An Improved Dual-Loop Detection System for Collecting Real-Time Truck Data

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Abstract

The Washington State Department of Transportation (WSDOT) has a loop detection system on its Greater Seattle freeway network to provide real-time traffic data. The dual-loop detectors installed in the system are used to measure vehicle lengths and then classify each detected vehicle into one of four categories according to its length. The dual-loop's capability of measuring vehicle length makes the loop detection system a potential real-time truck data source for freight movement studies because truck volume estimates by basic length category can be developed from the vehicle length measurements produced by the dual-loop detectors. However, a previous study found that the dual-loop detectors were consistently underreporting truck volumes, whereas the single-loop detectors were consistently over counting vehicle volumes.

As an extension of the previous study, the research project described here investigated possible causes of loop errors under non-forced-flow traffic conditions. A new dual-loop algorithm that can address these error causes and therefore tolerate erroneous loop actuation signals was developed to improve the performance of the WSDOT loop detection system. A quick remedy method was also recommended to address the dual-loop undercount problem without replacing any part of the existing system hardware or software. In addition, a laptop-based detector event data collection system (DEDAC) that can collect loop detector event data without interrupting a loop detection system's normal operation was developed in this research. The DEDAC system enables various kinds of transportation research and applications that could not otherwise be possible.

Keywords: freeway traffic, inductive loop detectors, event data collection, error detection, truck data.

INTRODUCTION

In the past decade, with the increasing emphasis on just-in-time inventories and the growing impact of freight mobility on our regional economy, vehicle-classification data and accurate timely data on truck movements have become an important factor for our regional growth and market competitiveness. Also, because of heavy weights and large turning radii, the characteristics of truck movements are very different from those of passenger cars and should be considered in transportation planning and traffic analysis models. Continuous collection of truck volume data along our region's freeways is imperative for a variety of purposes. For example, traffic operators need these data for real-time traffic management operations; the trucking industry needs these data for route selection and fleet monitoring; transportation researchers need these data to develop real-time algorithms or systems for analysis of freight movements. Therefore, a traffic data collection system that can continuously collect and deliver timely truck volume data is very desirable.

As one of the most popular automated traffic data collection methods, inductive loop detector technology was first introduced for detection of vehicles in the early 1960's (1), and today, after a 40-year evolution, it has become a ubiquitous means for collecting traffic data from freeways in the United States. Inductive loop detectors are frequently deployed as single-loop detectors, i.e., one loop per lane, or as speed traps formed by two consecutive single-loop detectors placed several meters apart in each lane. Single-loop detectors are used to measure volume and lane occupancy; while speed traps (also called dual-loop detectors, dual loops, or T loops in the state of Washington) provide two independent sets of volume and occupancy measurements and also measure speed and vehicle length.

The Washington State Department of Transportation (WSDOT) has a network of loop detectors on its Greater Seattle freeway network that provides real-time traffic data to its Advanced Traffic Management System (ATMS) and its Advanced Traveler Information System (ATIS). There are 620 loop stations installed along the freeway network. In total, there are approximately 4800 single-loop detectors and 1020 speed traps embedded in the pavement for traffic data collection.

Current WSDOT Single-Loop and Dual-Loop Algorithms

When there is no vehicle present on a single-loop detector, the detector rests in the "off" state. The detector changes its state from "off" to "on" when a vehicle arrives at the leading edge of the detector and from "on" to "off" when the vehicle departs from the rear edge of the detector. This change of state from "off" to "on" and then back to "off" represents the passage of a vehicle. The duration during which a vehicle occupies a single-loop detector is called the detector on-time, which can be aggregated to calculate lane occupancy for a particular interval. This is how a single-loop detector collects volume and lane occupancy data.

When a vehicle passes two single-loop detectors spaced a few meters apart (a dual-loop detector), shown in Figure 1, it first activates the upstream detector (designated as the M loop by WSDOT) and then the downstream detector (the S loop). The time it takes for the vehicle to travel from the upstream detector to the downstream detector is called the elapsed time. If the distance from the leading edge of the upstream detector to that of the downstream detector is known, the speed at which the vehicle traverses the dual-loop detector can be calculated by dividing this distance with the elapsed time. The calculated speed can then be used to calculate vehicle length using the detector on-time collected from either of the two single-loop detectors (M or S loop) and the known length of the loop. In the current WSDOT system, vehicles are classified by assigning each identified vehicle to one of four bins: (a) Bin 1 - PCs and smaller vehicles (length 26 ft or less); (b) Bin 2 - small trucks, etc. (26 ft to 39 ft); (c) Bin 3 - larger trucks and buses (39 ft to 65 ft); and (d) Bin 4 - largest trucks and articulated buses (length greater than 65 ft). Vehicles that fall inside Bins 2, 3, and 4 are considered recreation vehicles, trucks, or buses. There are eight validity checks implemented in the current WSDOT dual-loop algorithm. One of these calculates the difference between the two loop on-times and throws out data for vehicles that have absolute on-time differences greater than 10%.

Problem Statement

Since the overwhelming majority of vehicles in Bins 2 through 4 represent trucks, accurate vehicle counts and bin assignments would yield a ubiquitous means of obtaining truck flow data along a freeway network. However, a preliminary study (2) on Interstate 5 (I-5) in Seattle found that the dual-loop detectors were consistently underreporting truck volumes, whereas the single-loop detectors were consistently over counting vehicle volumes

Admittedly, dual-loop detectors were primarily deployed for measuring vehicle speeds rather than classification and bin volume data; nonetheless, if the capability of measuring vehicle length could be improved and fully utilized, they would become a widespread and cost-efficient truck data source for freeway freight movement study and economic analysis for the Seattle Metropolitan Region. This then raised the issue of the need for more accurate dual-loop bin volume data.

Research Objective

Inductive loop detection systems are subject to errors, which can be caused by system hardware and software. As an extension of the previous study (2), this research, sponsored by Transportation Northwest (TransNow), the USDOT University Transportation Center for Federal Region 10, aimed at identifying possible causes of dual-loop errors and developing a new dual-loop algorithm that could tolerate erroneous loop actuation signals to radically improve the WSDOT dual-loop detection system's ability to provide accurate timely truck data.

PREVIOUS WORK

Because of the vulnerability of the loop detectors, a means to timely identify and correct loop errors has been of a great interest to transportation professionals. Consequently, error detection and correction techniques have continued to evolve in the past three decades.

Loop detectors operate in presence mode (that is, a detector turns on and stays on as long as a vehicle is occupying the loop). At each station, the field microprocessor (usually a Model 170 controller) checks or scans the loop actuation signals 60 times per second. Typical freeway loop detection systems, under normal operations, aggregate these actuation signals into 20-second or 30-second flow and occupancy measurements. So, there are two types of loop data, raw loop actuation signals and aggregated loop data that can be made available for malfunction inspection. Accordingly, based on the type of data being inspected, two approaches were explored for erroneous loop data detection and malfunction identification. One was aggregate-data-based malfunction detection using data coming directly from the Model 170 controller, and the other was raw-actuations-based malfunction detection using event data coming directly from the loops before aggregation.

Aggregate-data-based malfunction detection applies reliability checks to the aggregate traffic measurements attempting to ensure the validity of traffic data prior to their use in traffic management and information system applications. Some commonly used tests establish certain thresholds beyond which the data cannot be said to reflect actual traffic operations. Maximum and minimum acceptable values for volume, speed, and occupancy are of this type. More sophisticated tests make use of the inherent relationships among traffic parameters such as speed, volume, and occupancy by applying traffic flow theory principles (3-7).

The raw-actuations-based malfunction detection method processes the raw loop actuation signals from a loop directly. Individual vehicle information, such as vehicle arrival, departure, and presence times (also called detector on-time), can be calculated from the loop's "on" and "off" indications. In this approach, the detector on-time is used as a test statistic to check the validity of detector operations and the quality of the loop data (8-10).

In addition to the loop error detection techniques, various techniques have been proposed to correct loop errors. Daily and Wall (11) developed an algorithm for correcting errors in archived freeway loop data that are the result of poorly calibrated sensors. Payne and Thompson (3), after examining the malfunction rates of I-880 data by applying 14 validity tests, developed a repair algorithm from the I-880 database utilizing historical traffic distributions as well as current measurements from surrounding sensors. Chen, et al. (12), developed a diagnostics algorithm to detect malfunctioning single-loop detectors from their volume and occupancy measurements.

Previous research has focused on checking the validity of loop data and correcting errors in the data. However, little has been done to identify where the errors occur in the loop detecting process so that the error source can be eliminated. Therefore, in this research the loop detecting process was examined to identify possible causes of loop errors.

DETERMINING ERROR CAUSES IN THE CURRENT WSDOT LOOP DETECTION SYSTEM

Typical freeway inductive loop detection systems, aggregate individual loop detector actuations sampled at 60 Hz into 20- or 30-second flow and lane occupancy measurements. While such aggregated data serve as appropriate inputs to control system algorithms and save disk space for archiving loop data, useful data about individual vehicles, such as arrival and departure times, speed, and length are lost. Yet these data are very desirable for in-depth investigation of loop error causes. Therefore, a detector event data collection (DEDAC) system, which provides loop event data for subsequent data analysis, was needed to study loop error causes. Although a desktop-based DEDAC system was developed in a previous study (13), the bulky desktop computer restricted the system’s usability. Since the desktop computer could not be placed inside the loop cabinet, it was extremely inconvenient for long-duration data collections, especially in inclement weather. Therefore, as part of the current study a laptop-based DEDAC system was developed to improve the system’s portability and usability.

Laptop-Based DEDAC System

A laptop-based DEDAC system was successfully developed in this research. The system user manual and data collection software can be downloaded from www.transnow.org. An overview of the system design is illustrated in Figure 2. There are two significant differences between the desktop-based DEDAC and the laptop-based DEDAC. The first, of course, is that the bulky desktop computer is replaced by a portable laptop. The other difference is that the data acquisition card is replaced by a USB digital Input/Output (I/O) adapter. System reliability tests conducted at WSDOT ITS laboratory indicated that the laptop-based DEDAC system was able to accurately collect loop detector actuation signals with high sampling rates under a variety of traffic conditions over long data collection periods (14).

The laptop-based DEDAC system greatly improves the DEDAC system’s portability and usability. The volume of the adapter is 0.9×10^{-3} m^3 (60 in^3). The volume of a regular laptop computer is about 0.7×10^{-2} m^3 (450 in^3). So, the space the laptop-based DEDAC system occupies is only 0.8×10^{-2} m^3 (510 in^3). At this size, the laptop-based DEDAC system can be easily placed in a traffic cabinet for event data collection. The improved portability in turn improves the usability of the DEDAC system. The system can now be placed in any loop station cabinet for long-duration event data collection regardless of weather conditions. Data collection personnel are no longer required to be present beside the traffic cabinet after they set up the equipment.

Procedure to Identify Loop Error Causes

Loop errors can be caused by any problematic step involved in the dual-loop detecting process. Therefore, a systematic examination of the entire process through which dual-loop detectors detect vehicles and produce measurements is needed to identify possible causes of loop errors. The WSDOT dual-loop detecting process is as follows: the Model 170 controller samples individual loop detector actuation signals at 60 Hz to get loop event data, which are then processed by applying the WSDOT dual-loop algorithm to get individual vehicle information such as length and speed. The individual vehicle information is aggregated into 20-second average velocity and length measurements and then sent to the Traffic System Management Center (TSMC). If any step of the process fails, the collected data will be erroneous.

The examination of error causes focuses on factors such as hardware malfunction, defects in the dual-loop algorithm, bugs in the code implementing the dual-loop algorithm, insufficient computing power of the cabinet controller, and any combination of these factors. The procedure to identify loop error causes is illustrated in Figure 3.

In order to identify where the errors occur in the dual-loop detecting process, a modified version of the current WSDOT dual-loop algorithm that runs on an independent Windows computer needed to be developed to process loop detector event data to produce individual vehicle data such as presence time, speed, and length. The modified algorithm still implemented the same validity checks as the current WSDOT dual-loop algorithm, but unlike the current algorithm, the modified algorithm did not discard the vehicles detected with error flags. The individual vehicle presence data were then compared to ground-truth vehicle presence data. If they did not agree, the event data would be problematic indicating the hardware was not functioning properly. If they agreed, it could be concluded that (1) the collected event data were sound in terms of detecting the presence of passing vehicles; and therefore (2) the current WSDOT dual-loop algorithm, or the 170 controller, or both had problems. If the latter case were true, more tests would be required to determine whether the current dual-loop algorithm or the 170 controller had problems.

Since the modified WSDOT algorithm does not discard the vehicles detected with error flags, the volume it records should be higher than that recorded by the current algorithm. If the difference between the two sets of volume data were approximately equal to the number of vehicles discarded by the current algorithm, then the validity checks that cause the current algorithm to discard vehicles would completely explain the dual-loop undercount problems. If this were not the case, more tests would be needed to determine whether the undercount problems were caused by insufficient computing power of the current 170 controller or by hidden bugs in the code that implements the current dual-loop algorithm.

To test whether the current 170 controller has insufficient computing power, the detector event data would need to be input to a new Model 170-compatible controller programmed with the current WSDOT dual-loop algorithm to get 20-second aggregate data. Since the new controller has substantially stronger computing power than the current one, it should successfully execute all the instructions requested by the current WSDOT algorithm. The collected volume data would then be compared to the volumes collected by applying the modified loop algorithm. If the difference were small, it could be concluded that the current 170 controller is insufficient in computing power. If not, the conclusion would be that the code that implements the current WSDOT algorithm is inadequate.

Since a dual-loop detector consists of two single-loop detectors, the error detecting procedure stated above can also be applied to a single-loop detection system for loop error detection and trouble-shooting.

Identified Error Causes

One-hour event data were collected from five dual-loop detectors located on I-5 at NE 130th Street in Seattle from 2:00 p.m. to 3:00 p.m. on May 16, 2002. A WSDOT surveillance camera was also employed to record traffic during the event data collection. The videotape provided by the WSDOT that had recorded the one-hour traffic was manually processed to obtain individual vehicle class and arrival time information. The number of vehicles that passed during the one-hour period was counted for each of the five lanes. The traffic data obtained by manually processing the video data were used as the ground-truth data in this research. The aggregate 20-second dual-loop bin-volume data for the same one-hour period were downloaded from the Traffic Data Acquisition and Distribution (TDAD) website at http://www.its.washington.edu/tdad/. For convenience, these aggregate 20-second data, which were output from the current WSDOT dual-loop algorithm, are called TDAD-based traffic data. All the obtained information was then analyzed by following the research procedure described in the previous section to determine possible causes of loop errors. The main findings from our data analysis are summarized as follows:

1. Under non-forced-flow traffic conditions, when both M and S loops appear to work properly, the main cause of dual-loop errors is the fact that the on-time difference between the two single loops in a dual-loop detector exceeds the WSDOT ±10% threshold value included in the current WSDOT algorithm. Sensitivity discrepancy between the two single loops is a direct cause of the large on-time difference.
2. No malfunctions were found that might indicate the insufficiency of computing power in the Model 170 controllers in the research. Further research may be needed to investigate the sufficiency of computing power of the current WSDOT 170 controllers.

DEVELOPMENT OF A NEW DUAL-LOOP ALGORITHM

The WSDOT current loop cabinet uses a Model 170 controller. The Central Processing Unit (CPU), an 8-bit 6808-based machine, was first released in 1975 by Motorola, Inc. The current WSDOT dual-loop algorithm was coded in Assembly (a low-level programming language that is not currently in common use) in order to efficiently utilize the limited hardware resources (memory, central processing unit, etc.). Since the software was coded in Assembly, it is difficult to understand and update. Also perhaps because of the limited computing power of the 170 controllers, erroneous loop actuation signals were simply screened out rather than corrected by the current WSDOT dual-loop algorithm. This screening process filtered out a tremendous amount of erroneous loop actuation signals that could have otherwise been corrected to give acceptable speed and vehicle length information.

The New Dual-Loop Algorithm

Nowadays, with advances in technologies, the computing power of controllers has been dramatically increased. The new generation of controllers is now capable of executing more involved applications. Therefore, based on the identified error causes, a new dual-loop algorithm was developed in this research to handle erroneous raw loop actuation signals. The new dual-loop algorithm is designed to filter out all the noise and keep as much individual vehicle information as possible despite some unreliability in the raw loop actuation signals. The advantages of the new dual-loop algorithm over the current WSDOT dual-loop algorithm include the following (14):

1. The new dual-loop algorithm employs a thorough noise filtering and post processing process to filter out noises occurring in the raw loop actuation signals

and to recover the on-time pulses broken by random noises. Since the current WSDOT dual-loop algorithm only has a rudimentary noise filtering process, a tremendous amount of noise is overlooked resulting in the single-loop over-count problem. With the implementation of the noise filter and the postprocessor in the new dual-loop algorithm, the single-loop over-count problem is expected to be significantly alleviated.

2. The new dual-loop algorithm conducts various checks to test the validity of the individual vehicle data. If any of the checks fails an appropriate error will be flagged. The current WSDOT dual-loop algorithm also conducts some validity checks, but the data with error flags are now simply discarded. The new dual-loop algorithm, however, keeps the individual vehicle data with error flags in the total count to reduce the dual-loop undercount problem.
3. The new dual-loop algorithm takes into account the fact that under non-forced-flow traffic conditions speeds of vehicles in a platoon should not differ significantly. So if the calculated speed of the current vehicle is problematic, the speed of the preceding vehicle is used to adjust the calculated speed. The current WSDOT dual-loop algorithm does not have this feature.

Evaluating the Effectiveness of the New Dual-Loop Algorithm in Counting Vehicles

In order to evaluate the effectiveness of the new dual-loop algorithm in counting vehicles, one-hour loop event data were collected from three dual-loop detectors located on SR167 at 34th Street NW in Auburn from 10:00 a.m. to 11:00 a.m. on November 21, 2003. Two of the dual-loop detectors were embedded in general purpose (GP) lanes and one was embedded in a high occupancy vehicle (HOV) lane. The one-hour loop event data were processed using the new dual-loop algorithm to get single-loop (M and S) and dual-loop volumes, which are called event-data-based traffic data hereafter in the paper. One-hour TDAD-based single-loop and dual-loop volumes were also downloaded for comparison purposes. One-hour video-ground-truth data were obtained by processing the videotape provided by the WSDOT. The event-data-based and TDAD-based single-loop volume data were each then compared to the video-ground-truth volume data to calculate volume count errors for each of the three lanes. These data are summarized in Table 1.

Table 1 shows that the event-data-based single-loop volume was almost equal to the video-ground-truth volume for each of the two GP lanes. During this one-hour period, the M and S loops on Lane 1 only over counted one and four vehicles respectively. The M loop on Lane 2 correctly counted all the passing vehicles, while the S loop only over-counted two vehicles. The M and S loops on the HOV lane correctly counted all the passing vehicles. The highest event-data-based over-count rate was only 0.32% during this one-hour period.

In contrast to the event-data-based single-loop volumes, the TDAD-based one-hour single-loop volumes were consistently higher than the video-ground-truth volumes. The M and S loops on Lane 1 over-counted 46 and 53 vehicles, respectively and the M and S loops on Lane 2 over-counted 61 and 71 vehicles, respectively. The M and S loops on the HOV lane over-counted 16 and 13 vehicles, respectively. The TDAD-based over-count rate ranged from 3.65% to 4.79%, which was much higher than the event-data-based over-count rate. The difference between event-data-based single-loop over-count rates and TDAD-based over-count rates were calculated and the results are summarized in the last two columns of Table 1. The over-count rate reductions for the event data base indicate that the noise filtering and post processing process effectively filtered out noise and corrected raw loop actuation signals when processing the event data.

One-hour event-data-based dual-loop volume and one-hour TDAD-based dual-loop volume were compared to the one-hour video-ground-truth volume to calculate the undercount rate for each of the three lanes. The results are summarized in Table 2. During this one-hour period, the number of passing vehicles and each individual vehicle's arrival time, calculated by applying the new dual-loop algorithm using event data, exactly matched of the corresponding video-ground-truth data except for one occasion when a dump-pup truck (the combination of a dump truck and a pup trailer) was counted as two vehicles by the new dual-loop algorithm. This error was due to the fact that there was not enough metal for proper loop detection in the long drawbar that connected the dump truck and the pup trailer. Therefore, when the drawbar traversed the loop, the loop shut off, indicating the end of the dump truck and did not go on again until the pup trailer's arrival.

The TDAD-based dual-loop volumes, in contrast, consistently undercounted vehicles that passed the detector zone during the one-hour period. The dual-loop detectors on Lanes 1, 2, and HOV undercounted 93, 146, and 14 vehicles, respectively. The undercount rate was as high as 9.22%. These results proved that the new dual-loop algorithm was able to improve the detection rate of the dual-loop detectors for this one-hour period.

It can be concluded that the new dual-loop algorithm considerably reduced the single-loop positive false alarm rate while noticeably improving the dual-loop detector detection rate for volume counts.

Evaluating the Effectiveness of the New Dual-Loop Algorithm in Classifying Vehicles

In order to evaluate how accurately the new dual-loop algorithm classifies vehicles, one-hour video-based vehicle classification data were compared to the same one-hour event-data-based vehicle classification data. The length ranges used by the current WSDOT dual-loop algorithm to classify vehicles into one of four bins were also adopted to classify observed vehicles when processing the video data and to classify vehicles detected by the new dual-loop algorithm. When observing the video, if we were certain about the bin class of an observed vehicle, the vehicle was then assigned to that bin; if we were not certain about the bin class of a vehicle because the length of the vehicle was close to one of the bin threshold values, the vehicle was dropped from the ground-truth sample. In other words, only vehicles classified by the authors with 100% confidence (for the ground-truth sample) were used to evaluate the accuracy of vehicle classification data calculated by the new dual-loop algorithm. The results are summarized in Table 3.

As shown in this table, 1144 (91% of the total number of vehicles that passed Lane 1), 1519 (96% of the total number of vehicles that passed Lane 2), and 328 (98% of the total number of vehicles that passed Lane HOV) vehicles that passed Lane 1, Lane 2, and Lane HOV respectively were classified into bins when manually processing the video ground-truth data. The selected samples accounted for an overwhelming majority of the vehicles that passed the dual-loop detection zone during that one-hour period and this sample was used to evaluate the accuracy of the new dual-loop algorithm and the current WSDOT algorithm. Of these vehicles, all but one were classified into the same bins as the ground-truth sample data by the new dual-loop algorithm for all three lanes. The vehicle that was misclassified by the new dual-loop algorithm was a dump-pup truck, which was incorrectly separated into two vehicles due to too little metal in the long drawbar that connects the two parts.

In order to evaluate how much the new dual-loop algorithm improved the quality of the vehicle classification data, the one-hour TDAD aggregate data were also examined to identify the vehicles that were correctly classified by the current WSDOT dual-loop algorithm. The results are also summarized in Table 3. As shown in this table, the WSDOT dual-loop algorithm correctly classified the majority of the vehicles for each of the three lanes. For Bin1, more than 90% of the vehicles were correctly classified for Lanes 1 and 2. For Bin2, 77% and 58% of the vehicles were correctly classified for Lane 1 and Lane 2, respectively. For Bin3, 80% and 70% of the vehicles were correctly classified for Lane 1 and Lane 2, respectively. For Bin4, 83% and 67% of the vehicles were correctly classified for Lane 1 and Lane 2, respectively.

By comparing the number of vehicles what were correctly classified by the new dual-loop algorithm to that by the current WSDOT dual-loop algorithm, one can find that the new dual-loop algorithm correctly classified significantly more vehicles than the current WSDOT dual-loop algorithm, especially Bin2, Bin3, and Bin4 vehicles where the new algorithm correctly classified up to 42% more vehicles than the current WSDOT algorithm.

It can be concluded from the above results that the new dual-loop algorithm correctly classified the overwhelming majority of the vehicles for this one-hour period. The new dual-loop algorithm considerably increased the capability of dual-loop detectors to accurately classify vehicles.

CONCLUSIONS

In this research, the WSDOT dual-loop detection system was systematically examined and possible error causes were identified. When both single-loop detectors seem to work properly under non-forced-flow traffic conditions, the main cause for the dual-loop undercount problem is the large on-time difference caused by the sensitivity discrepancy between the two single (M and S) loops because the current WSDOT dual-loop algorithm discards vehicles detected with on-time differences greater than the 10% threshold value.

Based on the identified error causes, a new dual-loop algorithm that can handle erroneous raw loop actuation signals was developed in this research. The new dual-loop algorithm is much more flexible than the current WSDOT dual-loop algorithm in that it is capable of including and correcting erroneous raw loop actuation signals and outputting acceptable volume and vehicle classification information (14). The data analysis conducted in this research verified the effectiveness of the new dual-loop algorithm.

The dual-loop detection system could become a good truck data source after implementing the new dual-loop algorithm if the sensitivity discrepancy between paired single-loop detectors can be adjusted so that the on-time difference of the two single-loop detectors that form a dual-loop detector falls within a reasonable range.

RECOMMENDATIONS FOR FUTURE RESEARCH

The dual-loop algorithm developed in this study cannot be incorporated into the WSDOT loop detection system until the current 170 controller can be replaced by the new generation of controllers that have substantially stronger computer power. However, replacing the current controllers may take years to implement. Therefore, to improve the performance of the current dual-loop detection system in a timely manner, a quick-fix method was also recommended. As identified in the data analysis, the relatively large sensitivity discrepancy between the two single-loop detectors that form a dual-loop detector is the main cause for the WSDOT dual-loop errors. The quick remedy method that does not involve replacing any part of the system hardware or software is adjustment of the sensitivity settings of the two single-loop detectors so that their absolute mean on-time difference is less than 10% for passing vehicles under non-forced-flow traffic conditions.

With the availability of the laptop-based DEDAC system, this sensitivity setting adjustment becomes possible. Adjustments that eliminate the sensitivity discrepancies based on a reasonable set of rules without further research into the best absolute sensitivity levels should still improve the system so that the dual-loop detectors will be able to collect a majority of the passing vehicles without replacing any part of the current WSDOT dual-loop detection system.

Although adjusting the sensitivities to remove loop sensitivity differences will significantly improve the accuracy of the dual loop data, further research is needed to determine the correct absolute sensitivity levels as well. Therefore, a recommended follow-up research project includes developing a program to be integrated into the current laptop-based DEDAC system. The program should calculate the sensitivity adjustment needed to calibrate every dual-loop detector that has a sensitivity discrepancy between the two single-loop detectors. A sensitivity adjustment that not only eliminates the sensitivity discrepancies but also identifies the correct absolute sensitivity levels for the loops would greatly improve dual-loop accuracy.

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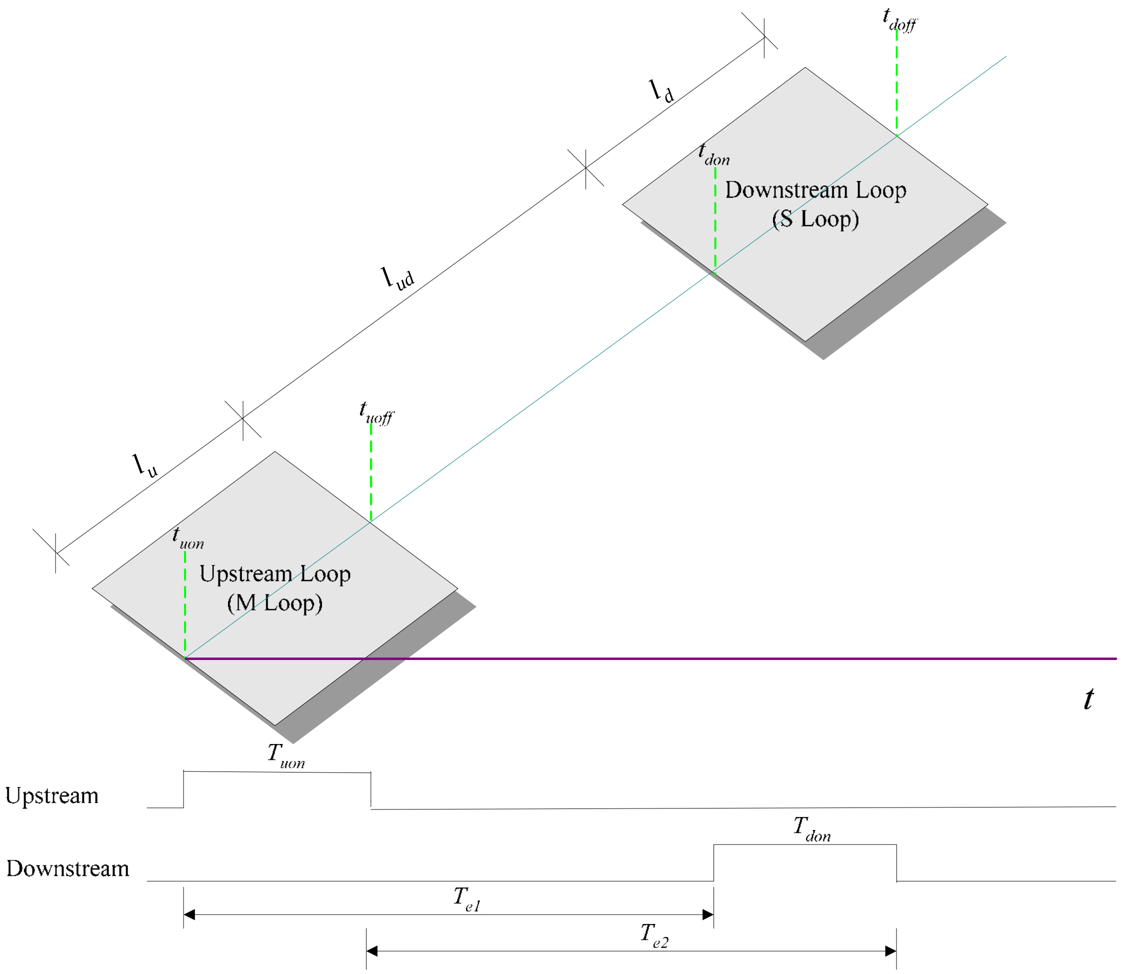
List of Figures and Tables



Where

t_{uon} = time when a vehicle hits the upstream loop's leading edge
t_{uoff} = time when a vehicle leaves the upstream loop's rear edge
t_{don} = time when a vehicle hits the downstream loop's leading edge
t_{doff} = time when a vehicle leaves the downstream loop's rear edge
l_u = length of the upstream loop
l_d = length of the downstream loop
l_{ud} = distance between the upstream and downstream single loops measured from the rear edge of the upstream loop to the leading edge of the downstream loop
T_{uon} = on-time at the upstream loop
T_{don} = on-time at the downstream loop
T_{e1} = elapsed time (leading edge to leading edge)
T_{e2} = elapsed time (rear edge to rear edge)

Figure 1. Illustration of a vehicle passing over a dual-loop detector

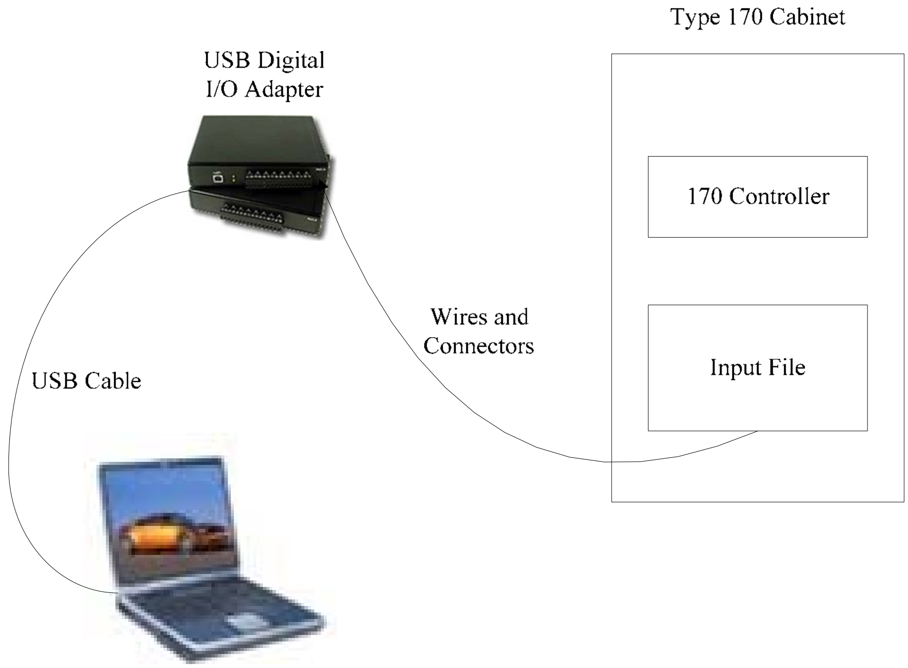


Figure 2. Overview of the laptop-based DEDAC system design

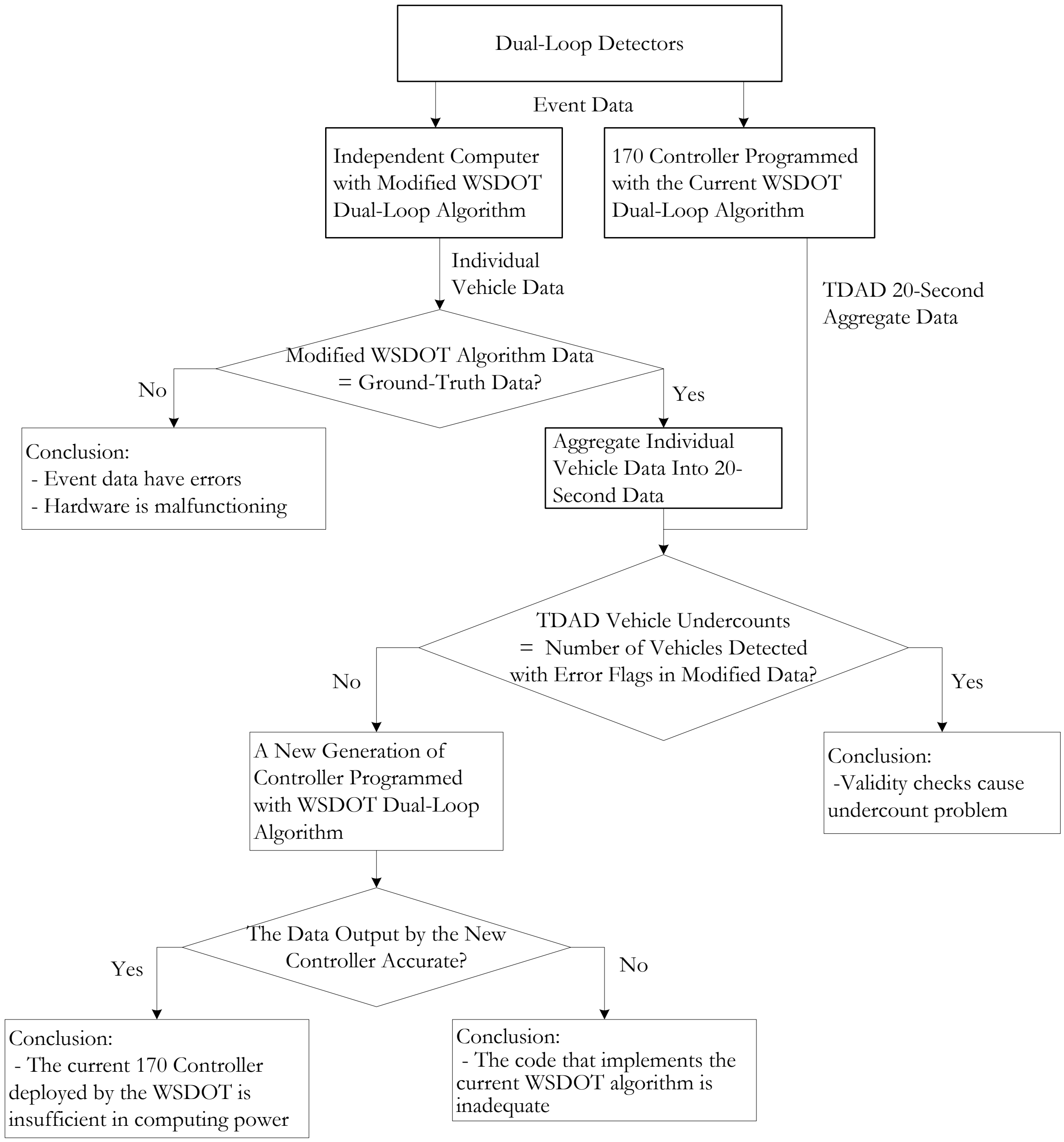


Figure 3. Flow chart of the error detecting process

Table 1. One-Hour TDAD-Based and Event-Data-Based Single-Loop and Video-Ground-Truth Volumes

Lane No	TDAD-Based				Event-Data-Based				Video-Ground-Truth	Over-Count Rate Reduction	
	M loop		S loop		M loop		S loop			M loop	S loop
	V_M	$\frac{V_M - V_V}{V_V}$	V_S	$\frac{V_S - V_V}{V_V}$	V_{EM}	$\frac{V_{EM} - V_V}{V_V}$	V_{ES}	$\frac{V_{ES} - V_V}{V_V}$	V_V	$\frac{V_M - V_{EM}}{V_V}$	$\frac{V_S - V_{ES}}{V_V}$
Lane 1	1308	3.65%	1315	4.19%	1263	0.08%	1266	0.32%	1262	3.57%	3.87%
Lane 2	1644	3.85%	1654	4.49%	1583	0.00%	1585	0.13%	1583	3.85%	4.36%
Lane HOV	350	4.79%	347	3.89%	334	0.00%	334	0.00%	334	4.79%	3.89%

V_M = TDAD-based M loop volume
V_S = TDAD-based S loop volume
V_{EM} = Event-data-based M loop volume
V_{ES} = Event-data-based S loop volume
V_V = Video-ground-truth volume

Table 2. One-Hour Event-Data-Based and TDAD-Based Dual-Loop Volume Undercount Rates

Lane No	V_T	V_{ET}	V_V	$\frac{V_T - V_V}{V_V}$	$\frac{V_{ET} - V_V}{V_V}$
Lane 1	1169	1263	1262	-7.37%	0.08%
Lane 2	1437	1583	1583	-9.22%	0.00%
Lane HOV	320	334	334	-4.19%	0.00%

V_T = TDAD-based dual-loop volume
V_{ET} = Event-data-based dual-loop volume
V_V = Video-ground-truth volume

Table 3. One-Hour Video-Based, Event-Data-Based, and TDAD-Based Vehicle Classification Data

Bin No.	Lane 1					Lane 2					Lane HOV				
	V_V	V_E	V_T	$\frac{V_E}{V_V}$	$\frac{V_T}{V_V}$	V_V	V_E	V_T	$\frac{V_E}{V_V}$	$\frac{V_T}{V_V}$	V_V	V_E	V_T	$\frac{V_E}{V_V}$	$\frac{V_T}{V_V}$
Bin1	973	973	914	100%	94%	1463	1463	1326	100%	91%	328	328	306	100%	93%
Bin2	39	39	30	100%	77%	12	12	7	100%	58%	0	0	0	----	----
Bin3	44	44	35	100%	80%	20	20	14	100%	70%	0	0	0	----	----
Bin4	88	87	73	99%	83%	24	24	16	100%	67%	0	0	0	----	----
Subtotal	1144	1143	1052	99.9%	92.0%	1519	1519	1363	100.0%	89.7%	328	328	306	100%	93.3%

V_v = Number of vehicles that were classified into bins when processing the videotape
V_E = Number of vehicles that were classified into the same bins by the new dual-loop algorithm and by processing the videotape
V_T = Number of vehicles that were classified into the same bins by the current WSDOT dual-loop algorithm and by processing the videotape