EVALUATION OF THE PERFORMANCE OF LOOP DETECTORS AND FREEWAY PERFORMANCE MEASUREMENT FROM LOOP DETECTORS

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ABSTRACT

A Freeway Management System (FMS) acquires data from the roadway and processes these data to identify and respond to problems, notifying operators and motorists of those problems. If some aspects of the data collection are unreliable, then the response decisions and the information given may well be faulty. Hence, accurate traffic data acquisition is essential for effective traffic surveillance and subsequent management applications.

Loop detectors, the most commonly used vehicle detectors for freeway traffic surveillance, are not always calibrated correctly, so it is necessary to identify potentially inaccurate detectors. This thesis presents an evaluation of the performance of the loop detectors on I-71 in Columbus, Ohio. The evaluation includes the percentage of vehicles actuating only one loop in a dual loop detector, and detector mapping error tracked by the relationship of speed and occupancy from a dual loop detector. In addition, loop correction factors for both single and dual loop detectors are calculated to improve the accuracy of speed estimates and measurements. The analysis employs both statistical trends gathered from the detectors and concurrent velocities collected from probe vehicles as they pass over the detectors. As shown herein, loop detector’s sensitivity can change over time which impacts speed and occupancy from that loop. So, the trend of daily median speed for off-peak time periods is used to determine the change in
sensitivity of loop detectors over long time periods. This trend is then used to illustrate the fact that the correction factors can abruptly change. In the course of this work performance measurements of the freeway using the corrected loop detector data are developed, namely average daily traffic and delay. The weekday median for both of the daily measures is calculated at each week to track trends over years. The weekly average daily traffic and delay present an overview of the freeway system usage and performance. Also, summary plots and summary difference plots are developed to show how traffic condition evolves over time and space for identifying traffic condition and recurring congestion.

Although presented in the context of the Columbus system, the tools should be generalizable to most freeway surveillance systems.

Key words:

Loop detectors; Sensitivity of loop detectors; Traffic surveillance; Performance measurements
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CHAPTER 1

INTRODUCTION

The development and deployment of Intelligent Transportation System (ITS) technologies provide a wide variety of opportunities for local, regional and state agencies to improve the capacity, reliability, and efficiency of their transportation systems. ITS deployments themselves typically include surveillance systems that enable a more comprehensive understanding of how the existing transportation system operates and facilitates proactive strategies for managing the transportation system more efficiently [1]. A Freeway Management System (FMS) is one such example, and it is intended to improve safety, optimize the capacity of the freeway and provide a better level of service to motorists without the addition of more traffic lanes [2]. The FMS acquires data from the roadway and processes these data to identify and respond to problems, notifying operators and motorists of those problems. If some aspects of the data are unreliable, then the response decisions and the information given may well be faulty. Hence, accurate traffic data acquisition is essential for effective traffic surveillance, the backbone of such ITS management applications.
There are two basic types of traffic surveillance systems: road-based and vehicle-based. Road-based detection systems such as loop detectors, radar detectors, and video cameras, have been a principal element of freeway surveillance and incident detection for many years. In particular, loop detectors are the most commonly used detectors. Vehicle-based traffic surveillance systems involve probe vehicles equipped with Global Positioning System (GPS). A GPS receiver collects the real-time latitude and longitude information of a vehicle and sends this information to a operations control center for processing either in real time or after the fact [3].

The Ohio Department of Transportation (ODOT), in conjunction with the city of Columbus and the Federal Highway Administration, is currently installing and implementing the intelligent Columbus Metropolitan Freeway Management System (CMFMS) in Columbus, Ohio. The CMFMS is designed to enhance traffic data collection, incident management, traffic management, and traveler information. CMFMS Phase 1 was completed in 2001, and the second phase for full build-out is currently under construction. This regional system includes traffic sensors, variable message signs (VMS), closed circuit television (CCTV) cameras, ramp metering, a telecommunications system and operating hardware and software to monitor and control this equipment [4,5,6].

The purpose of this thesis is to evaluate the performance of a freeway corridor using loop detector data. The CMFMS is the focus of this work and presented as a case study for other freeways. The first step in this evaluation is to assess the loop detectors themselves, as they are not always calibrated correctly and might have unexpected
physical problems. Otherwise, errors from incorrect detector data can propagate to subsequent performance measurements from the loop detectors. Several loop detector problems are tested for and addressed, in some cases the problems can be fixed, while in other cases the problem data are simply excluded. After the loop detector problems are addressed, the focus of this thesis shifts to developing several performance measurements and tools that present the freeway usage and performance over large time periods, over large distances, or both.

1.1 Measurements from loop detectors

There are two types of loop detectors, namely single and dual loop detectors. Figure 1.1 shows the time-space diagram of a vehicle passing over a single loop detector. The effective detection zone indicates the area in which the loop detects the presence or absence of vehicles, the size of which depends on the sensitivity of the loop detector. High sensitivity leads to a larger detection zone and low sensitivity leads to a smaller detection zone, in either case the zone can potentially be larger or smaller than the physical loop itself.\(^1\) As shown in Figure 1.1B, a single loop detector records two transitions, i.e., “turning-on” and “turning-off” when a vehicle passes over it. The “off” state indicates that there is no vehicle on the loop detector. When a vehicle arrives at the upstream edge of the detection zone, the state transitions to “on”. Similarly, the state transitions to “off” when a vehicle departures from the downstream edge of the detection

\(^1\) For brevity, unless otherwise specified, “detection zone” is used to refer to the effective detection zone throughout the remainder of this thesis.
zone. This change of state from “off” to “on”, and then back to “off” represents the passage of a vehicle, and looks like a pulse in the time series data, e.g., as shown in Figure 1.1B, [7].

Figure 1.1: A vehicle passing over a single loop detector, (A) effective detection zone and vehicle trajectory in time space plane (B) the associated turn-on and turn-off time

Flow \( q_i \) in sample period \( i \) is defined as the number of vehicles per unit time that pass over the given loop detector during sample period \( i \), and is given by:

\[
q_i = \frac{n_i}{T} \quad (1.1)
\]

Where,

\( n_i \) = number of vehicles that pass the detector during sample period \( i \),

\( T \) = duration of sampling period.
The duration which a vehicle occupies a single loop detector is called the detector on-time, i.e., $OT_k$ in Figure 1.1. Occupancy ($occ_i$), the percentage of time the detector occupied by vehicles in sample $i$, is as follows:

$$occ_i = \frac{\sum OT_k}{T}$$

(1.2)

Assuming vehicle lengths and speeds are uncorrelated, speed from a single loop detector is commonly estimated by the following equation$^2$:

$$\hat{v}_i = \frac{\hat{L}_{\text{mean}} \times q_i}{occ_i}$$

(1.3)

Where,

$\hat{v}_i$ = estimated mean speed of sample period $i$,

$\hat{L}_{\text{mean}}$ = assumed constant mean effective vehicle length$^3$.

From equation 1.1 and 1.2, flow ($q_i$) divided by occupancy ($occ_i$) corresponds to mean on-time in sample period $i$. If mean on-time in sample period $i$ is consistent with $\hat{L}_{\text{mean}}$, equation 1.3 provides a good estimate. However, this approach fails to account for the fact that the true but unmeasured $L$ changes from vehicle to vehicle, and hence the sample average, $L_{\text{mean}}$, also changes during the day. As noted in [9], if the discrepancy between $L_{\text{mean}}$ and $\hat{L}_{\text{mean}}$ is large, inconsistency between mean on-time in sample period $i$.

$^2$ See, e.g., [7] for a derivation of this commonly used estimation

$^3$ As shown in Figure 1.1, the effective vehicle length includes the vehicle’s physical length and the length of the effective detection zone. For brevity, unless otherwise specified, “vehicle length” is used to refer to the effective vehicle length in the remainder of this thesis.
and $\hat{L}_{\text{mean}}$ leads to a poor estimate of speed. A new aggregation methodology to estimate speed from a single loop detector was introduced in [9] to improve the consistency between assumed constant vehicle length and on-times, i.e., taking the median on-time to reduce the impact of long vehicles, as shown in equation 1.4. The median on-time is less sensitive to outliers in on-time such as from long vehicles, rather than mean on-time, and is more likely representative of on-time in a sample period. The new methodology showed that median estimated speed reduces significantly speed estimation errors (relative to equation 1.3) due to the long vehicles.

$$\hat{v}_i = \frac{\hat{L}}{\text{median on-time}_i} \quad (1.4)$$

Where,

$$\text{median on-time}_i = \text{median of all on-times observed in sample period } i,$$

$$\hat{L} = \text{assumed constant effective vehicle length}.$$ 

However, in equation 1.4, we still cannot guarantee that the assumed constant vehicle length is representative of true vehicle length and effective detection zone. If the true $L$ (and hence median on-time) for a given sample is not consistent with $\hat{L}$, equation 1.4 will yield a poor estimate of speed. As will be discussed in section 3.3.1, incorrect assumed constant vehicle length leads to errors in estimated speed.

A dual loop detector consists of two single loop detectors spaced a fixed distance apart (typically on the order of 20ft). When a vehicle passes over a dual loop detector, the upstream detector is activated and then the downstream detector. Each pulse at the
downstream loop is matched to the most recent pulse at the upstream loop that preceded it. After matching pulses between loops, Figure 1.2B shows the measurements at a dual loop detector when a vehicle passes over it [10], where on₁ and on₂ denote the times of the rising edges, off₁ and off₂ denote the times of the falling edges of the pulses. OT₁ and OT₂ indicate the on-time which the given loop was occupied by a vehicle. Dual loop traversal time (TTᵣ or TTᵱ) is defined as the difference of arrival time at the rising edges or the falling edges between first and second loop detection zones.

Figure 1.2: A vehicle passing over a double loop detector, (A) the two detection zones and vehicle trajectory in the time space plane (B) the associated turn-on and turn-off times at each detector. From [10].
Speed is calculated from the effective loop spacing\(^4\) (\(L_D\) in this figure) and traversal time that it takes for the vehicle to travel from the first loop detector to the second loop detector.

\[
\hat{v}_{tr} = \frac{L_D}{TT_r} \tag{1.5}
\]

\[
\hat{v}_r = \frac{L_D}{TT_r}
\]

The space mean speed for a sampling period is taken from a harmonic average of individual vehicles' speeds. Since flow and occupancy are available from both detectors, the average of estimates from the two detectors is used in the following analysis. As will be discussed in section 3.2.2, incorrect loop spacing leads to error in measured speed from equation 1.5.

\(^4\)As shown in Figure 1.2, the effective loop spacing depends primarily on the physical loop spacing. However, the sensitivity of the loops leads to changes in the size of the detection zone. Thus, the effective loop spacing could be larger or smaller than the physical loop spacing. For brevity, unless otherwise specified, “loop spacing” is used to refer to the effective loop spacing for a dual loop detector throughout the remainder of this thesis.
1.2 Organization of Thesis

This thesis is organized into five chapters. Chapter 1 is this introduction. Chapter 2 is a literature review, describing the validation and performance measures from loop detectors. Chapter 3 presents the performance evaluation of the CMFMS loop detectors, including the development and application of tools to identify loop detector problem such as correction factors for both single and dual loop detectors. After the loop detector problems are addressed, Chapter 4 describes the performance measurement from loop detectors. Several tools presenting the freeway usage and traffic conditions are developed. Chapter 5 presents conclusions.
CHAPTER 2

LITERATURE REVIEW

2.1 Validation of loop detectors

Loop detectors are the most common vehicle detectors for freeway traffic surveillance. Data obtained from loop detectors are used for applications such as ramp metering, incident detection and travel time prediction. Errors in detection could propagate to all control decisions. It is necessary to identify non-performing and inaccurate detectors. The most common test is to simply check that the detector seems to be counting the correct number of vehicles or that average speeds are “reasonable”. Even though such tests will catch severe errors, other problems cannot be caught as easily.

Many practitioners and some researchers have worked to formalize heuristic tests to check average measurements against statistical tolerances. Jacobson et al. [11] introduced a test for setting limits for acceptable values of volumes for any given occupancy on the basis of plausible ratios between flow and occupancy within specific occupancy ranges. Cleghorn et al. [12] improved the screening method so as to obtain a tighter upper bound from feasible flow-occupancy pairs. Also, they presented the additional screening for dual loop detectors. It includes comparison of the received
speed-flow-occupancy points and a calibrated three-dimensional speed-flow-occupancy region as well as comparison of measurements between upstream and downstream loops. Chen et al. [13] developed a diagnostic algorithm that detects bad data from single loop detectors based on the difference between the current sample and the recent trend in observations. The algorithm for loop error detection uses the time series of flow and occupancy measurements, rather than making a decision based on an individual sample. It is based on the empirical observation that good and bad detectors behave very differently over time.

Chen and May [14] deviated from the aggregate measurement approaches and used individual vehicle actuations to verify detector data. Their methodology examines the distribution of vehicles’ on-time. Unlike conventional aggregate measures, their approach is sensitive to errors such as “pulse breakups”, where a single vehicle is detected multiple times. Coifman [15] compared the measured on-times for each loop in a dual loop detector to identify errors. Because the two loops are closely spaced within a single lane in a dual loop, the on-times from the loops during free flow condition should be virtually identical regardless of vehicle length. If the difference of the two on-times deviates significantly from zero, it indicates hardware or software problems. At lower speeds vehicle acceleration can result in a difference of on-times and congested periods were excluded from the earlier analysis. To yield the difference of on-times, it is necessary to match actuations between the upstream and downstream loops in the given lane. Coifman and Dhoorjaty [10] developed eight new detector validation tests that identified detector errors both at single loop and dual loop detectors.
Similar to earlier studies, this thesis employs the relationships of speed and occupancy to identify physical problems at the detector stations, e.g., detector mapping errors. But deviating slightly from these earlier studies, in this thesis the percentage of unmatched pulses will be used to determine the quality of dual loop data, rather than the on-time difference. Calculating the on-time differences requires matching of pulses between the two detectors, and implicitly, any unmatched pulse is not included in the test. In contrast, the percentage of unmatched pulses presents quality of the original dual loop detector data before matching. Chapter 3 discusses the tests and their implementation.

2.2 Freeway Performance Measures

Data collection and surveillance systems are used to operate transportation systems on a day-to-day basis. Performance measures generated from traffic surveillance data might be helpful to plan, design, and operate transportation systems. As evidence of development of performance measures for operations, the National Cooperative Highway Research Program (NCHRP) Project 8-32(2) [16] indicates the movement toward the greater use of performance measures, and includes various sample performance measures in categories of mobility, economic development, quality of life, the environment, and resource conservation and safety. Based on this report, Bertini [17] generated a set of performance measures for a freeway corridor using loop detector data, and obtained information evaluating the functionality of the facility. Performance measures indicating the quality of mobility of the corridor were developed as follows: average daily traffic, travel time, vehicle or person miles traveled, vehicle or person hours traveled, and delay
per vehicle miles traveled. In California, the Performance Measurement System (PeMS) extracts information from real time and historical data, then generates performance measurements on the freeway, e.g., vehicle miles traveled, vehicle hours traveled, delay and travel time. It presents information in various forms to assist managers, traffic engineers, planners, freeway users, researchers, and traveler information service providers [18,19]. The application of PeMS is used to analyze existing operating conditions, to determine the level of service at several freeway segments, to identify the location of bottlenecks and assess their impacts, to analyze the impacts of major incidents, and to assess advanced control strategies. Ishimaru et al. [20] show general measures of facility usage and facility performance based on information from traffic surveillance data. Facility usage was estimated in two ways, average annual weekday volume and average peak vehicle volume. The performance of the freeway network along a corridor is measured by the following measures: facility-wide traffic patterns as a function of time of day and location on the corridor; average travel times along selected routes; and variability and reliability of travel times on those routes. While the performance at selected locations is measured by average vehicle volume, average speed, and average congestion frequency.

Based on earlier research, chapter 4 develops several performance measures for freeways using loop detector data. Historical performance measures over long time periods, e.g., ADT and delay trend, are used to present the freeway system usage and performance. This work develops what will be termed the weekly median to facilitate the clear presentation of such time series data over months and years without obscuring the
general trends. Like some of the earlier works, this thesis employs summary plots to capture conditions along the corridor over space in time. But the effort goes further and develops the summary difference plots, showing the difference between given date and the corresponding average of that day (weekday or weekend) at each location and time sample and the plot highlights non-recurring events. Meanwhile, the monthly average day (weekday or weekend) highlights recurring congestion.
CHAPTER 3

EVALUATION OF THE PERFORMANCE OF LOOP DETECTORS

Loop detectors are the most commonly used vehicle detectors for freeway traffic surveillance and they are employed as the primary detection system in the CMFMS. Loop detectors are not always calibrated correctly, so it is necessary to identify potentially inaccurate detectors. The redundancy between the two loops in a dual loop detector provides a simple but effective measure of the quality of the dual loop data. If everything is working properly, each passing vehicle should actuate both loops, with few unmatched pulses. Employing this fact, the percentage of unmatched pulses is calculated from the process of pulse matching in a dual loop detector. At a more sophisticated level, incorrect detector mapping at the dual loop detector stations is also tracked by the relationship of speed and occupancy. In addition, the errors in speed from both single and dual loops are identified with initially assumed constant effective vehicle length in single loops and initial effective loop spacing in dual loops. Loop correction factors for both single and dual loop detectors are calculated to improve the accuracy of speed estimates and measurements. The analysis employs both statistical trends gathered from the detectors and concurrent velocities collected from probe vehicles as they pass over the detectors.
3.1 Data and Vehicle Measurements

3.1.1 Loop detector data

Individual vehicle actuation data, as shown in Figure 1.1B and Figure 1.2B, were collected from the 45 detector stations on I-70/I-71 in the CMFMS, sampled at 240 Hz. These stations include 145 loop detectors on the northbound freeway mainline lanes and 140 loop detectors on the southbound freeway mainline lanes. Figure 3.1 shows a schematic of the corridor. For the most part there is one dual loop station every mile, with two single loop stations between dual loop stations. At dual loop stations, for all measurements that use information from the paired loops, the corresponding pulses from a given vehicle at both loops need to be matched. As explained later in this analysis, each pulse at a downstream loop is matched with most recent pulse observed at the upstream loop. All the individual vehicle measurements are calculated as per section 1.1.
Figure 3.1: A schematic of corridor
3.1.2 Travel run data (GPS data)

Travel run data are collected from a probe vehicle equipped with a GPS receiver to provide an independent validation of freeway operation. For each tour, drivers take a vehicle on two round trips during the morning peak (7hr-9hr) or evening peak (16hr-18hr), Tuesday through Thursday. Travel run data cover almost all detector stations on I-70/I-71 from downtown (station 102) to Polaris Parkway (station 33). Drivers are instructed to normally travel in the second lane from the left, though they can pass slow vehicles if warranted. The GPS receiver records the location of the vehicle (longitude and latitude), and velocity every second. Figure 3.2 shows the number of travel runs by month collected from the probe vehicle. Each run corresponds to two round trips, i.e., two travel measurements.

Figure 3.2: The number of travel runs by month (A) AM (7hr to 9hr), (B) PM (16hr to 18hr).

Since GPS data quality depends on visibility of satellites by a GPS receiver, GPS position errors cannot be avoided. Structures, terrain and even dense foliage can block
signal reception or cause multipath interference, resulting in position errors or possibly no position reading at all [21]. Figure 3.3 shows a detail of the GPS readings from one round trip, superimposed on an aerial photo of the region. The highlighted point in the figure shows an example of a position error due to an overpass interfering with signal reception. Fortunately, most GPS errors are local in nature, and they do not accumulate from one measurement to the next.

Figure 3.3: GPS position error from travel run data

To facilitate comparisons between runs, reducing local noise from measurement errors and passing maneuvers while providing a common reference distance across all runs, each position measurement is projected to a single reference run based on a method developed by Xin Wang in 2003 [22]. For each point on a run, the closest point on the
reference run is found. These snapped position data are then used throughout our analysis, the first application being loop detector speed validation. Note that the original GPS velocity measurements are not changed in the snapping. For verifying loop speed with GPS velocity, the coordinates associated with the location of loop detector stations are found from a georeferenced, high resolution aerial photo of I-70/I-71. The coordinates of the detector stations are presented in Appendix A.
3.2 Problems of loop detectors

3.2.1 Unmatched pulses 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. Sometimes, however, one loop may fail to actuate or it may actuate erroneously. The two loops can be used to validate one another. Each actuation at one loop should be uniquely matched to a single actuation at the other. Matching each downstream pulse with the most recent upstream pulse, any extra pulses at the upstream loop are considered unmatched. Repeating the process from the upstream loop, matching an upstream pulse with the immediate downstream pulse, any extra pulses at the downstream loop are also considered unmatched. The percentage of unmatched pulses is used as one measure of the quality of dual loop data and the status of the loop detectors. Figure 3.4 shows the percentage of unmatched pulses at upstream and downstream loops over the 15 dual loop stations on I-70/I-71, for both directions on July 12, 2004 over the entire 24-hr period. The percentage of unmatched pulses at each loop in a dual loop detector is calculated from the number of unmatched pulses at the loop divided by a total number of pulses at that loop. Stations 10, 16, 102 and 105 indicate that a percentage of unmatched pulse is relatively higher than the other stations. This process is repeated in detail on individual lanes shown in Figure 3.5. Both station 105 northbound and station 102 southbound exhibit a large number of unmatched pulses. As explained shortly, these stations have an incorrect detector mapping on the sample day.
Figure 3.4: Total percent of unmatched pulses at each loop in dual loop detectors at 15 stations. Top plots show northbound, bottom show southbound. The left column shows the results on a large vertical scale while the right column repeats the data on a smaller scale.

Figure 3.5: Total percent of unmatched pulses at each loop in a dual loop detector for A) northbound and B) southbound direction. Within each subfigure the top plots show the upstream loop detectors, bottom plots show the downstream loop detectors for each direction. The left column shows the results on a large vertical scale while the right column repeats the data on a smaller scale.
3.2.2 Incorrect dual loop detector mapping

Each loop detector input to a detector station’s controller has a unique number. The configuration data maps these somewhat arbitrary input numbers to physical lanes in the freeway and upstream or downstream loop if a dual loop detector. Maintenance activity, such as reinstallation of loop detectors after pavement rehabilitation, can lead to mapping errors, i.e., a discrepancy between the assumed location and actual location of a given loop. An incorrect detector mapping causes a relatively large number of unmatched pulses in a dual loop detector. The remaining pulses are matched incorrectly and result in incorrect traversal times, i.e., speed might be underestimated or overestimated. Occupancy, on the other hand, is measured without matching pulses between the two loops. Taking the average occupancy between the two loops, if they are in the correct lane but have the orientation switched it will still yield the correct occupancy even though the measured speed is inaccurate. If the loops are actually in different lanes the average occupancy between the two should be halfway between the true lane occupancy for those loops. The relationship of speed and occupancy is used to identify dual loop stations with incorrect loop detector mapping. Generally, speed monotonically decreases with increased occupancy. If the speed-occupancy relationship deviates highly from this general relationship, the dual loop detector is likely in error, potentially due to an incorrect detector mapping. The time period chosen to illustrate this test is July 1, 2004 through August 31, 2004. Using all of the aggregated data from these two months, most of the dual loop stations perform as expected, e.g., as shown in Figure 3.6. However, among detectors at all dual loop stations, station 102 and station 105 northbound, and
station 102 southbound present an anomalous relationship of speed and occupancy, as shown in Figure 3.7.

Figure 3.6: Example of good relationship of speed and occupancy A) Station 16 northbound, B) Station 103 southbound.
Figure 3.7: Anomalous relationship of speed and occupancy A) Station 102 northbound, B) Station 102 southbound, C) Station 105 northbound.

The speed-occupancy relationship differs from the expected relationship in lane 2 at station 102 northbound, and lane 1 and lane 2 at station 102 southbound. Also, all lanes at station 105 northbound appear to be anomalous, compared to general relationship of speed-occupancy. Plots of transition pulses for these loop stations indicate the patterns are related to incorrect detector mapping, as shown in Figure 3.8. The transition pulses are grouped into lanes based on the original detector mapping, and the orientation corresponds to vehicle direction of travel, i.e., upstream to downstream denoted “u” and
“d”, respectively. “RM” shows a loop detector on ramp. One would expect the downstream time series to lag the upstream by a fraction of a second during free flow condition. At station 102 one can see that the data thought to be SB1u actually leads the data thought to be SB2u.

Figure 3.8: Plots of transition pulses for a short time period A) Station 102 for both directions, B) Station 105 for northbound

Based on the plots of transition pulses in Figure 3.8, a new detector mapping for these loop stations is suggested in Table 3.1. The pairing of loops within a lane follows from the plots while the actual lane assignment compares lane by lane flow with adjacent stations assumed to have accurate lane mapping (See appendix B for detail). As will be discussed in section 3.4.3 and appendix B, the assumption that the adjacent station has an accurate lane mapping does not appear to hold at station 102. Rather, the adjacent station appears to have northbound lanes 1 and 2 swapped. So likewise, the corresponding rows of Table 3.1 should be adjusted as shown in Table 3.2.
Table 3.1: New detector mapping based on a plot of pulses, the contents of each cell reflect the lane assignment in use at the time of data collection.

<table>
<thead>
<tr>
<th>Station</th>
<th>St 102(NB)</th>
<th>St 102(SB)</th>
<th>St 105(NB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>upstream</td>
<td>downstream</td>
<td>upstream</td>
</tr>
<tr>
<td>Lane 1</td>
<td>u/s 1</td>
<td>d/s 1</td>
<td>u/s 1</td>
</tr>
<tr>
<td>Lane 2</td>
<td>d/s 2</td>
<td>u/s 2</td>
<td>d/s 1</td>
</tr>
<tr>
<td>Lane 3</td>
<td>u/s 3</td>
<td>d/s 3</td>
<td>u/s 3</td>
</tr>
<tr>
<td>Lane 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3.2: Adjusted new detector mapping based on a plot of pulses, the contents of each cell reflect the lane assignment in use at the time of data collection.

<table>
<thead>
<tr>
<th>Station</th>
<th>St 102(NB)</th>
<th>St 102(SB)</th>
<th>St 105(NB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>upstream</td>
<td>downstream</td>
<td>upstream</td>
</tr>
<tr>
<td>Lane 1</td>
<td>d/s 2</td>
<td>u/s 2</td>
<td>u/s 1</td>
</tr>
<tr>
<td>Lane 2</td>
<td>u/s 1</td>
<td>d/s 1</td>
<td>d/s 1</td>
</tr>
<tr>
<td>Lane 3</td>
<td>u/s 3</td>
<td>d/s 3</td>
<td>u/s 3</td>
</tr>
<tr>
<td>Lane 4</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
3.3 Calibration of Loop Detectors

3.3.1 Single Loop Detectors

Speed from a single loop detector is estimated from equation 1.4, i.e., effective vehicle length divided by median on-time in the given sample period. The on-time duration depends on the effective vehicle length and vehicle speed. As the length and speed cannot be measured directly at a single loop detector, effective vehicle length is usually assumed to be some constant value, e.g., 20ft. However, the assumed constant effective vehicle length might not become representative of length of all vehicles and detector’s sensitivity, in which case the median on-time will not be consistent with assumed constant value. Incorrect assumed constant effective vehicle length leads to underestimated or overestimated speed.

To identify incorrect effective vehicle length, the median speed during an off-peak time period is used, specifically 9hr to 15hr. We expect median speed in off-peak time periods to usually correspond to follow free-flow speed, and assume that drivers usually keep the posted speed limit in free flow condition. Taking the median of the large data set greatly reduces the impacts of transient events such as incidents. The time period chosen to illustrate this process is one month, April 1, 2005 through April 30, 2005.

5 Recall that the effective vehicle length includes the vehicle’s physical length and the length of the effective detection zone, as shown in Figure 1.1. At single loop detectors it is impossible to separate the impacts from physical vehicle length and effective detection zone on effective vehicle length, e.g., the effective detection zone can differ from the physical dimension of the loop detector. However, for this discussion, it is sufficient to note that the effective vehicle length can change due to one or both of these sources.
except for station 28 to station 34, which were not operational, so data for these stations were taken from the time period of April 1, 2003 to April 30, 2003. The median speed in each lane during these off-peak time periods on each weekday is found (termed the daily median speed) and the median of these daily values is shown in Figure 3.9. The median speed from such a hierarchical approach could be replaced by median across all observations; however, we follow the hierarchical approach to obtain median speed as trends in the daily median help to identify changes of the sensitivity of a loop detector over long time periods, as will be discussed in section 3.3.3.
Figure 3.9: Median speeds in off-peak time periods in single loop detectors A) Northbound direction, B) Southbound direction.

For the northbound direction, most stations show the median speed differs from the posted speed limit, i.e., 65mph in station 2 to station 34 and 55mph in the rest of stations.
For example, all detectors at station 12, 14, 15, 17, and 18 show the median speed is higher than the posted speed limit (65mph). Some stations show that the difference of speed across neighboring lanes is high. For example, median speed of lane 2 at station 2 northbound is 30 mph higher than the other lanes. Station 31, 32 and 34 northbound show that lane 3 is lower than other lanes, even lower than lane 4, the outside lane. For the southbound direction, lane 2 and lane 3 at station 18 show a median speed 30mph higher than lane 1. Station 34 shows that lane 3 is 30mph lower than the other lanes. Station 110 shows that the median speed in lane 2 is much higher than the other lanes. (Note that in station 110, lane 1 and lane 2 are on I-670, lane 3 and lane 4 are on I-71.) The discrepancy of speed in a single loop detector could be explained from incorrect assumed constant effective vehicle length, as mentioned previously. Note the initial assumed constant effective vehicle length used in the study is 20ft.

To address the discrepancy of speed from a single loop detector, a correction factor is applied to an initial assumed constant effective vehicle length. Two models are considered, first, employing a multiplicative correction factor ($\varepsilon_i$),

$$\hat{v}_i' = \hat{v}_i \times \varepsilon_i$$

$$= \frac{\hat{L}}{\text{median on time}} \times \varepsilon_i$$

(3.2)

where, $\hat{v}_i'$ is new estimated speed corrected by multiplicative correction factor.

Assuming drivers usually keep the posted speed limit in off-peak time periods, most of $\hat{v}_i'$ during these periods should be free flowing. Thus the multiplicative correction factor is as follow,
\[ \varepsilon_1 = \frac{\text{Free flow speed}}{\hat{\text{L}}} = \frac{65 \text{mph}}{\hat{\text{v}}_i} \quad (3.3) \]

Alternatively, we can think about an additive correction factor added to assumed constant effective vehicle length. It might be able to compensate for incorrect effective vehicle length including detector's sensitivity and differences arising from the true vehicle length.

Additive correction factor \((\varepsilon_2)\) and the model could be expressed as follows;

\[ \hat{\text{v}}'_i = \frac{\hat{\text{L}} + \varepsilon_2}{\text{median on _ time}_i} \quad (3.4) \]

where, \(\hat{\text{v}}'_i\) is new estimated speed corrected by additive correction factor.

Repeating our assumption of median speed in off-peak time period, the additive correction factor is as follows:

\[
\varepsilon_2 = \text{median on _ time}_i \times \left( 65 \text{mph} - \frac{\hat{\text{L}}}{\text{median on _ time}_i} \right)
\]

\[
= \frac{\hat{\text{L}}}{\hat{\text{v}}_i} \times (65 \text{mph} - \hat{\text{v}}_i)
\]

\[
= \hat{\text{L}} \times \frac{65 \text{mph}}{\hat{\text{v}}_i} - \hat{\text{L}}
\quad (3.5)
\]

The model with additive correction factor in equation 3.4 could be replaced by:
\[
\hat{\nu}_i^* = \frac{\hat{L} + \left( \hat{L} \times \frac{65\text{mph}}{\hat{\nu}_i} - \hat{L} \right)}{\text{median on - time}_i} \\
= \frac{\hat{L}}{\text{median on - time}_i} \times \frac{65\text{mph}}{\hat{\nu}_i} \\
= \frac{\hat{L}}{\text{median on - time}_i} \times \epsilon_i
\]

Thus, the additive correction factor model is equivalent to the multiplicative correction factor model. Choosing one form, the multiplicative correction factor model is used.

Assuming that the composition of the vehicle fleet does not change significantly between the off-peak time period (9hr to 15hr) and peak time periods, the correction factor calibrated during this off-peak time period should also be applicable during the peak time periods.\(^6\) To verify that the process of generating correction factors is valid, the corrected single loop speeds are compared against the corresponding GPS velocity measurements from the probe vehicle runs, which is generally accurate within 1mph [23]. Figure 3.10 shows loop speed versus GPS velocity in lane 2 at station 26 northbound. Recall that the GPS probe vehicle usually travels in lane 2. The discrepancy between loop speed and GPS velocity is found in the comparison of loop speed and GPS velocity, and the discrepancy is reduced after applying the correction factor to loop speed. Figure 3.11 and Figure 3.12 show the comparison between the single loop speed incorporating correction factor and the concurrent GPS velocity for all of single loops and the number of observations in the lower right hand corner. Most of the single loops show corrected

---

\(^6\) This assumption will be examined shortly in Figure 3.11 and Figure 3.12
loop speeds close to GPS velocities. However, stations 104, 3, 8, 12, 17, 21 and 23 northbound and station 110, 8, 12, 17, and 21 southbound show large discrepancies between loop speed and GPS velocity. At station 8 and station 12 for both directions, a large percentage of the pulses had zero on-time in the recorded data, i.e., the concurrent time of "on" and "off" when a vehicle passed over it, resulting in overestimated speed from the single loops. The rest of the single loop detectors showing the large discrepancy in comparison of speeds might be related to inappropriate correction factor for some periods due to changing sensitivity of loop detectors, choosing an incorrect vehicle length as a representative value, or both. However, as will be discussed in section 3.3.3, the evidence from the data suggest that most of the correction factor errors result from changing sensitivity and not generally due to changes in the distribution of vehicle lengths.

---

7 In particular, corrected loop speeds in peak time periods generally closes to GPS velocities, e.g., station 2, 9, 11 northbound and station 106, 112, 11, 14, 18 southbound. This confirms our assumption that the correction factor calibrated during off-peak time periods (9hr to 15hr) should also applicable during the peak time period.
Figure 3.10: Comparison of Loop speed and GPS velocity from station 26(lane 2). (A) Before applying correction factor the loop speed is higher than GPS velocity, i.e., loop speed overestimated. (B) After applying the correction factor the difference of loop speed and GPS velocity is within 10mph, and unbiased.
Figure 3.11: Comparison between single loop speed estimates with the correction factors and concurrent probe vehicle velocity measurements for northbound single loops. Each subplot shows a different loop, the total number of observations from the given loop is indicated on the plot.
Figure 3.12: Comparison between single loop speed estimates with the correction factors and concurrent probe vehicle velocity measurements for southbound single loops. Each subplot shows a different loop, the total number of observations from the given loop is indicated on the plot.
As presented in equation 3.2, the correction factors for single loop detectors are applied to a constant effective vehicle length, initially assumed to be 20ft. Thus, we can estimate a new constant effective vehicle length at each of the single loops, as shown in Figure 3.13. In general, the improved estimate of constant effective vehicle length differs from the initial assumption of 20ft. For example, the new effective vehicle length for each loop at station 2 northbound is below 20ft, i.e., 12.5ft for lane 1, 13ft for lane 2, and 14ft for lane 3 and lane 4. Relative to using the initial assumption of 20ft, the new estimated effective vehicle length improves the estimated speed from equation 1.4 at a single loop detector.
Figure 3.13: New constant effective vehicle length at single loop detectors A) Northbound direction, B) Southbound direction.
3.3.2 Dual Loop Detectors

As discussed in section 1.1, a dual loop detector provides measured speed from the traversal time between two loops, rather than just the estimated speed available from a single loop detector. As shown in equation 1.5, speed is calculated from the effective loop spacing divided by traversal time. When the assumed loop spacing is incorrect, it will result in systematic errors in the measured speeds. As shown in Figure 1.2, the loop spacing depends primarily on the physical separation of the loops, but the sensitivity of the loops leads to changes in the size of the detection zones. Impacts of the difference in sensitivity between the loops are indistinguishable from the impacts of physical loop spacing on the computed speed, hence the loop spacing used in this section is the effective loop spacing after accounting for both the physical spacing and any modification due to the sensitivity.

To investigate the impacts of incorrect loop spacing on measured speed from dual loop detectors, the median of the daily median speeds in off-peak time periods is once more used from April 1, 2005 through April 30, 2005, as shown in Figure 3.14. Again one would expect the results to be close to the posted speed limit, yet in many cases the speed differs. For the northbound direction most of the dual loop detectors show that median speeds in the off-peak time periods are in the range of 60mph to 70mph, except for stations 4, 10, 102, and 105. For the southbound direction, stations 1, 4, 22, 27, 102 and 108 show a large discrepancy of speed from the posted speed limit.
Figure 3.14: Median speeds in off-peak time periods in dual loop detectors

As mentioned previously, the discrepancy of speed in a dual loop detector can be explained at least in part from incorrect loop spacing. Correction factors for obtaining the
accurate loop spacing are applied to correct the discrepancy of speed for a dual loop detector. A multiplicative correction factor ($\varepsilon_1$) and speed corrected by this correction factor ($\hat{\nu}_i'$) could be expressed as follows:

$$\hat{\nu}_i' = \hat{\nu}_i \times \varepsilon_1$$

$$= \frac{\text{Loop spacing}}{\text{TT}_i} \times \varepsilon_1 \quad (3.6)$$

Where,

$$\text{TT}_i = \text{median traversal time via rising edges or falling edges in sample period } i.$$  

Again, assuming drivers usually keep the posted speed limit in off-peak time periods, most of speed ($\hat{\nu}_i$) during these periods should be free flowing. Thus multiplicative correction factor is as follows:

$$\varepsilon_1 = \frac{\text{Free flow speed}}{\text{Loop spacing}} = \frac{65 \text{ mph}}{\hat{\nu}_i} \quad (3.7)$$

Alternatively, we can think about an additive correction factor added to loop spacing. The model and additive correction factor ($\varepsilon_2$) could be expressed as follows:

$$\hat{\nu}_i^* = \frac{\text{Loop spacing} + \varepsilon_2}{\text{TT}_i}$$

$$= \frac{\text{Loop spacing} \times \left(1 + \frac{\varepsilon_2}{\text{Loop spacing}}\right)}{\text{TT}_i} \quad (3.8)$$

$$= \frac{\text{Loop spacing} \times \varepsilon}{\text{TT}_i}, \text{ where } \varepsilon = 1 + \frac{\varepsilon_2}{\text{Loop spacing}}$$

As long as the loop spacing in a dual loop detector is constant, the additive correction factor model is equivalent to the multiplicative correction factor, as shown in equation 3.8.
Choosing the multiplicative correction factor model in equation 3.7, multiplicative correction factors for obtaining the accurate loop spacing are once more found by the quotient of the median and expected value.

Figure 3.15 shows loop speed versus GPS velocity in lane 2 at station 22 southbound before and after applying the correction factor, and the discrepancy between loop speed and GPS velocity is reduced after the correction factor. Figure 3.16 and Figure 3.17 show the comparison, after the each of correction factors is applied, at each of the dual loops passed and the number of observations in the lower right hand corner. At station 102 both directions and station 105 northbound, many observations show that loop speed is lower than GPS velocity, consistent with the incorrect detector mapping mentioned in section 3.2.2.

---

8 After applying the correction factor to dual loop speed, the cloud of points around loop speed of 65mph likely arises from the fact that the 5 min average loop speed comes from many vehicles while the GPS velocity comes from a single vehicle. The cloud is denser at 65mph because only a few trips saw congested conditions.
Figure 3.15: Comparison of Loop speed and GPS velocity from lane 2 in station 22. (A) before applying correction factor loop speed is lower than GPS velocity. (B) after applying correction factor the difference of loop speed and GPS velocity is within 10mph.
Figure 3.16: Comparison between dual loop speed measurements incorporating correction factors versus concurrent probe vehicle velocity measurements for northbound dual loops. Each subplot shows a different loop, the total number of observations from the given loop is indicated on the plot.
Figure 3.17: Comparison between dual loop speed measurements incorporating correction factors versus concurrent probe vehicle velocity measurements for southbound dual loops. Each subplot shows a different loop, the total number of observations from the given loop is indicated on the plot.
Based on the correction factors for dual loop detectors and the original loop spacing, the corrected loop spacing can be calculated, as shown in Figure 3.19 and Figure 3.19. The original spacing is the original loop spacing measured by ODOT when a dual loop detector was installed. The corrected spacing is obtained by multiplying the original spacing by the calculated correction factor. Independent of our analysis, ODOT recently measured the effective loop spacing using a radar gun. These new factors are shown on the plots as “ODOT spacing” and generally concur with our calibration.

Figure 3.18: Loop spacing for dual loop detectors northbound
Figure 3.19: Loop spacing for dual loop detectors southbound
3.3.3 A sensitivity of loop detectors

As explained previously, speed from both single and dual loop detectors can be improved from the correction factor that adjusts for the bias arising from an incorrect assumption of the true but unknown effective vehicle length at single loops and spacing at dual loops. To this end, the correction factor is calculated from the median of the daily median speed over the given time periods of interest and the posted speed limit. Recall that the daily median speed comes from off-peak time periods. Thus, the daily median speed is assumed to be almost constant over long time, with occasional variation due to unexpected events such as incidents and bad weather. If the daily median speed deviates significantly from the general trend for more than a few days it might be related to changes of detector’s sensitivity, and in addition for single loops, such a deviation could also arise from a change in the proportion of long vehicles. But in this latter case, such a change in the composition of the vehicle fleet could be easily verified from corresponding changes at neighboring stations.

If conditions change from when the correction factor was calculated, loop speed incorporating the correction factor will generally underestimate or overestimate speed. To account for the possibility that the correction factors change over time, the trend in daily median speed for off-peak time periods is used. Figure 3.20 shows median speed at loop station 17 in off-peak time periods each day over four years. Daily median speed for February 2002 through June 2002 is higher than the rest of time period. Similar plots for the other stations are presented in Appendix C. In contrast to Figure 3.20, the daily median speed at station 18, 0.3 mile downstream, is almost constant over the same four years. This fact suggests that the unexpected change daily median speed at station 17 during the five months
of 2002 results from the changes of detector's sensitivity, and not a change in the composition of the vehicle fleet. Since the correction factor applied to loop speed was calculated under an entire month for April 2005, the loop speed in time periods of February 2002 through June 2002 will be overestimated, as shown by the cluster of estimated speeds around 90mph in Figure 3.21A. This unexpected median speed trend suggests that it is sometimes necessary to update the correction factor with respect to the sensitivity of the loop detector. In this case, two different correction factors are needed to correct the error in speed for single loops on the different dates. The comparison of loop speed after applying the different correction factors on different dates and GPS velocity is shown in Figure 3.21B. For more general application, the correction factor could be calculated periodically if the sensitivity of loop detector is not stable. For example, the correction factor could be updated every week, and the correction factor calculated in one week would be applied to loop data for the following week.

Figure 3.20: Daily median speed trends at loop station 17 northbound over four years
Figure 3.21: Comparison of Loop speed and GPS velocity, incorporating correction factor. A) after applying one correction factor, B) after applying two correction factors

Figure 3.22 shows median speed at station 23 northbound is not steady over four years, changing several times. After several adjustments, it stabilizes for approximately two years starting in May 2002. Speed in lane 2 dramatically increased in July 2004, and speed in lane 1 decreased after October 2004. In particular, since the correction factor for lane 2 is calculated during the month for April 2005 (high median speed), loop speed before July 2004 that incorporates this correction factor will be low, as shown in Figure 3.11. This problem could be solved by applying a different correction factor to different time periods. Closer examination of the data revealed that lane 2 was set to pulse mode after July 2004, which is an option used to detect the passage of a vehicle and it reports a constant on-time for all vehicles, independent of their actual on-times. Thus, after July, it becomes impossible to estimate speed in lane 2 with equation 1.4.
Figure 3.22: Daily median speed trend at loop station 23 northbound

As an example of the other findings from median speed trends, median speed trends at station 104 northbound suggest the possibility of incorrect detector mapping, as shown in Figure 3.23. Speed at lane 1 decreased after October 2003, but speed at lane 2 increased. Median speed at lane 1 after October 2003 is similar to median speed at lane 2 before October 2003. To verify this hypothesis at station 104, sample data are taken from April 18, 2003 and April 23, 2004. Then the traffic flow trend at station 104(NB) is compared to station 103(NB) in Figure 3.24A and Figure 3.25A. Since the section between station 104 and station 103 does not have any ramps, the 5-min volumes in a given lane for 24hr day should be similar if lane changing traffic volume is not large. Similarly, distributions of on-times of station 104 and station 103 over 24hrs are compared in Figure 3.24B and Figure 3.25B. In Figure 3.24A, as we expected, flow in a
given lane at station 103 and station 104 are similar. Likewise, in Figure 3.24B the on-
time distributions are similar within lanes between the two stations. However, in Figure
3.25A, flow of lane 2 at station 104 is similar to lane 1 at station 103, which is supported
by the on-time distributions in Figure 3.25B. Note that lane 3 at station 103 does not
function on April 18, 2003, and lane 2 and lane 3 at station 103 do not function on April
23, 2004. It appears that station 104 (NB) has an incorrect detector mapping after
October 2003, i.e., the loop detectors in lane 1 and lane 2 may be switched.

Figure 3.23: Daily median speed trends at loop station 104 northbound
Figure 3.24: 5-min flows and CDF of on-times on April 18, 2003 (A) 5-min flow at station 103 and station 104 northbound (B) the corresponding CDF of on-times for the entire 24hr day at both loop stations.

Figure 3.25: 5-min flows and CDF of on-times on April 23, 2004 (A) 5-min flow at station 103 and station 104 northbound (B) the corresponding CDF of on-times for the entire 24hr day at both loop stations.
CHAPTER 4

PERFORMANCE MEASUREMENT FROM LOOP DETECTORS

Performance measures generated from loop detector data are helpful for planning, design, and operation of the freeway and the larger transportation network. This chapter focuses primarily on evaluating the operation of the freeway. As presented in Chapter 3, loop detectors are not always calibrated correctly and might have a physical problem, e.g., detectors mapping error. If a performance measure inadvertently incorporates detector errors, it will likely lead to unanticipated and potentially undetected errors in the performance measure as well. In this chapter, several tools presenting the freeway usage and performance are developed.

4.1 Performance measurement and monitoring

4.1.1 Average Daily Traffic and Delay

Average Daily Traffic (ADT) was chosen to measure throughput and vehicle delay was chosen to measure congestion. In this case ADT refers to total flow during 24hrs. Delay is defined as the difference in travel times for the given sample and what it
would be during free flow conditions, multiplied by the number of vehicles that pass. Travel time is estimated from the length of the link (measured from the mid-point between stations) divided by the speed. They are written as:

\[ ADT = \sum_{i=1}^{N} q_i \]  
(4.1)

Where,

\[ q_i = \text{flow in sample period } i \]

\[ N = \text{maximum sample period over 24hr} \]

\[ \text{Delay} = \sum_{i=1}^{N} \max \left( 0, \frac{D}{V_i} - \frac{D}{\text{FF}} \right) \times q_i \]  
(4.2)

Where,

\[ D = \text{distance of midway between adjacent detector stations} \]

\[ \text{FF} = \text{free flow speed} \]

\[ V_i = \text{estimated or measured speed in sample period } i \]

\[ q_i = \text{flow in sample period } i \]

When plotting ADT or daily delay for several successive days, it quickly becomes difficult to follow general trends. To facilitate tracking trends over years and avoid unexpected events such as incidents, we find the weekday median each week for both of the daily measures, henceforth referred to as the weekly median. In the event that the detectors in one or more lanes fail, the ADT and daily delay measurements will probably be inaccurate. Rather than suppressing entirely such data, we track the operation of the
detectors (as discussed in Appendix D) and clearly indicate when one or more lanes are down for one or more days during the given week in the given direction at the station. A casual reader should ignore the data during these time periods and simply consider the indication that one or more lanes fail to report data, a critical distinction that could otherwise be easily overlooked. For a more in-depth reader, in the case of transient problems, e.g., a detector is down for a few days, the specific values have little meaning. However, in the presence of chronic problems, e.g., a detector is down for many weeks, while the problem is present the relative changes from one week to the next may still be informative.

Figure 4.1 shows an example of the weekly median at station 109. In both plots, the horizontal axis shows the cumulative week since the CMFMS became operational (vertical delineations show the start of each month, abbreviated by the first letter on the plots) and the vertical axis shows median weekly ADT (10,000 vehicles per day) or median weekly delay (vehicle-hours per day). The detector status is explicitly shown by the color of the curve, gray and black, indicating respectively either “All loops reporting” or “Some loops not reporting” during the given week. This format will be repeated in following plots. However, since the scale of vertical axis differs between loop detector stations, the reader should be careful when comparing the ADT and Delay between different stations.

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9 Note that detector errors that do not last an entire calendar day would not be marked. Provided such short duration errors are non-recurring, they should have little impact on the weekly median for two reasons. First, most of these errors are on the order of minutes not hours, and second, even when the errors last many hours, the weekly median will usually exclude the problem days. This criterion assumes that chronic or recurring detector problems would be identified and corrected by some other means, e.g., by examining the time series data from the detector, or comparing ADT between adjacent stations.
Figure 4.1: Weekly ADT and Delay for Station 109 northbound
4.1.2 Monitoring traffic conditions during the I-670 closure and reopening

I-670 between SR 315 and I-71 closed for 18 months for widening and reconstruction, March 2002 through September 2003. Due to this closure, cross-town traffic was detoured onto I-70 via I-71 and SR 315. Figure 4.2 shows a schematic of the impacted freeways due to the I-670 closure. Based on information collected at selected locations, an overview of the freeway system usage and performance can be obtained.

Plots of median weekly average daily traffic and median weekly delay are used to represent the traffic changes when I-670 closed and opened. Figure 4.3 and Figure 4.4 show the median weekly average daily traffic and the median weekly delay for each direction at four stations over three years. The impacts of the I-670 closure are evident in the plots, for example, I-670 offered an alternative route for traffic on the southern portion of the instrumented corridor, i.e., station 102 and station 106. For northbound traffic, the periods that I-670 was closed show that delay at station 102 increases with the closure while delay at station 106 dropped with the reopening. Prior to reconstruction, northbound traffic from I-70 or I-71 could not take I-670 and were restricted by bottleneck north of station 106. After reconstruction, this traffic could also take I-670, bypassing the former restriction. As a result, after I-670 opened, station 1 and station 3 had increased delay due to traffic from I-670. In the ADT plots, demand dropped at station 102 and 106 while increasing slightly at station 1 and 3 after reopening. In the

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10 Note that as mentioned in section 3.2.2, there was an incorrect detector mapping at station 102 from August 2003 to February 2005, this mapping error was corrected prior to generating the figures. In addition, the ADT and Delay at station 102 before correcting mapping errors is presented in Appendix E.
southbound direction, I-71 demand increased south of I-670 due to its closure and delay increased as well. After I-670 reopened, delay was alleviated at station 3, 1, and 106.

Figure 4.2: A schematic of corridor near I-670
Figure 4.3: Northbound weekly median average daily traffic and median weekly delay for the four detector stations, i.e., 102, 106, 1, and 3, over three years.
Figure 4.4: Southbound weekly median average daily traffic and median weekly delay for the four detector stations, i.e., 102, 106, 1, and 3, over three years

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4.2 Tools for representing traffic condition

4.2.1 Summary plots

The basic summary plot for speed shows directional traffic conditions along the entire corridor over time and space and provides an overview of the performance of a freeway. Figure 4.5 shows an example of a summary plot showing the evolution of traffic conditions for northbound direction over the entire corridor, shown in Figure 3.1, over 24hr. Traffic flows from bottom to top. The vertical axis is distance along the roadway, as indicated on the left, with a second axis on the right showing the station number. A continuous gradient between 0 mph (dark gray) and 65 mph (white)\(^\text{11}\) is used to represent traffic speed averaged across all lanes every 5 min at each station. The traffic speed in the summary plot incorporates the correction factors from section 3.3.\(^\text{12}\) In the absence of any speed data in a given sample at a given station is coded in black, whether due to communication outages or none of the detectors being operational\(^\text{13}\). This daily summary plot quickly shows the traffic state over 24hrs, and using such plots from several days can help distinguish whether congestion is due to incidents or recurring bottlenecks [24, 25].

---

\(^{11}\) Speeds over 65 mph are indicative of free flow conditions and are also shown with white.

\(^{12}\) The traffic speed without a correction factor should either decrease or increase from what is shown in the figure, proportional to the correction factor; thus, the corresponding row indicating the given detector station in the summary plot would become darker or lighter, respectively, compared to the values with the correction factor.

\(^{13}\) There are no black cells in Figure 4.5, i.e., at least one loop detector at each of the detector stations report data in each sample time period. When present for more than one sample, such black regions should appear as solid horizontal stripes, e.g., as seen in Figure 4.7.
Figure 4.5: A sample summary plot over the entire corridor over 24hrs

Based on daily summary plots, monthly average summary plots are generated to show recurring bottlenecks and the evolution of traffic patterns. As the name implies, the average monthly summary plots represent speed averaged separately in each sample time period at each station over all weekdays during a given month, i.e., each cell indicates average speed in a given sample period at a given detector station during a given month. Average monthly summary plots highlight recurring congestion. Figure 4.6 shows the average summary plot for an entire month of northbound traffic. The impacts of a recurring bottleneck around I-71/I-670 junction (just above station 109 in the plot) can be seen in the recurring congestion around 7hr and again around 15hr at station 109. Also, due to lane drop near station 4 (11th Ave), a recurring bottleneck is observed around 15hr.
Figure 4.6: A sample average monthly summary plot for an entire month

Average monthly summary plots can be organized in calendar format to show the evolution of recurring traffic conditions over extended time periods. Figure 4.7 and Figure 4.8 show examples of such a presentation\textsuperscript{14}. The twelve columns show January through December. The five rows correspond to year 2001 through 2005. These plots present the change of recurring bottlenecks due to I-670 closure / reopening. For example, average monthly summary plots surrounded by a dashed line represent average monthly speed on I-71/70 during the I-670 construction. For the northbound direction, periods that I-670 was closed due to construction show recurring congestion moving

\textsuperscript{14} Note that as mentioned section 3.2.2, there are incorrect detector mapping for station 102 northbound and southbound from August 2003 to February 2005, and station 105 northbound from August 2003 to September 2004. These mapping errors were corrected prior to generating the figures. In addition, monthly average summary plots before correcting mapping errors is presented in Appendix E
upstream, i.e., towards the bottom of the plots. In other words, the decreased traffic from I-670 to I-71 alleviated congestion around the lane drop at station 4, and the traffic condition between station 102 and station 105 became more congested than the traffic condition before the re-construction of I-670. This result is consistent with the detouring traffic from I-670 discussed previously.

For the southbound direction, during the I-670 closure the congestion is observed near station 1 for morning and evening peaks. Note that as with the northbound summary plots, the direction of travel is from bottom to top, so the mile markers and station numbers are in reverse order relative to the northbound plots. After the reopening I-670, the southbound evening peak congestion is alleviated, and morning peak congestion is reduced for several months.
Figure 4.7: Monthly average summary plot for northbound direction
Figure 4.8: Monthly average summary plot for southbound direction
4.2.2 Summary difference plots

The summary difference plot for speed shows how conditions differ from "normal" on a given day. The difference plot particularly highlights the congestion due to unexpected events such as incidents that do not occur regularly. A daily summary difference plot is obtained from the difference between the daily conditions and the respective monthly average conditions (weekday or weekend average). In this case, non-recurring events, i.e., faster or slower than average speed, are highlighted [24, 25]. Figure 4.9 shows a summary difference plot corresponding to Figure 4.5. Now the color scale has changed, it now spans from −65mph to +65mph, with dark gray denoting slower than average speed and light gray faster (the darker [lighter] the cell, the slower [faster] it is compared to the average day). The plot highlights non-recurring events on the given day.

Figure 4.9: A sample summary difference plot over the entire corridor over 24hrs
Monthly summary difference plots represent the difference of traffic conditions between a given year and the previous year in the same month. The monthly summary difference plots highlight changing traffic patterns due to major events on freeway, e.g., road construction. The monthly summary difference plots are calculated as follows;

\[
\text{Monthly average diff velocity}_{(i,j)} = \text{Monthly average Velocity}_{(i,j)} - \text{Monthly average velocity}_{(i-1,j)} \quad (4.3)
\]

Where,
\[
i = \text{year } i, i-1 = \text{previous year } i-1
\]
\[
j = \text{month } j
\]

Figure 4.10 shows a monthly summary difference plot between December 2003 and December 2002, for northbound traffic\textsuperscript{15}. Dark gray denotes speed in 2003 is slower than the same time/location in 2002, and light gray denotes faster. The fainter the color, the smaller the difference of monthly average speed, and gray indicates no difference. If any detector does not function for the entire month, the difference speed for this station is colored black in the Figure. After I-670 reopened, downstream of I-71/I-670 junction became more congested, while the traffic conditions upstream improved compared to the preceding year. It suggests that some traffic from I-70 took I-670, instead of I-71.

\textsuperscript{15} Note that as mentioned section 3.2.2, there are incorrect detector mapping for station 102 northbound and southbound from August 2003 to February 2005, and station 105 northbound from August 2003 to September 2004. These mapping errors were corrected prior to generating the figure.
Figure 4.10: A sample monthly summary difference plot showing the changing of traffic conditions

Like the summary plot, the summary difference plot can be organized in a calendar format, as shown in Figure 4.11 and Figure 4.12. The twelve columns show January through December, respectively. The five rows correspond to year 2001 through 2005. Even though data are available from December 2001, the monthly summary difference plots are only presented after December 2002 since the data in previous year must also be available. Monthly summary difference plots surrounded by a dotted line correspond to time periods during the I-670 closure. For the northbound direction, after I-670 reopened, downstream of I-71/I-670 junction was more congested, i.e., station 1 to station 5. For southbound direction, the location around I-71/I-670 junction was more congested during I-670 closure, and congestion was alleviated after I-670 reopened.

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16 Note that as mentioned section 3.2.2, there are incorrect detector mapping for station 102 northbound and southbound, and station 105 northbound, these mapping errors were corrected prior to generating the figure. In addition, monthly summary difference plots before correcting mapping errors is presented in Appendix E.
Figure 4.12: Monthly summary difference plot for southbound direction
CHAPTER 5

SUMMARY AND CONCLUSIONS

A Freeway Management System (FMS) acquires data from the roadway and process these data to identify and respond to problems, notifying operators and motorist of those problems. Performance measures generated from traffic surveillance data are helpful to plan, design, and operate transportation systems. Loop detectors are the most commonly used vehicle detector for freeway traffic surveillance and they are employed as the primary detection system in the Columbus Metropolitan Freeway Management System (CMFMS).

Loop detectors are not always calibrated correctly, so it is necessary to identify potentially inaccurate detectors. If some aspects of data are unreliable, errors caused from the incorrect data could propagate to control decisions based on the detector’s data. The first part of this thesis focused on identifying potentially inaccurate detectors. The percentage of unmatched pulses is used as one measure of the quality of dual loop data. Since each actuation at one loop should be uniquely matched to a single actuation at the other, any extra pulses at upstream/downstream loop are considered unmatched. Using the relationship of speed and occupancy from loop detectors, severe detector errors were
caught. In particular, loop stations with incorrect detector mapping were found, and a new detector mapping was suggested in Table 3.2.

Next, this thesis showed that the accuracy of speed from single and dual loop detectors could be improved by applying multiplicative correction factors. The correction factor corresponds to a ratio of the posted speed limit or assumed free flow speed and median speed during off-peak time periods. This correction only uses data reported by the detector. To verify the correction factor, the corrected loop speed is compared against corresponding GPS velocity measurements from a GPS equipped probe vehicle. The discrepancy between loop speed and GPS velocity is reduced after applying the correction factor to loop speed. The trend of daily median speed for off-peak time periods is used to determine the change in sensitivity of loop detectors and obtain the appropriate correction factors over long time periods.

Employing these correction factors, this thesis then develops several performance measurements of the freeway using loop detector data. They include average daily traffic to measure throughput and delay to measure congestion. The weekday median each week for both of the daily measures was used to track trends over years. The weekly ADT and Delay presented an overview of the freeway system usage and performance. Summary plot and summary difference plot was developed to show traffic conditions and recurring congestion.

The tools presented in the thesis have been used to identify the status of surveillance in the CMFMS. Although presented in the context of the Columbus system, the tools should be generalizable to most FMSs.
LIST OF REFERENCES


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APPENDIX A

THE COORDINATES OF LOOP DETECTOR STATIONS ON I-71/I-70
<table>
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Table A.1: Coordinates of loop stations on I-70/I-71

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APPENDIX B

VERIFICATION OF INCORRECT DETECTOR MAPPING USING COMPARISON OF FLOW
Figure B.1 shows a schematic of loop stations with incorrect detector mapping and the adjacent loop stations. Loop stations are represented by square and circle, the square represents the problematic loop stations (station 102 and station 105) with severe detector mapping error in section 3.3.2. Flow by lane at station 102 is compared to flow by lane at station 104, and station 105 northbound is compared to station 106 northbound. In particular, lane 1 and lane 2 at station 105 are matched to station 106 on I-71, and lane 3 and lane 4 are matched to station 106 on I-70.

Figure B.1: A schematic of loop stations with incorrect detector mapping and adjacent loop stations

Flow after applying a new detector mapping is calculated, then it is compared to flows before new detector mapping. Figure B.2 shows flows over 24hrs at incorrect mapping stations and adjacent stations. Figure B.2A, B.2C and B.2E show flows before new detector mapping, and Figure B.2B, B.2D and B.2F show flows after new detector mapping. For station 102 northbound, flows at lanes before and after correcting the new detector mapping do not change because flow at a dual loop detector is taken from average of upstream and downstream loop detector. Also, lane 1 and 2 swapped in station 102 could not be verified because an adjacent station, e.g., station 104, has lane 1 and lane 2 swapped. It will be discussed in detail below. For station 102 southbound, flows at lane 1 and lane 2 after the correction mapping is similar to an upstream loop detector, i.e., station 104 southbound. For station 105 northbound, a large discrepancy of flows between station 105 and station 106 at I-71 disappear when new detector mapping is applied to station 105.
Figure B.2: Comparison of flow by lanes at station 102, 105 and adjacent stations
Figure B.3: Flows in off-peak time periods at each day over four years at each of three loop stations

Figure B.3 shows flow in off-peak time periods at each data over four years at station 102 northbound, station 104 northbound, and station 103 northbound, respectively. Flows at three loop stations are similar before October 2003. After October 2003, flow at lane 2 at station 102 and station 104 decreases, but flow at lane 1 and lane 3 both stations is relatively similar to flow before October 2003. However, flow at lane 1 and lane 2 at station 102 after March 2005 deviated from a trend of flows after October 2003 and flows at lane 1 and lane 2 at station 104. Flow at lane 1 at station 103, on the other hand, is similar to flow at lane 1 at station 102 after March 2005. Based on the fact that an incorrect detector mapping at station 102 is fixed after March 2005, it appears that station 102 and 104 has incorrect detector mapping after October 2003.
APPENDIX C

DAILY MEDIAN SPEED TREND OVER FOUR YEARS
Figure C. 1: Northbound direction
Figure C.1 continued
Figure C. 2 Southbound direction
Figure C.2 continued
APPENDIX D

A MEASURE OF OPERATIONAL DAYS AT A DETECTOR
There are many errors that can occur at a loop detector or detector station. The most fundamental errors prevent measurements in one or more lanes. Given the data format in the CMFMS, it is impossible to differentiate between the absence of vehicles and short duration data loss. As the time lag grows, a detector error becomes more likely. To eliminate the chronic errors, a very coarse measure is used, namely, “operational days.” Detector errors that do not last an entire calendar day are not marked by this test. The percentage of detector days not recorded in the data at a loop station is as follows:

\[
\text{Percentage of detectors not reporting at station } i = \left( 1 - \frac{\sum_{t=1}^{N} \# \text{detectors reporting}}{\# \text{detectors} \times N} \right) \times 100(\%)
\]  

(D.1)

Where,

- \# detectors: Number of detectors at a loop detector station \( i \). It corresponds to number of single or dual loops at the given station.
- \( N \): Number of days in the sample. It is set to weekly, monthly, or yearly.
- \# detectors reporting: Number of operational detectors at detector station \( i \) at day \( t \)

If a loop detector does not report any data on a day, the detector is considered as non-operational for that day.\(^{17}\) Consider an example at station 23 northbound. January 2003 should have 3 lanes times 31 days, for a total of 93 lane-days. Hypothetically, the number of lanes reporting for January 2003 was 80 lane-days, so the percentage of detectors not reporting at station 23 for January 2003 would be equal to 14%. However, 86% of the expected lane-days do not mean loop detectors are completely operated, e.g., it might be possible to operate just for a few hours at such a day. The shortcoming of this method could be compensated for summary plot that will be introduced in section 4.2. Summary plot presents traffic condition in speed as well as non-operational detectors in 5-min

---

\(^{17}\) Even a single actuation on a day will allow the given loop to pass on that day. Again, remember that this is a coarse test.
sample time periods. Using real data, Figure D.1 shows a percentage of detector data not reported in March 2005 by station for the northbound direction.

![Graph showing percentage of detector data not reported by station number.](Image)

Figure D.1: The non-operational status of the detectors in March 2005 for northbound direction. The percentage of detectors not reporting is shown on the vertical axis, and the station number is shown on the horizontal axis.

From the plot, it is evident that loop detectors on station 28 to station 34 do not report any data for the entire month of March 2005. These loop stations were taken off line due to the Polaris interchange rebuilding that began in August 2004. Loop station 103 indicates that detectors did not report 68% of the expected lane-days. Closer inspection revealed that the loop station did not report any data for 10 days in March 2005. Monthly non-operational detector station plots can be organized in calendar format to show the loop station status over years, as shown in Figure D.2 to D.5. Each page shows six months in the six columns, either January through June, or July through December. The five rows correspond to year 2001 through 2005.
Figure D.3: Monthly non-operational detectors by calendar format (Northbound, July to December)
Figure D.2 includes the data from Figure D.1 (fifth row third column). A quick glance at this plot can reveal the evolution of the non-operational status of the detectors over long periods, e.g., station 28 to station 34 do not report any data from September 2004 to April 2005 in those figures.

The non-operational status of detector stations can also be aggregated over an entire year of data, as shown in Figure D.6. Each subfigure shows the yearly non-operational status of detectors for both directions, e.g., Figure D.6C shows the station 21 has not reported data for most of year 2004.

Figure D.6: Yearly non-operational detectors over all stations. Within each subfigure the top plot shows northbound, and bottom shows southbound conditions. Note results for year 2005 only include the first four months.
APPENDIX E

MEASUREMENTS BEFORE CORRECTING MAPPING ERROR
Figure E.1: Weekly median average daily traffic and median weekly delay for station 102 northbound before correcting detectors mapping error.

Figure E.2: Weekly median average daily traffic and median weekly delay for station 102 southbound before correcting detectors mapping error.
Figure E.3: Monthly average summary plot for northbound direction before correcting detector mapping error. Incorrect detector mapping for station 102 and station 105 caused erroneously low speed measurements at these stations for some months, i.e., station 102 has the problem from August 2003 to February 2005, and station 105 has the problem from August 2003 to September 2004.
Figure E.4: Monthly average summary plot for southbound direction before correcting detector mapping error. The impact of the incorrect detector mapping is once more observed at station 102 from August 2003, continuing until February 2005.
Figure E.5: Monthly summary difference plot for northbound direction before correcting detector mapping error.
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**Figure E.6:** Monthly summary difference plot for southbound direction before correcting detector mapping error