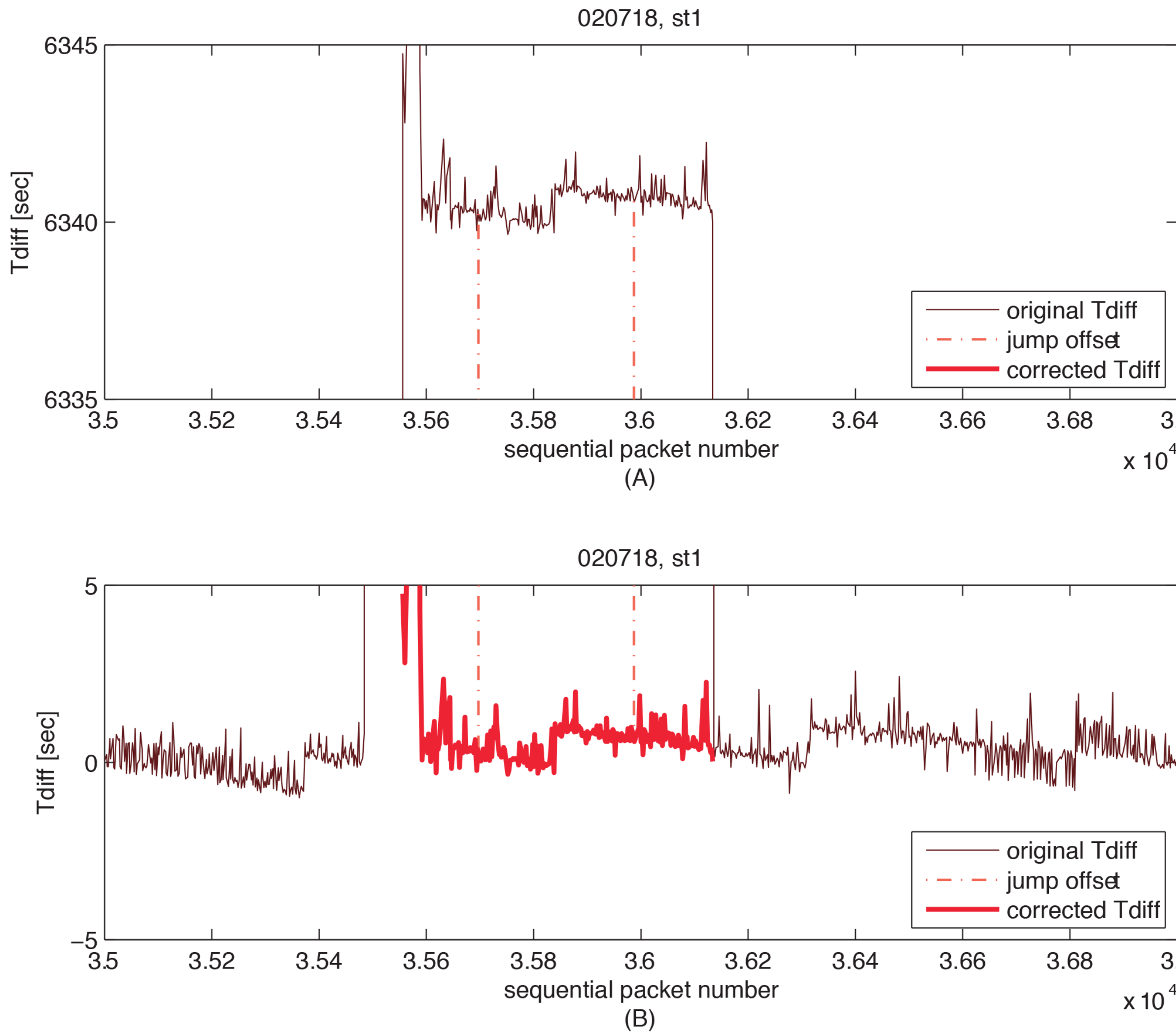


Figure 11 (A) the original and (B) corrected Tdiff at Station 1 on July 18, 2002.

3.2.2 Stagnancy

A single station (Station 53) exhibits another time stamp error similar to the time jump, but more severe. Figure 6D shows an example of this error, between 10:00 and 19:00 (transitions 40,000 to 120,000) almost all of the recorded transition time stamps fall in a narrow time window around 14:00. There are intermittent time jumps as well throughout this period. This error is termed "stagnancy" since the time stamps are stagnant for an extended period. Figure 12 shows a detail with three time jumps (the curve leaves the lower bound of the plotted times) and a few dozen "saw teeth" related to the stagnancy. The transition time stamps continue to progress forward in time, but then repeatedly make these small jumps backward in time.

This research developed an algorithm to detect stagnancy. Exploiting the saw tooth shape, where the series slowly rises and then abruptly falls back in time, the main idea of the detection algorithm is to identify these basic features in the transition time sequence. The detailed steps are as follows:

i. Take the difference between all successive transitions over the day at a given station. Find any differences less than -5 sec and mark it as a "possible foot" in the saw tooth ripples.

ii. Define a "possible peak" as the transition right before a "possible foot". Each pair of "possible peak" and "possible foot" roughly defines a single cycle of a possible saw tooth shaped ripple.

iii. A possible saw tooth shaped ripple is considered to be a true saw tooth ripple if all following criteria are satisfied (for brevity, for the remainder of this section "possible" is omitted before "foot" and "peak"):

   a. Near-linear increment:
      abs (average of all transition time – average of foot and peak time) < (peak time – next foot time) / 10;

   b. Near same level of neighboring feet or peaks:
      abs (foot time – next foot time) < (peak time – next foot time) / 3
      OR
      abs (peak time – previous peak time) < (peak time – next foot time) / 3;

   c. No significant time jump:
      Increment in transition time by one transition must be smaller than 300 sec.

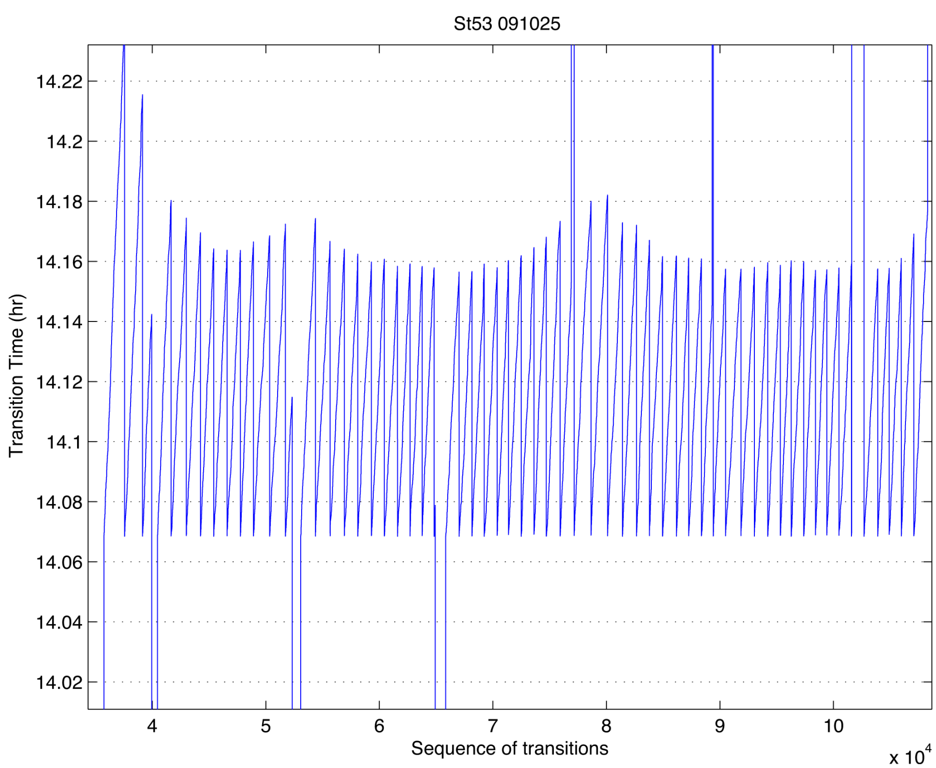


Figure 12 Detail of the larger dashed circle in Figure 6D.

Example results of stagnancy detection are shown in Figure 13. Figure 13A shows the results when applied to the data in Figure 6D. One can see that almost all of the transitions exhibiting stagnancy that are manually detected in Figure 6D are correctly caught by the algorithm in Figure 13A. False negatives only appear in the very first ripple of each contiguous stagnancy period. Meanwhile, Figure 13B is an example of the results when applied to a transition series records with no stagnancy (although a lot of time jumps). Not a single false positive occurs. The algorithm has been tested on numerous stations and days data and the two examples here are representative of almost all situations observed. Due to the nature of stagnancy, it is hard to fix all of the occurrences. So on days when stagnancy is detected the station is marked as bad for that day and excluded from the vehicle classification.

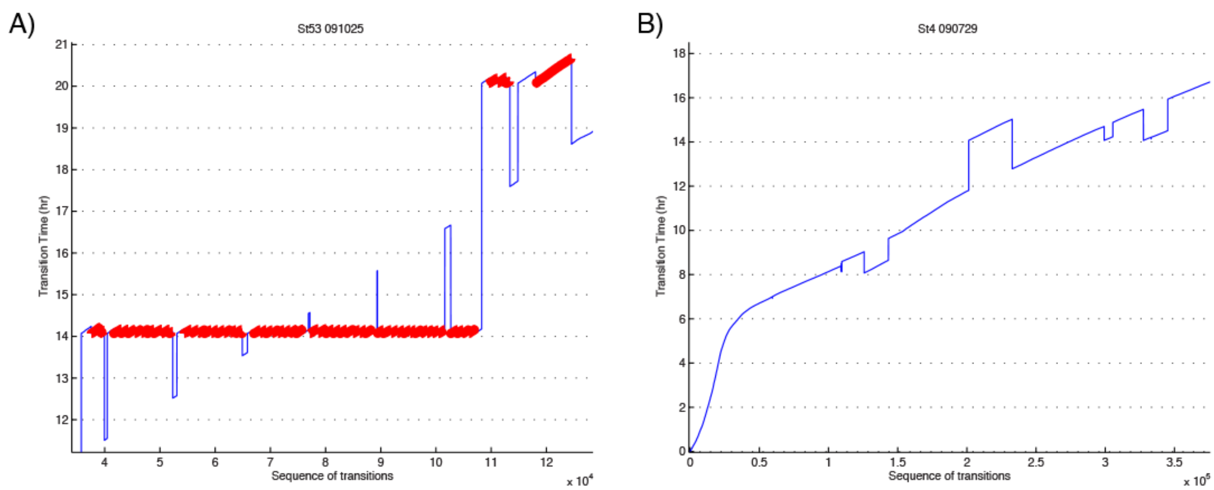


Figure 13 Example of output from the stagnancy detection for (A) a station exhibiting heavy stagnancy problems, and (B) a station exhibiting no stagnancy problems, but several time jumps. Almost all of the stagnancy in part A is detected (as indicated in bold), whereas no stagnancy is detected in part B.

3.2.3 Inconsistency between transition time and packet time

One of the key indicators of time jumps and stagnancy is the fact that the transition time differs greatly from the packet time stamp from the ODOT server. While a few second lag is expected, and we occasionally see latency up to a few dozen seconds, and large time differences in excess of 60 sec between the transition time and packet time should be rare. So if the difference is larger than 60 sec, this work labels it as a time inconsistency. This threshold test will catch most time jumps and stagnancy events, but about 10% of the positive outcomes from the test are not due to a time jump or stagnancy. These events are most likely due to a large, transient latency somewhere in the communication network, but they are still considered to be suspicious. Whenever possible, this work will avoid stations exhibiting a relatively high portion of inconsistent transition times.

3.2.4 Low sampling frequency

Normally the loop detector's sampling frequency is 240 Hz, which means the precision of the transition time is 1/240 sec. However some loops exhibit a lower effective sampling frequency. The low sampling frequency could reduce the accuracy of transition time and subsequently degrade the quality of vehicle speed and length measurement. To illustrate this problem, Figure 14 shows a histogram of on-times during free flow conditions with 1/240 sec bin width, one plot for each detector at Station 50 on July 1, 2009. For 10 out of 12 detectors in the figure, bins exhibit the expected bell-curve shape, with no gap between bins. It implies that these detectors are indeed exhibiting a sampling frequency of 240 Hz as expected. However, for the two histograms in Figure 14I-J, there are large gaps between bins with data, indicating a lower effective sampling frequency for these two detectors.

To detect this problem, an algorithm takes the absolute difference between successive bins from 0 to 30/60 sec. The largest two differences are discarded, in case the distribution of on-time is extremely centralized. Then the algorithm takes the sum of the remaining absolute differences and divides this total by the sum of all bins from 0 to 30/60 sec to derive a penalty score. Figure 14 shows the calculated penalty score for each detector above the corresponding histogram. The higher the penalty score, the higher probability that there is a low effective sampling frequency. A threshold 0.5 penalty score is used to separate detectors with normal and low sampling frequency. This outcome will be accounted for in Section 5.3, when selecting representative stations for a given link.

3.2.5 Time correction factor issue

From the field to the archive there are at least three independent clocks for each detector station: controller, ODOT server, and OSU server. Out of these clocks only the OSU server is adjusted to UTC. Furthermore, there are two ODOT servers (main and backup) and these two servers will occasionally switch roles. It is quite possible that the clocks for the two ODOT servers are not synchronized. In extracting the data several problems were found:

- The ODOT server clock drifts over the day relative to the OSU server.
- The controller clocks usually do not appear to drift more than a second from the ODOT server clock, except for the occasional time jump problem (discussed above).
- The concurrent ODOT server and OSU server times are only reported to integer seconds, limiting the resolution at which the ODOT server time can be corrected in post processing.

This work derives transition correction factors to synchronize the ODOT server time to the OSU server time as follows. First, the work obtains a transition time correction factor every second of the day by subtracting the ODOT server time from the OSU server time recorded in the header of each packet in the raw data. To balance the errors due to time drift throughout the day, the work sets the daily time correction factor at noon as the uniform time correction factor to correct transition time in the whole day. It then records the relative correction factors for every 5 min throughout the day.

3.2.6 Daylight Saving Time Issue

As mentioned in Section 3.2.5, the corrected transition time is based on the OSU server clock, which is adjusted to UTC time. However, the OSU server was last configured prior to the newest federal law of Daylight Saving Time (DST), which came into practice from Year 2007. The old DST starts from the first Sunday in April and ends on the last Sunday in October. The new DST starts from the second Sunday in March and ends on the first Sunday in

November. For all years since the new law was enacted, over the few weeks where the two laws diverge, the OSU server clock is off by an hour.

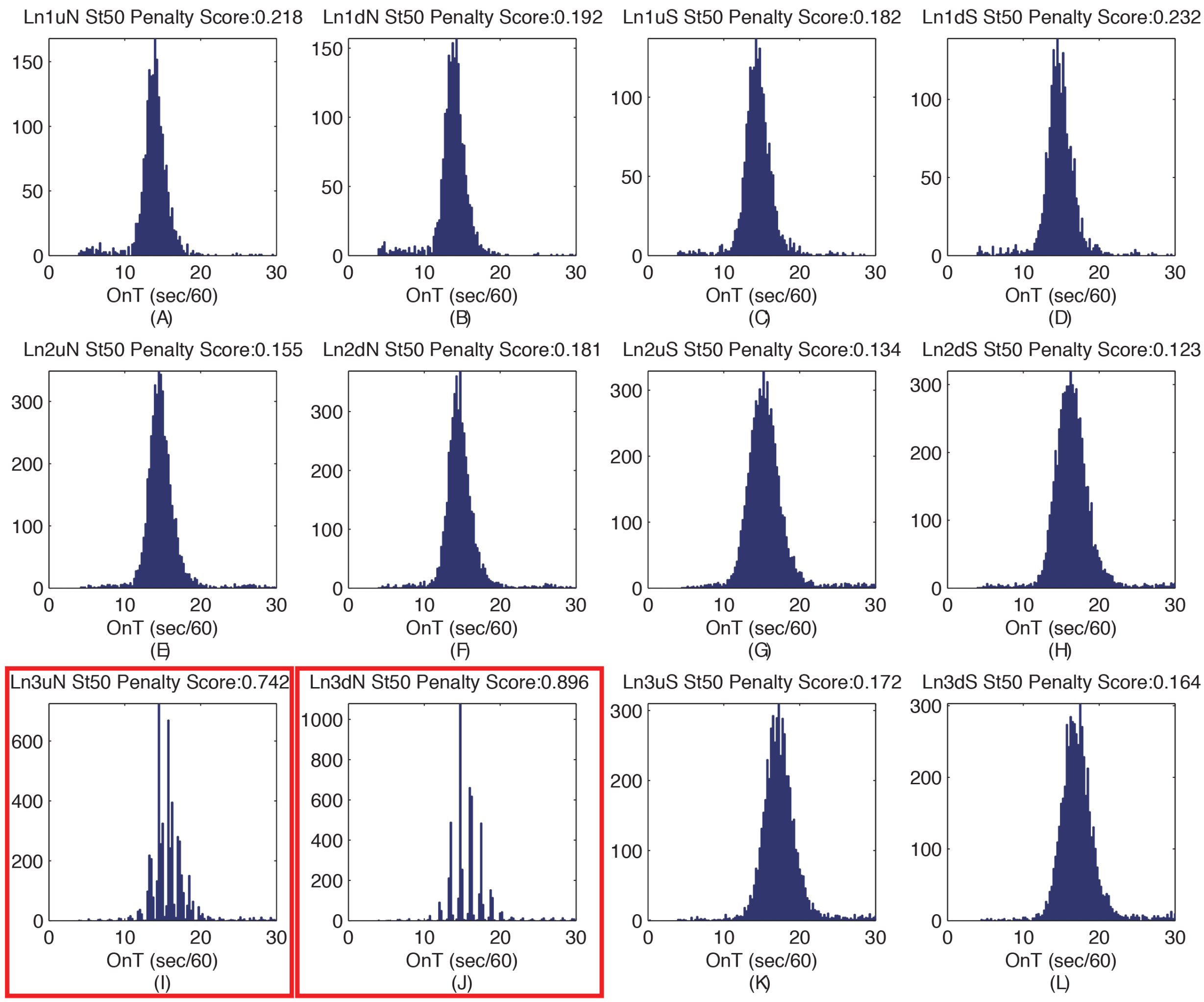


Figure 14 Histograms of on-time for all detectors at Station 50 with 1/240 sec bin width for 9 am to 3 pm (mostly free flow) on July 1, 2009. The label above each subplot shows the calculated penalty score, e.g., “Ln1uN” means the upstream detector on Lane 1 northbound, “Ln3dS” means the downstream detector on Lane 3 southbound. Detectors with low sampling frequency are highlighted with squares around the plots in parts I and J.

The ODOT server does not follow DST and the OSU server only corrects for DST at the start of the day. So in all years the day on which DST begins (as per the pre 2007 law) the archived data file only contains 23 hours of data since the OSU server clock jumped ahead at the correct time and the day ends an hour sooner. The time stamps should correspond to 0:00 to 2:00 and 3:00 to 24:00 since the clock is set forward by one hour at 2 am. However, our old correction failed to account for the 2 am jump because it was set at the very start of the day, and so the times were incorrect on the day that the clock jumped forward. They would be caught the following day since the starting time stamp incorporated the DST. Similarly, on the day when DST ends (as per the pre 2007 law) the archived file includes 25 hours, which should be 0:00 to 24:00 with 1:00 to 2:00 repeated since the clock is set backward by one hour at 2 am. These corrections have been implemented in the revised data extraction developed for this work.

From 2007 onward, the time jumps are made on the incorrect day, so for the dates falling in the gap between the old and new DST definitions one hour of data is transferred from the start of one day to the end of the previous day. The corresponding time stamps are adjusted accordingly for these periods, including the partial days on the dates of the new start and end dates.

3.2.7 End / beginning of the day problem

The OSU server partitions the raw data into daily files with the break point for a new day occurring at midnight on the OSU server clock. Since the transition time stamps come from the controllers, which are synchronized to the ODOT server, typically on the OSU server there will be a few minutes of data either at the start of the daily file with time stamps from the previous day, or at the end of the daily file with time stamps from the following day. After using the daily correction factor, some of these transition times will be corrected into the current day. The remaining transitions are then moved to the correct day so that each day of extracted data now contains all of the data from that calendar day and only data from that calendar day (after applying the correction factor and DST correction from the previous subsections).

3.3 Loop Detector Calibration

The loop detector calibration followed the process laid out in [2] with the following modifications. First, recognizing the fact that there is often a speed gradient during free flow conditions from the left lane to the right lane, the current work does not assume free flow traffic travels at exactly the speed limit. Rather, once a month for all of the loop detectors (both single loops and individually for the paired loops in a dual loop detector) the following five steps are used to find the on-time correction factor to account for the unknown size of the effective detection zone and the sensitivity settings. These same five steps are then followed again once a month to calculate the unknown dual loop spacing at the dual loop detectors.

I. Calculate the median of monthly median speed across all lanes, both directions at a given station.

II. Use step I to calculate a preliminary correction factor (pre_cor_fac) for each station, with the target speed set to the speed limit.

III. Use pre_cor_fac to adjust the detector spacing to correct the original monthly median speed (all lanes, both directions in one station use the same factor).

IV. Sort all stations in to one of four groups based on the following criteria: number of lanes ≤ 3 or ≥ 4; posted speed limit 55 mph or 65 mph. Within each group the reference speed for lane 1 is set to the median of the station monthly median daily speed in lane 1 (from step III) across all of the stations in the group. For the remaining lanes the reference speed was set to the speed limit.

V. Use the reference speed to calculate the final correction factor in each lane at each station.

Second, recognizing that some lanes have a high percentage of trucks, we check to see whether a given single loop detector exhibits a bimodal on-time distribution. If so, the higher mode likely corresponds to trucks (as per [15]) and the higher mode is suppressed. Otherwise, it will cause errors when taking the daily median on-time for calibration purposes.

Third, recognizing that occasionally the two loops in a dual loop detector may have different sized detection zones, the current work separately calculates the detector spacing correction for the front bumper (measured from the difference in turn-on times at the paired loops) and for the rear bumper (measured from the difference in turn-off times).

3.3.1 Catching chronic detector errors

In addition to calibrating the detectors, the monthly analysis also looks for chronic detector errors, namely: pulse-breakup (PBU) and splashover (SpOV). Pulse breakup is a detector error in which a single pulse from a vehicle breaks up into two or more pulses because the detector momentarily drops out. Lee and Coifman [8] have already developed an effective method to identify and correct pulse breakup errors for single loops. The process of detecting this error begins by finding short off-times and comparing the on-times from the two successive pulses bounding a given short off-time. To differentiate between pulse breakup and tailgating, the method includes several comparisons of the adjacent on-times with respect to the ambient traffic conditions. A total of six steps are included in the method. If two successive pulses satisfy all of the steps, these pulses are a suspected pulse breakup. The pulse breakup rate, which is the number of suspected broken-up pulses divided by the total number of pulses at the detector during the day, is used to decide whether the detector has chronic pulse breakups. Currently we consider pulse breakup rate greater than 1% as the condition for being labeled as exhibiting chronic pulse breakups.

Meanwhile, Splashover is the erroneous detection in one lane of a vehicle from an adjacent lane. According to the Traffic Detector Handbook [21], splashover usually occurs when the sensitivity level of a loop detector is set too high or a loop is too close to an adjacent lane, though there are many other factors that could cause splashover as well, such as cross-talk. Lee and Coifman [7] developed an algorithm to identify chronic splashover problems. The algorithm is based on the fact that an erroneous pulse arising from splashover in one lane should usually be bounded by the valid pulse from the vehicle in its lane of travel. However, any given splashover event in the data stream is usually indistinguishable from the non-splashover event of two vehicles passing the detector station at the same time yielding valid concurrent actuations. To control for non-splashover events, a dynamic threshold rate of false positives (TRFP) is calculated as a function of the observed traffic conditions. The adjusted rate of suspected splashover (ARSS) is calculated based on the rate of suspected splashover events and TRFP, which will be used to decide whether the detector has chronic splashover. Currently we consider ARSS greater than 1% as the condition for being labeled as exhibiting chronic splashover. Note that if a detector has chronic splashover, it will probably also be considered to have chronic pulse breakups by the diagnostic test. Therefore we need to exclude detectors from the list of having chronic pulse breakups if they are also diagnosed to have chronic splashover.

3.4 Structure of Extracted Data

For the convenience of further analysis, the extracted data are stored in Matlab format (.mat). As shown in Figure 15, the data structure has four levels: file folders, mat files, Matlab variables, and columns in some of the variables. Each day's extracted data forms a folder. In this folder, there are three types of data files, the file named "Station_#" contains transition records for all detectors for the given station (where "#" in the file name denotes the specific station number and there is one file per station reporting data on that day) as well as transition time correction factor and the IDs of all detectors in the station that have any transition that appear on this day. The file named as "metadata" contains daily median & mode on-time, bimodal on-time distribution flags as well as thresholds and criteria values of splashover and low sampling frequency detection tests for all detectors of all stations seen on that date. The last file, "rel_TimeCorFac", contains relative transition time correction factors for all detectors at all stations seen on that date. Correction factors for on-time and loop spacing are stored monthly in a separate folder (which is not shown in Figure 15).

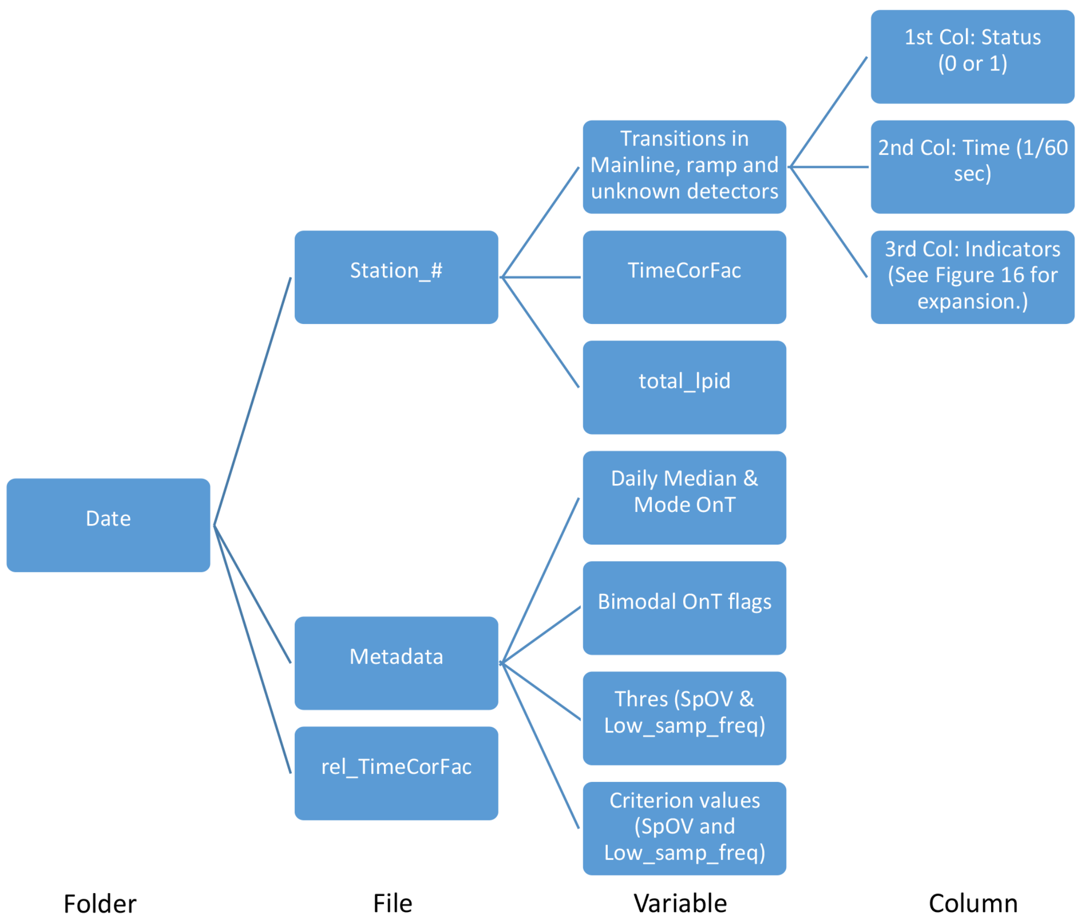


Figure 15 Format of the extracted data in Matlab format (.mat). Where: TimeCorFac / rel_TimeCorFac: time correction factor / relative time correction factor; total_lpid: a variable recording all loop IDs if the corresponding loops report any transition; Bimodal OnT flags: Bimodal on-time distribution flags; Thres (SpOV & Low_samp_freq): thresholds of splashover and low sampling frequency tests.

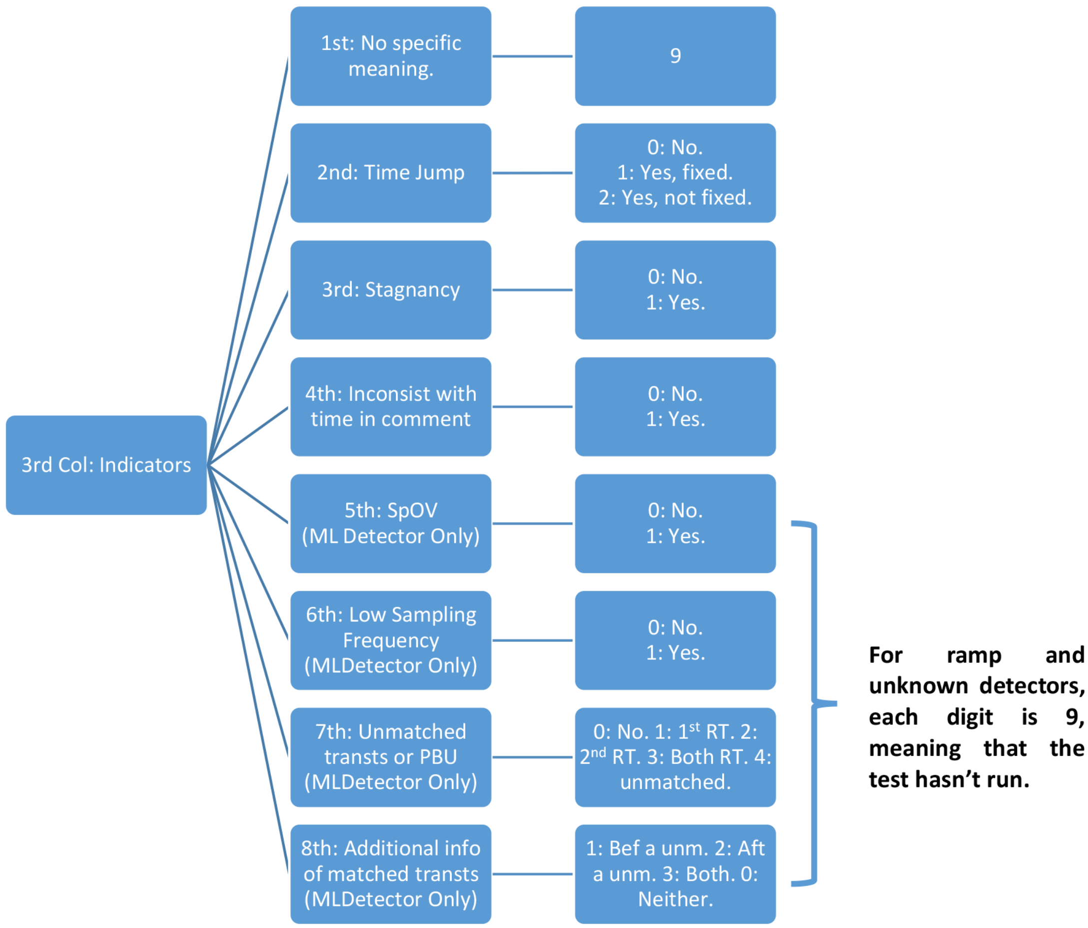


Figure 16 Structure of the indicator column from Figure 15. Where: SpOV = splashover, ML = mainline, transts = transitions, RT = rising transition, Bef = before, Aft = after.

For each detector the Matlab variable storing the transitions has three columns: transition status, transition time and indicators. The indicator column uses different digits to indicate the results of various quality tests, as defined in Figure 16. We use digits instead of multiple variables in order to save storage space. For mainline detectors, all digits are meaningful except the first digit. However, for ramp and unknown detectors, some quality tests are not applied. Therefore only the 2^{nd}, 3^{rd} and 4^{th} digits are meaningful for these detectors. Meaningless digits are assigned with the value 9 to avoid confusion.

The last 2 digits (7^{th} and 8^{th}) of the indicator column are unlike the other digits, which only focus on one field. The 7^{th} digit carries information about both unmatched transitions and pulse breakups. Value "0" means the transition is neither an unmatched transition nor in a broken-up pulse. This outcome is the most common that a transition shows. Value "1" indicates the transition is the first rising transition in a broken pulse and "2" indicates it is the second rising transition. Here an assumption has been made that the pulse can only break up into two parts, which is by far the most common case for pulse breakups. However, under very rare circumstances, a pulse can actually break into more than two parts. It will be treated as multiple successive overlapping pairs of pulses with each break. The rising transition of the shared part is marked as "3" in the 7^{th} digit (see Figure 17 for an illustrative example). While value “1” to “3” are for pulse breakups, value “4” is for unmatched transitions. For time series transitions, all consecutive rising transitions (“1”s) except the last in the series and all consecutive falling transitions (“0”s) except the first in the series are considered as unmatched and marked as “4” in the 7th digit (see Figure 18 for an illustrative example).

The 8th digit provides additional information about matched transitions near unmatched transitions (marked as “4” in the 7th digit). Value “1” means the transition is matched but it is right before an unmatched transition. Value “2” means the transition is matched but it is right after an unmatched transition. Most transitions are neither right before nor right after an unmatched transition, in which case they will be marked with value “0” in the 8th digit. Note that an unmatched transition also satisfies the criterion and will also has value “0” in the 8th digit (once more, see Figure 18 for an example).

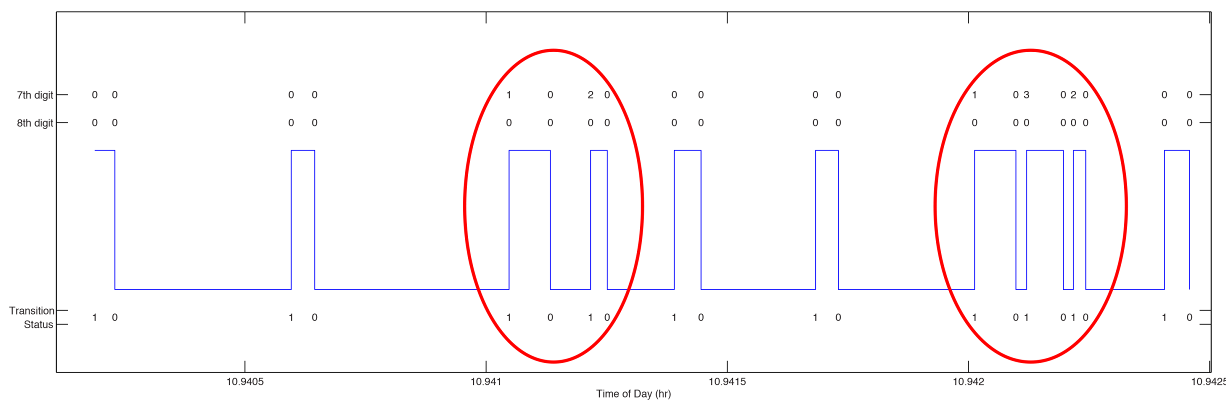


Figure 17 An example where the 7th digit indicates pulse breakups. In the first circle, the pulse breaks into 2 parts. In the second circle, the pulse breaks into 3 parts and the rising transition of the middle part is marked as “3” in the 7th digit. Note that most detectors do not have such frequent pulse breakups.

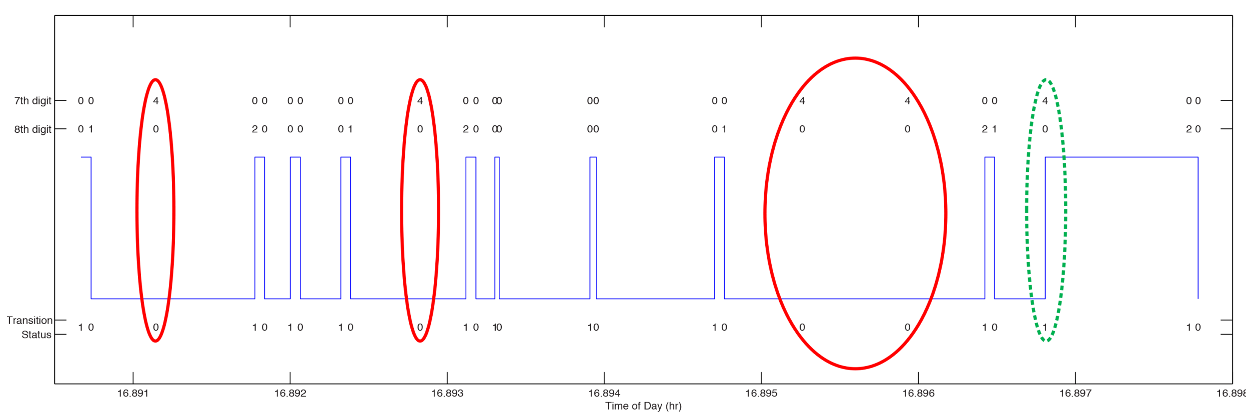


Figure 18 An example where the 7th digit indicates unmatched transitions and the 8th digit shows additional information near unmatched transitions. Red solid circles enclose unmatched falling transitions (“0”s) while green dashed circles enclose unmatched rising transitions (“1”s). The 3rd circle has two consecutive unmatched transitions while other circles only have one unmatched transitions. Note that most detectors do not have such frequent unmatched transitions.

4 Pulse Matching at Dual Loop Detectors

A dual loop detector consists of two single loop detectors spaced a fixed distance apart. Normally, when a vehicle passes over a dual loop detector, the upstream loop detector is activated and then the downstream loop detector. Each actuation at one loop should be uniquely matched to a single actuation at the other. Usually we measure individual vehicle speed from dual loop detectors by dividing the constant and known loop spacing (from Section 3.3) by the vehicle's traversal time. In order to get the traversal time, we need an algorithm to match upstream and downstream pulses corresponding to the same vehicle together.

Ideally, each upstream pulse is followed by a downstream pulse shortly after and they are uniquely matched. Unfortunately, there are pulses that cannot be matched so simply. Figure 19 shows examples of matched (u1:d1 to u3:d3) and unmatched pulses (aa and bb) at a hypothetical dual loop detector. One cause of unmatched pulses is when one loop fails to actuate and misses a vehicle. Under this scenario the corresponding pulse at the other detector has no match, and thus, one cannot measure speed for this vehicle. Whenever a transition is lost before it reaches the archive, the remaining turn-on time or turn-off time is recorded but the other one is missing. In this scenario, we may be able to recover the missing transition in free flow traffic. Since the two loops are closely spaced within a single lane, without a detector error, the on-times from the paired loops should be virtually identical during free flow conditions regardless of vehicle length. Using this principle, during free flow conditions we now attempt to recover the missing transition at one loop by matching the on-time with the corresponding complete pulse at the other loop.

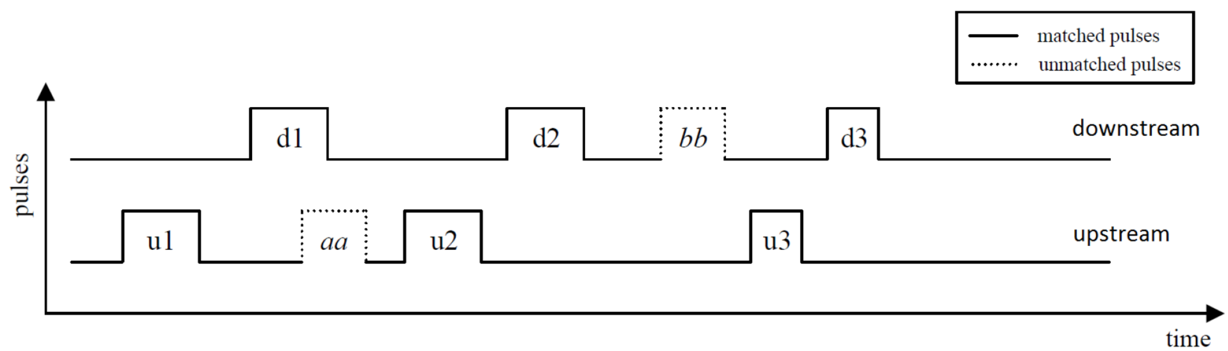


Figure 19 Examples of matched and unmatched pulses.

Besides missing pulses, there can also be extra, non-vehicle pulses in the data. The two most common causes for adding extra pulses are pulse-breakup (PBU) and splashover (SpOV), as discussed in Section 3.3.1. In the context of individual loop detectors (either a single loop detector or one of the paired loops in dual loop detector) we apply the method from [8] to fix pulse breakups when the given detector has been labeled as exhibiting chronic pulse breakup in Section 3.3.1. At dual loop detectors we also use the fact that during free flow conditions both the front and rear bumper traversal times should be virtually identical for a given vehicle, regardless of vehicle speed since the high free flow speeds virtually eliminate the impacts of acceleration on the two measured traversal times. We use this fact to fix additional pulse breakup events at some of the dual loop detectors using the process described in Section 4.2.2. Although PBU events can be fixed, even at a station exhibiting chronic PBU, unfortunately there is no effective way to fix SpOV based on the archived CMFMS loop detector data. So stations exhibiting chronic SpOV are addressed at a later step in the processing (as discussed in Section 5.3).

In order to match as many pulses as possible while maintaining a good matching quality, the work developed a three-round pulse matching algorithm, described in detail below. As an overview of the steps: the first round uses a basic algorithm, which only matches those absolutely correct pairs. For the remaining pulses, the second round does a finer matching with different strategies in free flow (with or without pulse breakup fixing incorporating comparisons between the paired loops) and congestion. The third round takes care of all remaining unmatched pulses and tries to match them with unmatched transitions to recover incomplete pulses.

4.1 First Round: Basic algorithm

For each dual loop detector the basic algorithm combines all of the upstream detector and downstream detector pulses from the two loops together, sorts them by rising edge transition time (i.e., the turn-on time as a vehicle enters the detector). Most of the time the pulses should alternate "upstream detector" then "downstream detector", indicating a direct one-to-one match between the two detectors. These matched pulses are noted as a preliminary matched pair. Whenever two successive pulses are seen at a given detector, the repeated pulses are subject to additional scrutiny in the next rounds. Specifically, the unmatched pulse is considered to be the first pulse in a successive pair of upstream pulses or the second pulse in a successive pair of downstream pulses. Figure 20 shows a flow chart of how the first two rounds of processing fit together.

4.2 Second Round: Different Strategies for Different Traffic Conditions

The second round applies a more critical pass to the data to differentiate between free flow and congested conditions. It applies different strategies for free flow and congestion. In this case the threshold for free flow is made using a non-causal filter, namely, that the median speed over 11 matched pulses (five preceding, self, and five following) is larger than 30 mph [11] or the corresponding occupancy is smaller than 0.08 [12]. If traffic is congested, the pulse matching follows Section 4.2.1. If the traffic is free flowing and exactly one of the two detectors has been classified as exhibiting chronic pulse breakup and neither loop has been labeled as exhibiting chronic splashover, this work uses the method discussed in Section 4.2.2. Otherwise, the pulse matching follows Section 4.2.3.

Depending on the final outcome on the bottom right of Figure 20 (congested or not, chronic pulse breakup or not, chronic splashover or not), the pulses are then matched using the method described in one of the three following subsections. In the following discussion, all unmatched pulses embedded between two matched pairs of pulses as a “cell” (i.e., including the last preceding matched pair and first following matched pair of pulses). For each “cell”, the method calculates the moving median traversal time with ±5 matched pairs, in the same manner used to establish free flow or congestion for the preliminary matched pairs. We then define a sub-organization in a cell, which contains several consecutive pulses from upstream (with no intervening pulses from downstream) and then several consecutive pulses from downstream (with no intervening pulses from upstream) in temporal order, as a “sub”.

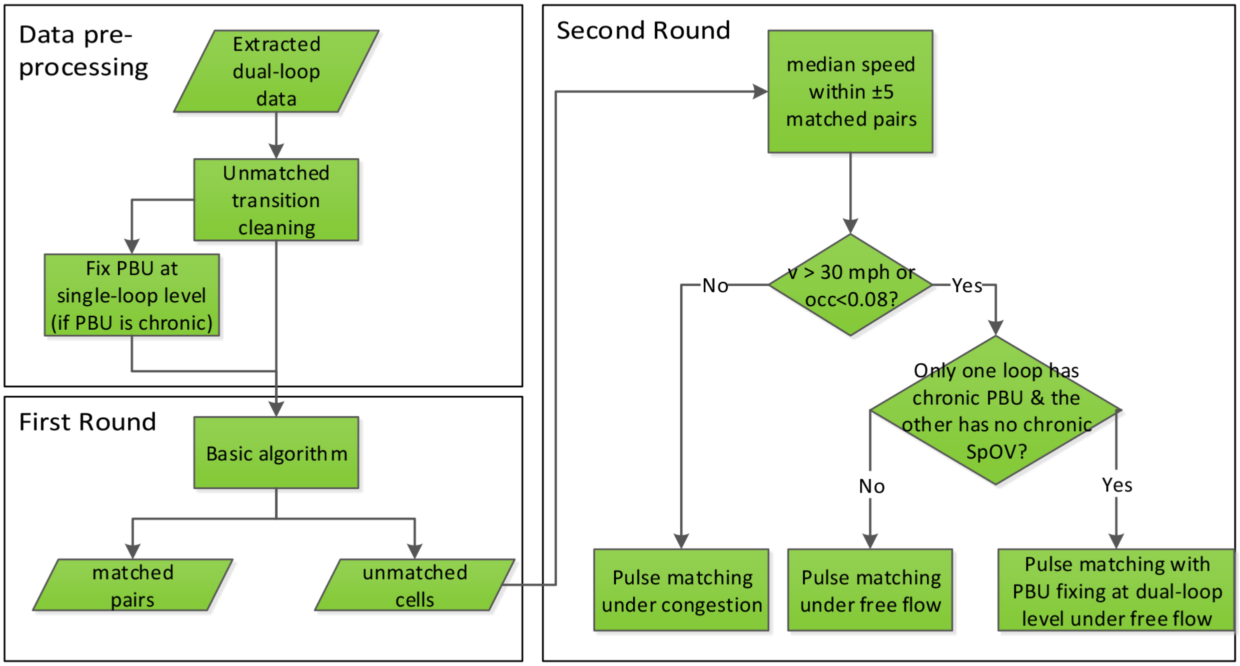


Figure 20 Flowchart key steps in the first and second rounds of pulse matching as well as data pre-processing. Note that PBU denotes pulse breakup and SpOV denotes splashover.

4.2.1 Pulse matching during congestion

During congestion one cannot ignore the impact of acceleration, so the duration of the upstream and downstream pulses from the same vehicle can differ significantly even with perfect, error free detection [22]. As a result, the redundancy of the dual loop detector cannot be used to catch detector errors and there is little that can be done beyond the preliminary matches. So in this case the unmatched pulses and unmatched transitions are not processed any further.

4.2.2 Pulse matching with pulse breakup fixing at dual-loop level during free flow conditions

If the traffic is free flowing and exactly one of the two detectors has been classified as exhibiting chronic pulse breakup and neither loop has been labeled as exhibiting chronic splashover, then at this stage the preliminary matches are taken as true except those immediately adjacent to unmatched pulses (and thus, have already been bundled in cells).

a) In each “cell”, take the loop without chronic pulse breakups as “reference” loop and the other loop is the "target" loop.

b) For each pulse from the reference loop, search the pulses in the cell from the target loop to find the pulse with a valid rising-edge traversal time (non-negative) that is closest to the moving median traversal time. If no target pulse meets the criteria, this reference pulse is considered as a “stray pulse”.

c) Otherwise, for the same reference pulse, the process is repeated to find the target loop pulse with a valid falling-edge traversal time closest to the moving median traversal time. If no target pulse meets the criteria, this reference pulse is considered as a “stray pulse”.

d) Otherwise all of the pulses between the target pulse selected in step b and the target pulse selected in step c are merged into a single pulse (with the rising-edge from b and falling edge from c). This new merged target pulse is subsequently considered to be the unique match for the reference pulse. Note that in many cases the "merged" pulse will consist of a single pulse form the target loop.

e) Move to next reference pulse in the cell and repeat until all reference pulses in the cell have been processed.

Figure 21 shows an example of matched pulses before (dashed line) and after (solid line) this cleanup step at a station that has been identified as exhibiting chronic pulse breakup problems.

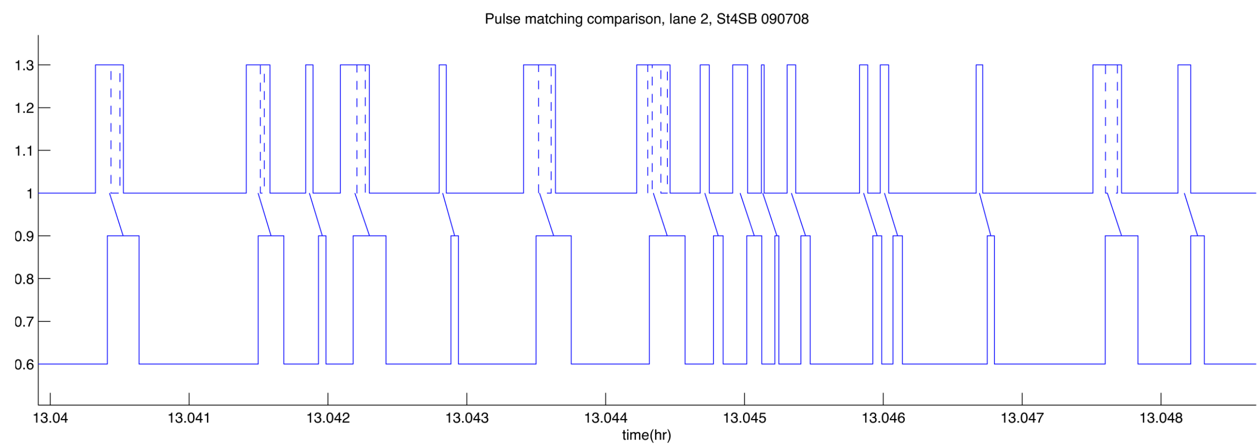


Figure 21 An example of merging broken pulses in lane 2 at Station 4 southbound (a dual loop flagged as exhibiting chronic pulse breakup) during free flow conditions. The top pulse stream is from the upstream detector the before data (dashed curve) shows several pulse breakup events that are corrected in the after data (solid curve). Diagonal lines between the upstream and downstream pulse streams denote the resulting matched pairs of pulses.

4.2.3 Pulse matching without pulse breakup fixing at dual-loop level during free flow

Like the previous section, at this stage the preliminary matches are taken as true except those immediately adjacent to unmatched pulses (and thus, have already been bundled in cells).

a) In each “cell”, take the loop fewer pulses as “reference” loop and the other loop is the "target" loop.

b) For each pair of consecutive pulses from the reference loop, if the reference loop is the upstream detector mark the first pulse in each pair as a "stray pulse"; otherwise, if the reference loop is the downstream detector mark the second pulse in each pair as a "stray pulse". If more than two successive reference pulses, repeat the pairwise comparison until a single reference pulse remains.

c) For each reference pulse, find the pulse with valid rising and falling-edge traversal time (both from the same pulse) closest to the moving median in the other loop. Match these two pulses. If no target pulse meets the criteria, this reference pulse is considered as a “stray pulse”.

d) Move to next reference pulse in the cell and repeat until all reference pulses in the cell have been processed.

4.3 Third Round: Fix Unmatched Transitions and Match to Unmatched/Stray Pulses

For all remaining unmatched and stray pulses remaining after the second round processing, the third round processing seeks to find possible unmatched transitions at the other detector that could correspond to a missing pulse with a traversal time closest to the ± 3 min’s traffic’s median traversal time (medTT_3min). If the resulting travel time for the recovered pulse is between 0 and 2*medTT_3min, the unmatched transition will be recovered to the complete pulses with the on-time of the corresponding unmatched pulse. If there is more than one such match, then the choice will be the one with the traversal time closest to medTT_3min. Finally they will be matched together.

5 Selection of Links and Representative Stations

ODOT specified that they wanted classification data for links that were defined from one ramp to the next. In many cases the CMFMS has a far greater density of detector stations than would be needed for such link definitions. Section 5.1 presents the different links and the fact that many links span multiple detector stations. Section 5.2 discusses the data availability. When there is more than one station in a given link this work exploits the redundancy and the best station is chosen on a monthly based the data availability and data quality, as discussed in Section 5.3.

5.1 Definition of Links

Figure 22 shows the resulting links from the CMFMS, using different colors for different freeways. There are a few stations that either give no data for the entire period, or work incorrectly all the time, namely Stations 8, 12 and 61, so they are excluded from all links and are not shown in the figure. Station 111 is also excluded from all links since it only contains connector ramp detectors. In some cases the bidirectional configuration differs for a given station, e.g., northbound falls within an interchange while southbound do not. As such, the north and southbound loops at a given station may be assigned to different links. Appendix A uses a tabular format to list the specific links and the stations contained therein. Note that Stations 27 and 29 to 34 are excluded from all links. During Phase I these stations did not provide sufficient accuracy and after the introduction of Phase II, were either moved to an unknown location, replaced by RTMS sensors that did not provide individual vehicle actuations, or completely removed.

5.2 Data Availability

Although the detector stations are supposed to be operational at all times, they will occasionally fail due to various reasons, such as power outage, communication loss, and detector errors. A long period of data outage during a given day will greatly undermine the traffic count. This section develops the threshold, above which the data availability for a given day and station is satisfactory and below which the station is considered to be unacceptable. For a specific day, a detector station is said to have available data only if

- Weekdays:
  - Rush hour (7:00~9:00 & 16:00~19:00)
    - For each lane, the volume in at most three 5-min counts are allowed to be 0;
  - Off-peak hour (9:00~16:00 & 19:00~24:00)
    - Each and every 5-min count summed across all lanes must be greater than 0;
  - Early morning and late night (0:00~7:00)
    - Each and every 1-hr count summed across all lanes must be greater than 0;
- Weekends:

- Off-peak hour (9:00~24:00)
    - Each and every 5-min count summed across all lanes must be greater than 0;
- Early morning and late night (0:00~9:00)
    - Each and every 1-hr count summed across all lanes must be greater than 0;

This data availability test can still reject a good station under special circumstances on the road, such as traffic accidents, road construction, lane closure and bad weather. In such cases, the extremely low traffic reported by the station is unusual but real.

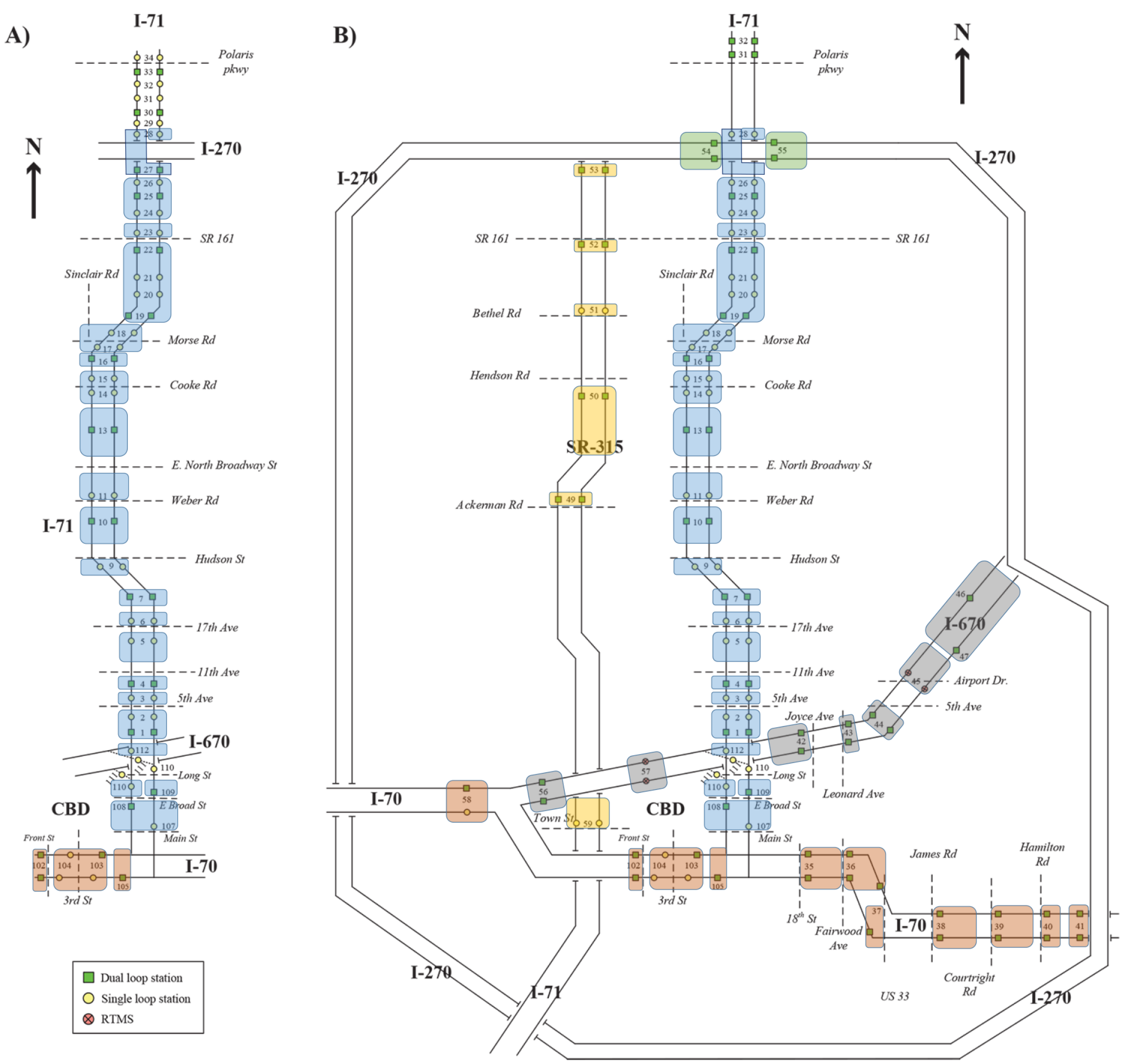


Figure 22 Vehicle classification links in Columbus Freeway Management System spanning from ramp to ramp (A) before February 2007 and (B) after February 2007. Each bubble denotes a link of the road (occasionally the links will differ slightly in the two directions). Orange: I-70; Blue: I-71 (except shared with I-70); Green: I-270; Grey: I-670; Yellow: OH-315. Stations 27 and 29 - 34 and 111 are excluded from all links throughout the entire archived period.

Special cases are included for lane drops at Station 2 northbound, where Lane 4 ends shortly past the station, and Station 31 after it was reinstalled at a new location in 2007 (recall from Section 2.1 that the lanes are numbered from inside to out). For Station 2 northbound, we still use general rules above for lanes 1-3 and also check whether Lane 4 has traffic for each hour except early morning and late night (0:00-7:00 for weekdays and 0:00-9:00 for weekends). For Station 31 from 2007 onward, we treat it as a dual-loop station except for Lane 3 (both northbound and southbound) since the upstream detectors were not in operation for these two lanes. So in both directions lane 3 is treated as a single loop detector.

5.3 Selection of Representative Stations

This section presents the method for selecting the representative detector station for a given link. This process is conducted for all links on a monthly basis. For the first stage, preference is given to stations that have at least one complete day of data for all seven days of the week during the month based on the data availability from Section 5.2. If there are no such stations in the link, the process is repeated allowing for fewer than complete days of the week with preference given to the largest number of days of the week.

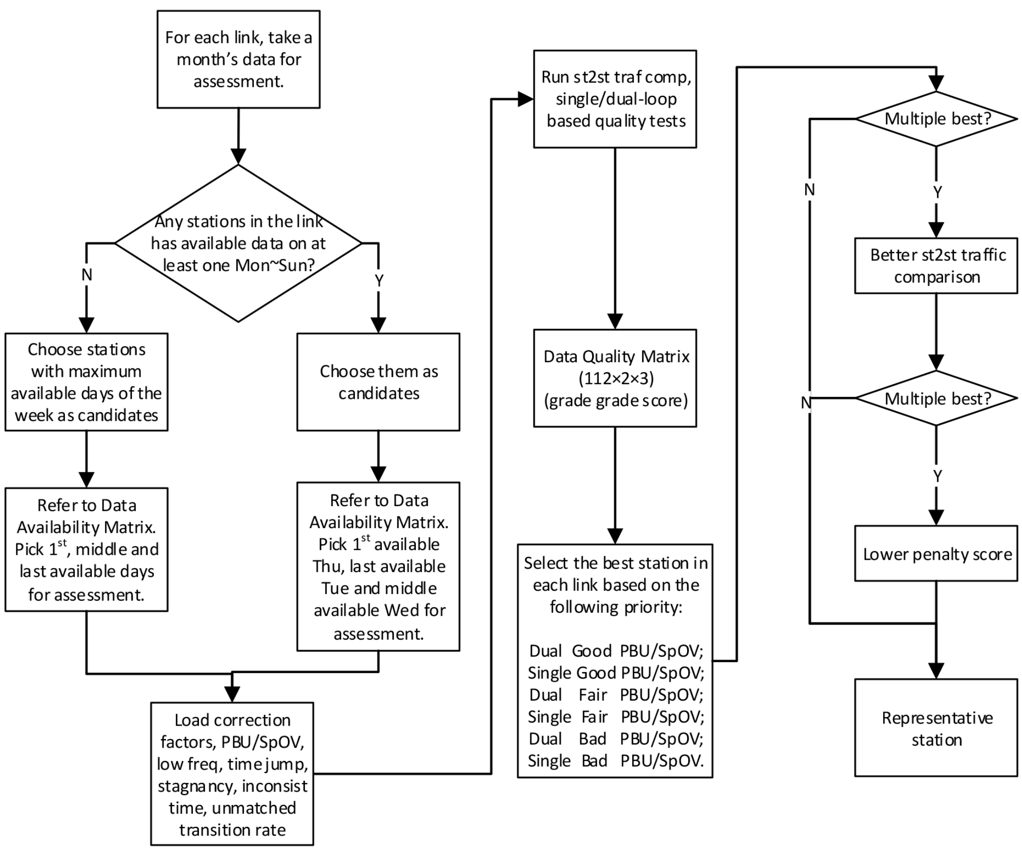


Figure 23 Flowchart showing the process of selecting a representative station selection in a given link, as applied on a monthly basis. Where, st2st traf comp: station-to-station traffic comparison; PBU / SpOV: pulse breakup / splashover; low freq: low sampling frequency; and inconsist time: Inconsistency between transition time and packet time.

All of the stations selected in the first stage are passed to the second stage to evaluate the data quality. This evaluation consists of a series of tests, starting with all of the tests from Section 3 and then continuing to the tests presented in the remainder of this section. The last of these tests distills the outcomes from the preceding tests to select the representative station that will be used for vehicle classification in the given link for the given month. Figure 23 shows a flowchart of this selection process.

5.3.1 Station-to-station traffic comparison

For any two successive stations on a given freeway, with Station A upstream of Station B, the relationship between their daily volume summed across all lanes in the same direction should adhere to one of the following four conditions:

a) No ramp between A and B:
The daily volume should be the same for A and B (within a small tolerance for minor detection errors)

b) Only on-ramps between A and B:
The daily volume at B should be greater than A due to the entering traffic

c) Only off-ramps between A and B:
The daily volume at B should be less than A due to the exiting traffic

d) Both on and off-ramps between A and B:
A and B are not comparable and no conclusion can be made.

To this end, all directional pairs of successive detector stations in the CMFMS are compared to see if they indeed follow the applicable constraint from these four scenarios. In principle, more precise comparison can be made if we utilize traffic counts from ramp detectors; however, not all ramps in the CMFMS are instrumented and those that are often exhibit large count errors due to the fact that drivers frequently have poor lane adherence on ramps. After all possible pairs of stations have been compared the results are stored in a Boolean matrix named as "fail_flag", whose elements are defined as per Equation 2. Each station's failure score, P, is calculated via Equation 3 for the i^{th} station and serves as the numerical output of station-to-station traffic comparison test. Where m_i = # of comparisons that Station i participates in and N_j is defined via Equation 4. The logic behind defining N_j in this way is to avoid increasing the number of failures for good stations simply due to their comparisons with bad stations. The "worse" the comparison station j is, the larger N_j will be, which means the less contribution (or no contribution if # of failures reaches or exceeds a threshold of 3) to related stations' failure scores it will make. Finally, the higher the failure score for the i^{th} directional station, the higher the suspicion of detector errors at that station.

$$fail\_flag_{ij} = \begin{cases} 1 & \text{if Station i to Station j comparison passes} \\ 0 & \text{if Station i to Station j comparison fails} \end{cases} \tag{2}$$

$$P_i = \sum_{j=1}^{m_i} \frac{fail\_flag_{ij}}{N_j} \tag{3}$$

$$N_j = \begin{cases} \text{\# of failures related to Station j} & \text{if \# of failures related to Station j} < 3 \\ \infty & \text{if \# of failures related to Station j} \geq 3 \end{cases} \quad (4)$$

5.3.2 Other single-loop detector based quality tests

Borrowing tests from [23-24] the analysis conducts four single loop quality tests.

Mode of on-times:

As the name suggests, the objective of this test is to determine the mode value of the on-times during free flow conditions. As most of the day vehicles will be free flowing, the mode on-times observed should correspond to free flow conditions (speeds around speed limit). One should also expect a little higher mode in the outer lanes because the traffic there tends to move at a lower speed and consist of longer vehicles. Any mode far from the expected value is taken as suspect.

- Condition to FAIL ---- < 10/60 sec or > 16/60 sec

Under Minimum On-time:

One cannot expect any speeds greater than certain maximum speed (which corresponds to some minimum on-time). The percentage of on-times that are less than the cut-off on-time is calculated. If there is a significant percentage of low on-times it would therefore indicate some error in the loop detector. This test will be helpful when the low on-times are not frequent enough to change the mode.

- Minimum On-Time ---- 10/60 sec
- Condition to FAIL ---- > 8%

Over Maximum On-time:

This test looks at the other extreme of on-times but now the analysis should be restricted to free flow conditions as the on-times for congested conditions can take any value greater than 18/60 sec (if congested conditions are defined as velocity less than 45 mph). The percentage of on-times greater than maximum on-time during free flow conditions is calculated. Almost all the on-times during free flow are expected to be less than the maximum on-time.

- Maximum On-Time ---- 75/60 sec
- Condition to FAIL ---- > 1%

Under Minimum Off-time:

Drivers maintain a certain "safe" gap between vehicles when driving and one can find a critical gap (off-time) such that all drivers exceed this value. Any gaps below this critical value cannot be feasible. The percentage of off-times that are less than the critical gap during free flow conditions helps in assessing the seriousness of this problem. A loop with a significant value of low off-time percentage will be a suspect. Typically, low off-times can be attributed to pulse breakups, tailgating or flicker.

- Minimum Off-Time ---- 20/60 sec
- Condition to FAIL ---- > 5%

5.3.3 Other dual-loop based quality tests

Borrowing tests from [23-24] the analysis conducts eight dual loop quality tests

Transition numbers difference:

Ideally, all pulses at the upstream and downstream loops are perfectly matched with each other. They should have exactly the same number of transitions. The percentage of extra transitions in the loop with more transitions is calculated. If the loops are functioning properly, such a percentage should be extremely small.

- Condition to FAIL ---- > 2%

Correction factor ratio:

The ratio (less than or equal to 1) between the upstream and downstream on-time correction factors is calculated in this test. Normally the ratio should be close to 1. The closer it is to 0, the more serious problem there will be with the sensitivity setting with one or both of the loops.

- Condition to FAIL ---- < 0.8

On-time difference:

Under free flow conditions, the time each detector is occupied by a given vehicle should be almost the same, irrespective of vehicle length. But, due to many hardware problems, the two on-times may differ. The percentage of vehicles with on-time differences greater than a threshold value is calculated. If the loops are functioning properly, only a small percentage of the differences should be over the threshold.

- Maximum On-Time Difference ---- 2.5/60 sec
- Condition to FAIL ---- > 5%

Off time difference:

This is similar to the above test but uses off-times instead of on-times.

- Maximum Off-Time Difference ---- 10/60 sec
- Condition to FAIL ---- > 5%

Under Minimum Distance:

The percentage of vehicles with a physical gap smaller than a critical gap during free flow conditions is calculated in this test.

- Minimum Distance ---- 22 ft
- Condition to FAIL ---- > 2%

Under Minimum Length:

The percentage of vehicles with measured lengths less than a minimum length is calculated.

- Minimum Length ---- 10 ft
- Condition to FAIL ---- > 2%

Over Maximum Length:

The percentage of vehicles with measured lengths greater than maximum length is calculated.

- Maximum Length ---- 90 ft
- Condition to FAIL ---- > 1%

Moving median velocity difference test:

This test compares the individual vehicle velocity against the median of 11 velocity measurements centered on the given vehicle. If the difference between the two exceeds a preset threshold, the velocity measurement is considered erroneous. This test helps to remove transient errors in velocities.

- Minimum Difference ---- median velocity/4
- Condition to FAIL ---- > 5%

5.3.4 Synthesis of the test results and priority of the criteria

While all of the various tests from Section 5.3 are valuable, except for the direct station-to-station comparison in Section 5.3.1 there is no strictly quantitative way to find the "best" station when comparing two stations together given the large number of tests or the fact that most of the tests are applied on a lane by lane basis (e.g., often one station will perform better in one test while the other station performs better on a different test). So this section describes how the work distills the results from the multiple tests across several lanes and stations into a small number of comparative grades.

The first step is simply compiling monthly median results of all tests, which is done with the Data Quality Matrix (DQM) for each month. The DQM is 112*2*3, where the first dimension is the station ID number. The second dimension represents the direction: 1 for northbound and eastbound, 2 for southbound and westbound. The third dimension has 3 items: (i) is pulse breakup / splashover grade for each station, which can be “Good”, “Fair” or “Bad” based on the percent of detectors with chronic pulse breakup or chronic splashover at the given station. Similarly, (ii) is the station-to-station traffic comparison grade, and (iii) is the penalty score, a weighted sum of all other tests except pulse breakup, splashover and station-to-station traffic comparison. The weight shows the level of importance of each test, where these weights are as used in the weighted sum, and overall the higher the weighted sum value, the lower quality of data.

The dual-loop based quality tests (except pulse breakup, splashover and station-to-station traffic comparison) are sorted into different levels of weights as follows:

- Weight=4: low sampling frequency, transition numbers difference, (unfixable) time jumps, (unfixable) stagnancy, Inconsistency between transition time and packet time, correction factor ratio.
- Weight=3: under minimum length and over maximum length.
- Weight=2: on-time difference and moving median velocity difference.
- Weight=1: under minimum distance.

The single-loop based quality tests (except pulse breakup, splashover and station-to-station traffic comparison) are sorted into different levels of weights as follows:

- Weight=4: low sampling frequency, unmatched transitions, (unfixable) time jumps, (unfixable) stagnancy, Inconsistency between transition time and packet time, mode of on-times.
- Weight=2: under minimum on-time, over maximum on-time and under minimum off-time.

We notice that the number of tests involved in the penalty score is different between single-loop and dual-loop stations. In order to make the penalty score of single-loop and dual-loop stations comparable with each other, the penalty score of single-loop stations is multiplied by a scaling factor of 11/9 to normalize for the number of tests involved.

The work then chooses a representative station for each link for the given month based on the DQM and detector type (single or dual loop detectors). Since the criteria have different levels of importance, they are considered in the order of priority. The two most significant criteria are the detector type and chronic pulse breakup/splashover grade (from Section 3.3.1) since they have the largest impact on the data quality. The selection priority is as follows:

a. Dual loop detector station with a good pulse breakup / splashover grade;
b. Single loop detector station with a good pulse breakup / splashover grade;
c. Dual loop detector station with a fair pulse breakup / splashover grade;
d. Single loop detector station with a fair pulse breakup / splashover grade;
e. Dual loop detector station with a bad pulse breakup / splashover grade;
f. Single loop detector station with a bad pulse breakup / splashover grade.

In short, the selection process prefers dual loop detector stations over single loop detector stations and then better pulse breakup / splashover grade. If we cannot get both, the pulse breakup / splashover grade is more important since only having the single loop detector measurements from good detectors is still far better than the impacts of erroneous measurements from a dual loop detector station.

If after this stage if there is more than one station with the highest grade for a given link, the station-to-station traffic comparison grades from the DQM is used to select the representative station. If multiple stations remain for the link, the station with the lowest penalty score as the representative (this work has not encountered a link with multiple representative stations after considering the penalty score, so there is no need for further tie breakers). Finally, the representative station will be used for vehicle classification in the given link for the given month.

6 Vehicle Length Calculation and Length-based Classification

One of the final steps of the length-based vehicle classification methodology is to calculate the effective vehicle length, L, which is the physical vehicle length plus the size of the detection zone. For brevity, unless otherwise specified, "vehicle length" is used to refer to the effective vehicle length throughout the remainder of this section.

Ideally, vehicle length is equal to the vehicle's speed multiplied by the on-time of corresponding actuation in the loop detector. As noted previously, 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 lane. Both types can provide accurate on-time measurement if there are few detection errors. However, for speed, while 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, or 6 m), single loop detectors can only estimate speed using the assumed constant vehicle length of a passenger car (since it is the most common vehicle in traffic) divided by the median on-time in a certain period. Due to this different nature, we treat dual loop detectors and single loop detectors differently for vehicle length calculation.

Once the vehicle length is measured, the boundaries of length-based vehicle classification are shown as follows:

- Class 1: $L \leq 28$ ft;
- Class 2: $L > 28$ ft & $L \leq 46$ ft;
- Class 3: $L > 46$ ft.

6.1 Dual Loop Detectors

As discussed in Section 5, the representative station selection prefers dual loop stations since they explicitly measure vehicle speed. To ensure the best quality of vehicle length calculation, this work uses different algorithms for free flow condition and congestion. The definition of free flow here is unconventional but consistent with Section 4.2 on pulse matching, i.e., the traffic is treated as free flowing if the median speed within ±5 nearby matched pairs is larger than 30 mph or the corresponding occupancy is smaller than 0.08. All other traffic conditions are considered as congested.

6.1.1 Free flow traffic

One vehicle passage over a dual loop detector will result in two on-time measurements (OnT_u and OnT_d from upstream and downstream loop, respectively) and two speed measurements (V_r and V_f from rising-edge and falling-edge traversal time, respectively). For passenger vehicles OnT_u and V_r are measured roughly concurrently, similarly OnT_d and V_f are measured roughly concurrently [22]. So this work uses Equations 5-6 as preliminary measures of vehicle length.

$$L_r = V_r * OnT_u \tag{5}$$

$$L_f = V_f * OnT_d \tag{6}$$

Under free flow, successive vehicles in a given lane should exhibit similar traversal times over a dual loop detector. Based on this fact, we refine the two measurements by using the moving median test [4], which is set to fail if the speed differs by more than 25% from the median speed from ±5 vehicles. If only V_r or only V_f fails the test, this work will use the other speed measurement in Equations 5-6 (i.e., both equations will use V_r or both equations will use V_f). In this case, although the speed used in Equations 5-6 are the same, we will still get two different length measurements, L_r and L_f, from the upstream and downstream on-times.

If both L_r and L_f fall in the same class, the vehicle will be assigned the corresponding class. If they belong to different classes, the single vehicle count will be split proportionately between the two classes based on the ratio of the count of single class vehicles in the two classes seen that day (by lane).

6.1.2 Congested traffic

Following the method from [22], in congestion (i.e. when the median speed within ±5 nearby matched pairs is smaller than 30 mph and the corresponding occupancy is larger than 0.08) this work stops using Equations 5-6 and switches to L_{CM+}, as defined by Equation 7.

$$L_{CM+} = \frac{V_r * T_u + V_f * T_d}{2} \tag{7}$$

When individual vehicle speed drops below 10 mph, all dual loop detector based length measurement techniques perform badly [22]. We will stop calculating vehicle length and temporarily mark the vehicle as unclassifiable. At the end of the day the unclassifiable vehicles are sorted in to the three length bins by lane on the percentages of classifiable traffic seen on that day.

6.2 Single Loop Detectors

At single loop detectors there is a single on-time measurement that includes the impacts of both speed and vehicle length. Taken alone, the two sources can not be separated. However, exploiting underlying features of the traffic, it is possible to first estimate the speed and then using conventional dual loop techniques estimate vehicle length (finding the product of an individual vehicle's speed and on-time) provided traffic is moving at least 30 mph. The logic behind this threshold is discussed in Section 6.2.1.

The key to accurate length estimates from single loop detectors is estimating speed accurately. The simplest technique recognizes that on an urban freeway most of the time the vast majority of vehicles will be passenger vehicles with length falling in a very small range, typically 18-22 ft [11]. Taking the moving median on-time of ±10 neighboring vehicle actuations centered on the current vehicle and using Equation 8 to estimate the individual vehicle speed. Assuming most vehicles in the traffic are passenger cars, the median vehicle length will be roughly a constant, L_m = 20 ft. Since the median will exclude the relatively uncommon longer vehicles, this approach provides good speed estimates even for these vehicles provided the median speed is high enough above zero.

$$v_{est} = \frac{L_m}{median(on-time)} \tag{8}$$

This approach can fail during early morning hours when there are very few passenger cars on the road and the percentage of trucks increases. Fortunately these periods are also characterized by few vehicles, so the occupancy will be very low. Following [12], this work uses a threshold of 8% occupancy, below which traffic is taken to be traveling free flow. When occupancy is below 8%, if Equation 8 yields as speed lower than the posted speed limit (e.g., because it is early morning and most vehicles in the sample were trucks, with true length much larger than L_m), the estimated speed is set to the speed limit.

When v_{est} falls below 30 mph (and occ is above 8%) the moving median speed estimate breaks down. Vehicles that pass the detector station under these speed conditions are marked as unclassifiable. As a further safety net, this work also uses an occupancy threshold. If occupancy is above 30% here too the estimated speeds are taken to be unreliable and the passing vehicles will also be labeled as unclassifiable. So the final criteria for classifying vehicles from single loop detectors is: occupancy < 8% or (estimated speed > 30 mph and occupancy < 30%). As with dual loop detectors, at the end of the day the unclassifiable vehicles are sorted in to the three length bins by lane on the percentages of classifiable traffic seen on that day.

6.2.1 Establishing the threshold for estimating vehicle lengths from single loop detectors

The threshold of 30 mph, below which vehicle length is no longer estimated, was established based on the following analysis. The basic idea is to use dual loop detectors and compare the speed estimated from the single upstream and downstream detectors (sp_est) against the speed measured by the dual loops (sp_measure). If the difference is relatively small, this work considers the speed estimation is good quality. However, as the traffic becomes more and more congested, the difference will increase and the speed estimation's quality degrades and beyond a certain point it becomes too noisy. Two criteria are used to evaluate the quality of estimated speed:

a. Average normalized abs(sp_est - sp_measure):
   Here "normalization" means abs(sp_est - sp_measure) / sp_measure.
   This index indicates the average magnitude of the difference.

b. Standard deviation of normalized (sp_est - sp_measure):
   "Normalization" has similar meaning.
   This index indicates the variation of the difference.

In both cases larger values indicate worse estimation quality. To illustrate this process, Figure 24 shows typical results for these criteria versus the measured speed from three typical dual loop detectors at different stations on a typical day. The figure shows that the two criteria remain low until reaching the 15-30 mph range. Based on these typical results, 30 mph was chosen to be the threshold, below which, the speed estimation is considered to be too noisy to provide reliable length based vehicle classification. So vehicles passing single loop detectors at estimated speeds below this threshold will be labeled as "unclassifiable vehicles."

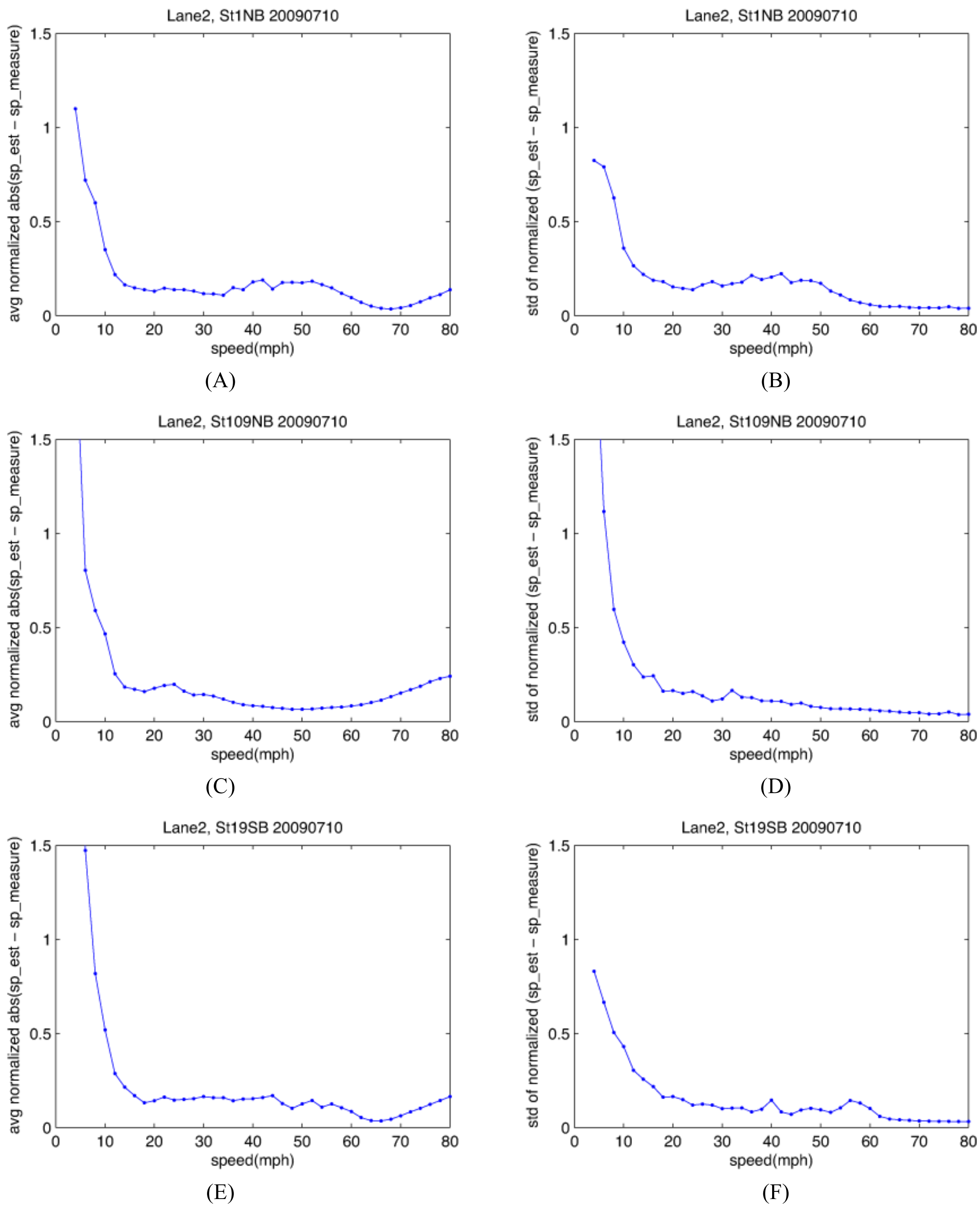


Figure 24 Examples of the two criteria used to establish the quality of estimated speed, each versus the measured speed at three typical dual loop detectors for a single day. The left column shows the average normalized abs(sp_est - sp_measure) and the right column shows the standard deviation of normalized (sp_est - sp_measure). All of the data come from July 10, 2009. The top row (A)-(B) come from Station 1, northbound lane 2, middle row (C)-(D) from Station 109 northbound lane 2, and bottom row (E)-(F) from Station 19 southbound lane 2.

7 Investigating Continued Real-Time Operations

The second thrust of this work sought to develop an on-going process collect these data into the future. The real-time aspect of the CMFMS was decommissioned in 2011 with the statewide move to vendor collected traffic speed and travel time data for real-time operations. Most of the CMFMS loop detector stations, however, remained fully functional and with the advances from the first thrust, could be used to classify vehicles. Although preliminary work was positive, unfortunately we were not able to realize this second thrust due to restricted access to the necessary ODOT communication links, several resurfacing projects that disrupted the loops, and the unanticipated need for frequent visits to the roadside controller cabinets. The goal of this activity was:

1. To determine the possibility of recreating our previous capabilities, provided through the Columbus TMC Transdyne DYNAC System, to collect time stamped raw loop transition data from the existing VDS loop stations in the field.
2. To ascertain the status and health of the existing field equipment and communications systems
3. To develop and implement a system that would collect this data and make it available to OSU and other researchers
4. To monitor, detect failures, and assist in the maintenance and upkeep of the field equipment, if possible, in order to prolong the life and usefulness of the previously installed equipment

The Transdyne DYNAC system, which monitored the CMFMS loop detector system and also provided raw, unprocessed loop transition data to an OSU computer and data collection system installed at the Columbus TMC, was retired around December 2011. However, the field equipment, as well as the OSU computer installed in the TMC, was left in place and powered, and we believed that it should be possible to communicate with the VDS controller stations in the field with an OSU designed and implemented replacement system capable of collecting and archiving the loop transitions in a format compatible with our historical data set covering roughly December 2001 - December 2011. OSU had significant pre-existing knowledge about the DYNAC system. Having been involved with the DYNAC system since its initial installation, and having access to the system while it was operational.

The initial steps in this effort involved multiple visits to the Columbus Traffic Management Center (POC: Gary Holt) to review documentation and drawings from the Transdyne DYNAC system- leading to the recovery of the documentation volume for the VDS software and communication protocols and several volumes regarding the software, hardware, and communication systems of the CMFMS DYNAC system. In addition, visual inspections were performed of the wiring and hardware configuration at the TMC to understand the current communications infrastructure connecting ODOT, the TMC, and the VDS stations in the field.

ODOT (POC: Nick Hegemier) also provided access to one of the retired DYNAC OpenVMS servers and Sybase servers. Those systems were studied in order to extract and preserve configuration information files, database files, and any other documentation or code that might be useful in the future.

Using the existing Redhat Linux data collection system at the TMC, test software was written to communicate with the field VDS stations by sending a properly formatted command stream to each VDS station and receiving any responses. This verified that sufficient information is available to allow basic communication with the VDS stations and provided the ability to test the communication path and the VDS stations themselves. It also allowed us to collect sample loop transition data from those stations that responded. At this point, we concluded that it would be possible to implement the replacement data collection. However, only 7 VDS stations, roughly 15% of the former stations, ever responded to data requests, and several of those stations were only intermittently available. This outcome was not surprising since the stations had been abandoned in place 1-2 years prior.

We made several field visits to a number of the controller cabinets in the field (this tour was led by ODOT traffic operations). Several of the stations we visited were without communications, likely due to a fiber break or a repeater being off-line. Other issues found included disconnected or misconnected cables, failed hardware, and power. After discussions with ODOT staff, we concluded that there were

- Communications issues between the field stations and the TMC, involving either the fiber links connecting the stations or the communication servers (Digi Portservers) network serial devices
- Maintenance and power issues at a number of VDS stations
- Maintenance issues with the controller hardware in the stations
- In some locations, possible issues with the loops themselves due either to construction, resurfacing, or other damage, including the I-70/I-71/I-670 interchange rebuild project

Overall, the state of the communications infrastructure in particular was far worse than we had anticipated. This, unfortunately, could not be determined until we performed our testing and evaluation, as much of the infrastructure had not been actively exercised since the decommissioning of the DYNAC system. We also explored possible data communications workarounds, mostly involving bypassing nonfunctional components or even creating a new communications link to the field hardware, but none were deemed feasible.

We visited the ODOT maintenance facilities to explore the testing and maintenance procedures involved with the field cabinet equipment in possible preparation for OSU personnel assisting with the restoration, debugging, and continued maintenance of the field VDS stations. Proceeding beyond this point depended, in large measure, on the availability of ODOT resources and personnel to assist in any needed repairs, replacements, or restoration of field hardware and communication systems. This could represent a nontrivial resource allocation, and was not within OSU control. One possibility, which we explored, involved OSU personnel taking over as much of the maintenance and repair tasks as possible- however this required giving significant access to the ODOT sites, systems, and network to OSU employees who would undertake the necessary work.

Another significant problem occurred when the Columbus TMC was decommissioned. Our pre-existing server was also removed into storage, and we lost the OSU-ODOT VPN connection that allowed us access to the required sections of ODOT's internal network. Restoring this access was critical to the success of any reactivation efforts. We explored several potential solutions:

- installing an OSU computer somewhere at ODOT with the needed network access, and providing OSU ongoing external access to that system
- providing a virtual machine at the SOCC
- reconfiguring the OSU-ODOT VPN route

Unfortunately, we encountered administrative and IT hurdles, including network and computer security issues, with all the possibilities we explored for regaining access to the internal portions of the ODOT network that serve the field stations. We were unable to make progress in this area.

8 Closing and Discussion

This study leveraged the existing archived detector data from the Columbus Metropolitan Freeway Management System (CMFMS) to generate classification data from critical freeways where the Traffic Monitoring Section has not been able to collect much classification data in the past due to site limitations. The CMFMS was deployed in an unconventional manner because it included an extensive fiber optic network, frontloading most of the communications costs, and rather than aggregating the data in the field, the detector stations sent all of the individual per-vehicle actuations (i.e., PVR data) to the traffic management center (TMC). The work yielded length based vehicle classification data from roughly 40 bi-directional miles of urban freeways in Columbus, Ohio over a continuous monitoring period of up to 10 years. The facilities span I-70, I-71, I-270, I-670, and SR-315, including the heavily congested inner-belt. Prior to this study, these facilities previously had either gone completely unmonitored or were only subject to infrequent, short-term counts. Although the CMFMS was decommissioned in 2011, many of the detector stations remain at or near operational status. This research also investigated the possibility of restarting the CMFMS to continue collecting vehicle classification data from these stations, exploiting the low communications costs associated with the existing fiber optic network. While it appears to be technically feasible, the demands to do so proved to be far too great to justify at this time, and were beyond the scope of this project.

As described in this report, the research undertook extensive diagnostics and cleaning to extract the vehicle classification data from detectors originally deployed for traffic operations. The classified vehicle counts were reported separately to ODOT, for three vehicle length classes (intended to roughly mapping to passenger vehicles, single unit trucks and multi-unit trucks), aggregated to 60 min periods over the entire duration of the archived data. Figure 25 shows an example of the classified daily counts over 3,500 days on I-71 northbound between I-670 southern and northern on-ramp, and on I-71 southbound between 5th Ave on-ramp and Leonard Ave off-ramp. In this case the selected northbound detector station frequently switches between Stations 1 and 2, while the detector station selected to be representative of southbound link remained stable across almost all of the months shown (primarily Station 1, as indicated on the plots).

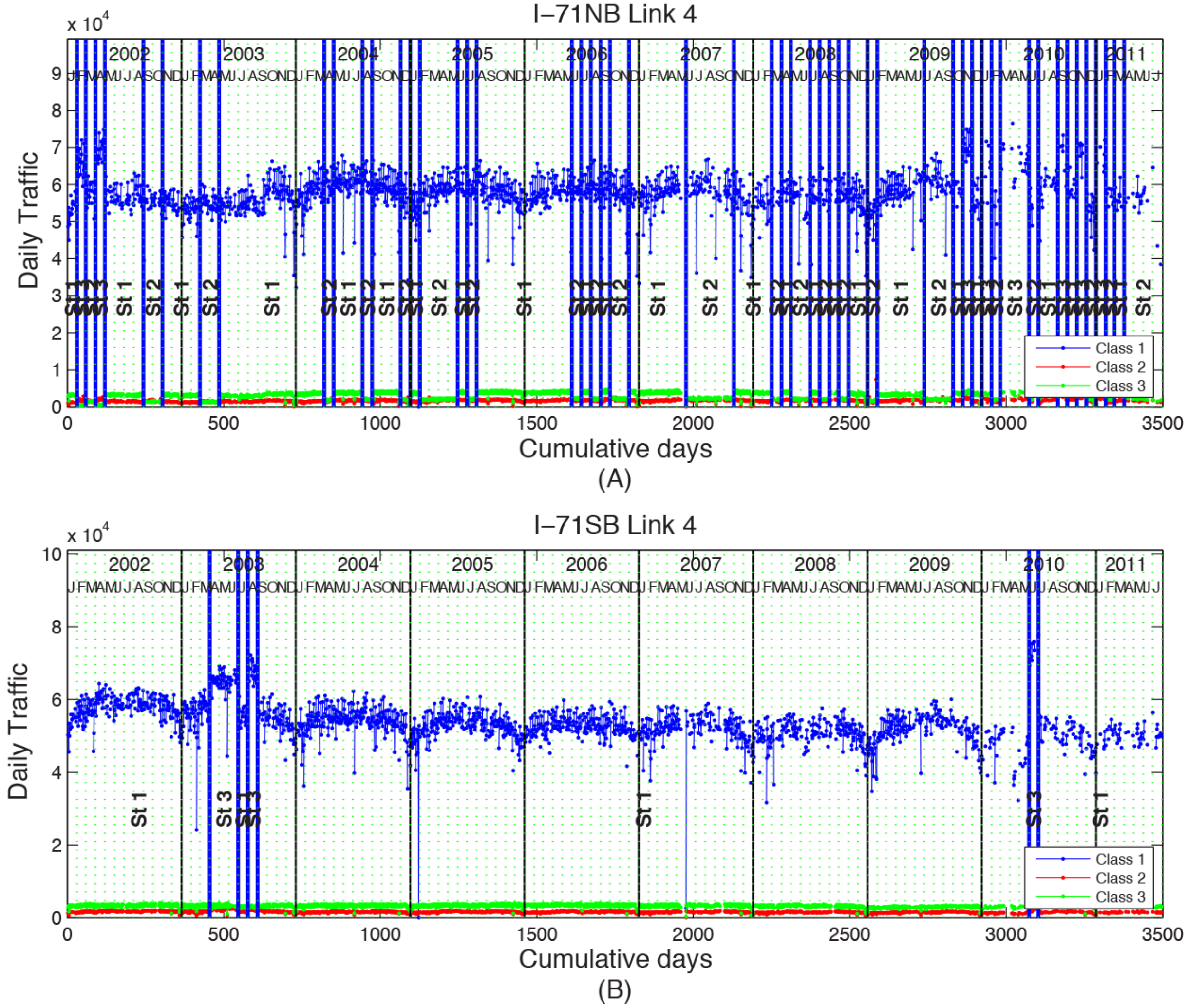


Figure 25 Daily traffic of vehicles in Class 1, 2 and 3 for Link 4 on (A) I-71 NB and (B) I-71 SB from January 1, 2002 to July 31, 2011.

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Appendix A Detailed Definition of Links

Table A-1 Detailed definition of links on I-70 EB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	Wilson ENT-Hague ENT	58	58	
2	Front EXT-Livingston EXT	102		102
3	4th St EXT-3rd St ENT	104,103	104,103	
4	3rd St ENT -I71NB EXT	105		105
5	I71SB ENT-Miller EXT	35		35
6	Kelton ENT-US33 EXT	36		36
7	US33 EXT-James EXT	37		37
8	James EXT-James ENT	38		38
9	James ENT-Hamilton EXT	39		39
10	Hamilton EXT-Hamilton ENT	40		40
11	I270 EXT-I270SB ENT	41		41

Table A-2 Detailed definition of links on I-70 WB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	I670WB ENT-Hague EXT	58		58
2	3rd St ENT-Front ENT	102		102
3	4th St EXT -3rd St ENT	104,103	104	103
4	N/A			
5	Miller ENT-I71NB EXT	35		35
6	US33 ENT-Kelton EXT	36,37		36,37
7	N/A			
8	James EXT-James ENT	38		38
9	Hamilton ENT-James EXT	39		39
10	Hamilton EXT-Hamilton ENT	40		40
11	I270SB EXT-I270SB ENT	41		41

Table A-3 Detailed definition of links on I-71 NB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	I70 ENT-Broad EXT	107	107	
2	Broad EXT- Broad ENT	109		109
3	Broad ENT-Long ENT	110	110	
4	N/A			
5	I670 ENT S- I670 ENT N	1,2	2	1
6	5th Ave EXT-5th Ave ENT	3	3	
7	5th Ave ENT-11th Ave EXT	4		4
8	11th Ave ENT-17th Ave EXT	5	5	
9	17th Ave EXT-17th Ave ENT	6	6	
10	17th Ave ENT-Hudson EXT	7		7
11	Hudson EXT- Hudson ENT	9	9	
12	Hudson ENT-Weber EXT	10		10
13	Weber EXT- Weber ENT	11	11	
14	N.Broadway ENT-Cooke EXT	13		13
15	Cooke EXT–Cooke ENT	14,15	14,15	
16	Cooke ENT-Morse EXT	16		16
17	Morse EXT-Morse ENT	17,18	17,18	
18	Morse ENT-SR161 EXT	19,20,21,22	20,21	19,22
19	SR161 EXT- SR161 ENT	23	23	
20	SR161 ENT-I270 EXT	24,25,26	25	24,26
21	I270 EXT- I270EB ENT	27		27
22	I270EB ENT-I270WB ENT	28	28	
23	I270WB ENT-Polaris EXT	29,30,31,32	29,31,32	30
24	Polaris EXT- Polaris ENT	33,34	34	33

Table A-4 Detailed definition of links on I-71 SB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	Broad EXT-I70 ENT	108		108
2	N/A			
3	I670EB ENT N-I670EB ENT S	110	110	
4	Spring EXT-I670EB ENT N	112		112
5	5th Ave ENT-Leonard Ave EXT	1,2	2	1
6	5th Ave EXT-5th Ave ENT	3	3	
7	11th Ave ENT-5th Ave EXT	4		4
8	17th Ave ENT-11th Ave EXT	5	5	
9	17th Ave EXT-17th Ave ENT	6	6	
10	Hudson ENT-17th Ave EXT	7		7
11	Hudson EXT- Hudson ENT	9	9	
12	Weber ENT-Hudson EXT	10		10
13	Weber EXT- Weber ENT	11	11	
14	Cooke ENT-N.Broadway EXT	13		13
15	Cooke EXT–Cooke ENT	14,15	14,15	
16	Morse ENT-Cooke EXT	16		16
17	Morse EXT-Morse ENT	17,18	17,18	
18	SR161 ENT-Morse EXT	19,20,21,22	20,21	19,22
19	SR161 EXT- SR161 ENT	23	23	
20	I270 ENT-SR161 EXT	24,25,26	25	24,26
21	I270WB EXT- I270EB EXT	27, 28	28	27
22	N/A			
23	Polaris ENT-I270WB EXT	29,30,31,32	29,31,32	30
24	Polaris EXT- Polaris ENT	33,34	34	33

Table A-5 Detailed definition of links on I-270 EB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	SR315NB ENT-I71 EXT	54		54
2	I71SB ENT-I71NB ENT	55		55

Table A-6 Detailed definition of links on I-270 WB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	I71 ENT-SR315NB EXT	54		54
2	I71 EXT-I71 ENT	55		55

Table A-7 Detailed definition of links on I-670 EB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	I70EB ENT-US33 ENT	56		56
2	3rd St EXT-3rd St ENT	57	57	
3	E Merge-Leonard EXT	42		42
4	Leonard EXT-Leonard ENT	43		43
5	5th Ave EXT-5th Ave ENT	44		44
6	Airport EXT-Airport ENT	45	45	
7	International ENT-END	47		47

Table A-8 Detailed definition of links on I-670 WB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	US33 EXT-I70WB EXT	56		56
2	W Merge-3rd St ENT	57	57	
3	Leonard ENT-I71 EXT	42		42
4	Leonard EXT-Leonard ENT	43		43
5	5th Ave EXT-5th Ave ENT	44		44
6	Airport ENT-5th Ave EXT	45	45	
7	START-Airport EXT	46		46

Table A-9 Detailed definition of links on SR-315 NB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	Rich EXT-Town ENT	59	59	
2	Ackerman EXT-Ackerman ENT	49		49
3	N.Broadway ENT-Henderson EXT	50		50
4	Bethel EXT-Bethel ENT	51		51
5	SR161 EXT-SR161 ENT	52		52
6	I270EB EXT-I270EB ENT	53		53

Table A-10 Detailed definition of links on SR-315 SB

Link Number	Road Sec	Station list	Single loop stations	Dual loop stations
1	Town EXT-Rich ENT	59	59	
2	Ackerman EXT-Ackerman ENT	49		49
3	Henderson ENT-N.Broadway EXT	50		50
4	Bethel EXT-Bethel ENT	51		51
5	SR161 EXT-SR161 ENT	52		52
6	I270EB EXT-I270 ENT	53		53

Appendix B, Further validation on lane mapping

To further validate lane mapping, our group compared instrumented probe vehicle data against the loop detector data over the period from October 23, 2008 to the end of archived CMFMS data. After analyzing stations 102-112 and 1-33, the work found that almost all of these stations either have correct lane mapping or the lane mapping errors discovered directly from the loop detector data (as discussed in Section 2.1.2). The one exception is stations 102 to 104 westbound, which have incorrect lane mapping even after the revisions described in Section 2.1.2. Of these three stations, two were in error; thus, misleading the majority voting process for these stations. Based on that work, the revised lane mapping is shown in Table B-1. Since the majority of stations exhibited the same lane mapping error in this segment the independent validation was necessary to catch and fix the error.

Table B-1 Original and revised lane mapping for Stations 102 - 105; where Ln 2 upst and Ln 2 dnst denote the lane 2 upstream and lane 2 downstream loops, respectively. The cells show the Loop ID's or "-" for no such loop. Station 103 eastbound and 104 only have single loop detectors, which are all shown as upst in this table. Changes in the revision are highlighted with a bold font and shaded background.

		Ln1 upst	Ln1 dnst	Ln2 upst	Ln2 dnst	Ln3 upst	Ln3 dnst	Ln4 upst	Ln4 dnst
St 102 EB	original	13	14	19	20	21	22	-	-
	revised	13	14	19	20	21	22	-	-
St 102 WB	original	23	24	15	16	27	28	-	-
	revised	23	24	15	16	27	28	-	-
St 103 EB	original	15	-	16	-	17	-	-	-
	revised	15	-	16	-	17	-	-	-
St 103 WB	original	22	21	20	19	14	13	-	-
	revised	**20**	**19**	**22**	**21**	14	13	-	-
St 104 EB	original	13	-	14	-	19	-	-	-
	revised	**14**	-	**13**	-	19	-	-	-
St 104 WB	original	21	-	22	-	23	-	-	-
	revised	**22**	-	**21**	-	23	-	-	-
St 105 EB	original	14	13	20	19	22	21	24	23
	revised	14	13	20	19	22	**23**	**21**	**24**