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Dual Loop Error

Evaluation of Dual-Loop Data Accuracy Using Video Ground Truth Data

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by

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EXECUTIVE SUMMARY

The Washington State Department of Transportation (WSDOT) initiated a research project entitled "Monitoring Freight on Puget Sound Freeways" in September 1999. Dual-loop data from the Seattle area freeway system were selected as the main data source for this project. However, preliminary verification tests performed on the dual-loop data indicated that the data were not reliable; therefore, the truck movements estimated by the dual-loop detectors on the Seattle FLOW system failed to represent the real freight activities. Consequently, a part of the WSDOT freight project had to be shelved.

If sufficiently accurate, dual-loop detectors can be very cost-effective collectors of real-time vehicle-classification and speed data. This report describes a WSDOT/TransNow-funded study that addresses the problems with the existing detection system encountered by the original freight study, and recommends remedial actions to rectify these problems. The researchers 1) investigated the level of inaccuracies in the existing WSDOT dual-loop freeway detectors, 2) identified the types and potential causes of these inaccuracies, and 3) proposed methods to effectively improve the quality of the dual-loop data.

The objectives of the project were to 1) identify a station of good dual-loop detectors to represent the WSDOT system, 2) quantitatively analyze the data collected from the selected station and determine the accuracy of the sample dual-loop measurements for vehicle volumes and vehicle classifications, 3) identify the types and potential causes of the observed inaccuracies, and 4) recommend appropriate methods to improve overall dual-loop data quality.

The dual-loop errors documented in the report are the differences between dual-loop measurements and the corresponding ground truth data manually extracted from videotapes. In general, three types of dual-loop errors were identified:

(1) Dual-loop detectors tend, for the most part, to underestimate bin volumes, although overestimation errors occasionally occur.

(2) Dual-loop detectors often mistakenly assign Bin 3 vehicles to Bin 4, but reverse assignments (Bin 4 vehicles to Bin3) do not occur.

(3) Dual-loop detectors have difficulties distinguishing Bin 2 vehicles from Bin 3 vehicles. They sometimes assign Bin 2 vehicles to Bin 3.

On the basis of the above analysis, the report concludes that the existing WSDOT dual-loop bin-volume data are not reliable, and, since the selected analysis site was known to be relatively free of hardware malfunctions, it is suggested that future research should focus on scrutinizing the underlying dual-loop algorithm and the implementation code. These future research findings may provide effective solutions to the current dual-loop problems.

INTRODUCTION

RESEARCH BACKGROUND

Commercial trucks are an important component of our regional economic activity. As a consequence, freeway usage and performance patterns that affect trucking activities have potentially serious impacts on commercial, industrial, and transport-related business throughout the Puget Sound region. Furthermore, since heavy weights and large turning radii make the characteristics of truck movements quite different from those of passenger cars, the monitoring of freight movements is imperative for successful traffic management, planning, and policy analysis programs.

In September 1999, the Washington State Department of Transportation (WSDOT) initiated a research project entitled "Monitoring Freight on Puget Sound Freeways." Its objectives were to enhance the FLOW system evaluation methodology and supplement the tool set that is now used to analyze vehicle usage and performance on the central Puget Sound freeway network. The methodology and tool set enhancements would enable analysts to produce estimates of the size and performance of freight (truck) movements on Puget Sound freeways and help monitor trends in trucking activities over time. By using vehicle length categories as a surrogate for various categories of trucks, the nature of trucking activities in the region could be estimated. To produce volume data sorted by vehicle length categories, the dual-loop data collected by the WSDOT FLOW system were selected as the main data source for the project. Unfortunately, preliminary tests performed on the dual-loop data indicated that these data were not reliable.

Consequently, a part of the project was temporarily suspended until the accuracy of the dual-loop data could be improved or a better data source found.

Because dual-loop detectors, if sufficiently accurate, can be extremely cost-effective collectors of real-time vehicle classification and speed data, further research on the existing problem and potential remedies was sought. The current project addressed this concern by performing further analyses of dual-loop data inaccuracies, investigating the types and potential causes of these inaccuracies, and proposing necessary steps to improve data quality.

DUAL-LOOP DATA BACKGROUND INFORMATION

A dual-loop detector, also known as a speed trap, T loop, double-loop detector, and automatic vehicle classifier, consists of two consecutive single inductance loops (one called the "M loop" and the other "S loop") spaced a few feet apart. When the first single loop detects a vehicle, a timer is started for the dual-loop system. The timer runs until the same vehicle is detected at the second single loop. The distance between the two single-loop detectors is divided by the elapsed time and converted to miles per hour to calculate vehicle travel speed. This calculated speed, and the lane-occupancy detected by the first single-loop detector are then used to calculate vehicle length and the vehicle in question is assigned to one of four categories or bins as follows:

Bin 1—personal vehicles and smaller vehicles (length 26 ft or less)

Bin 2—small trucks, etc. (26 ft to 39 ft)

Bin 3—larger trucks and buses (39 ft to 65), and

Bin 4—largest trucks and articulated buses (length greater than 65 ft).

The total classified vehicle volume measured by a dual-loop detector during a 20-second interval is the sum of the four bin counts for that interval, and the estimated truck volume for that interval is the sum of the counts for bins 2, 3 and 4. The speed, length, and volume data, aggregated into 20-second intervals for output, are sent to the Traffic Systems Management Center (TSMC) to be archived with the volume/occupancy data. As shown in Table 1, dual-loop data archived at the TSMC contain average vehicle speed and length, vehicle volume by vehicle length category (four bins), and error flags for every 20-second interval.

Table 1. Dual-Loop Data Output

SENSOR_ID	DATA_TIME	Speed	Length	Flag1	Flag2	BIN1	BIN2	BIN3	BIN4
ES-137R: _MN _T3	20000325082811000	70	17.2	16	8	4	0	0	0
ES-137R: _MN _T3	20000325082831000	65.7	16.3	0	8	3	0	0	0
ES-137R: _MN _T3	20000325082851000	67.1	19	80	8	7	0	0	0
ES-137R: _MN _T3	20000325082911000	70.5	16.3	0	8	6	0	0	0

The WSDOT dual-loop detection system identifies eight types of errors, and the identification results are shown in the Flag 1 field. Another flag, Flag 2,is used to show whether there are any measured data in the current interval. Though the bits in the Flag 1 field indicate the types of errors that have occurred for each 20-second interval, they cannot reflect how many times these errors have occurred.

The Flag 1 field is represented by a byte, which contains 8 bits. Each bit of the Flag 1 field corresponds to one type of error. If the bit is set (with value 1), the corresponding error has occurred. The error types and their corresponding bits are as follows:

- Bit 8—Operator disabled a loop in the speed pair;
- Bit 7—Two vehicles in the dual-loop detector—Calculation aborted for those two vehicles.
- Bit 6—Lost vehicle (vehicle hits only one loop)—Calculation aborted for that vehicle.
- Bit 5—Bad occupancy ratio between loops. (If the measured occupancy difference between the two single loops is larger than 10%, this bit will be set.) —Calculation aborted for that vehicle.
- Bit4—Vehicle speed less than the minimum speed (5 mile/hour) is detected and allowed.
- Bit3— Vehicle speed greater than the maximum speed (100 mile/hour) is detected and allowed.
- Bit2—Vehicle length less than the minimum length (5 feet) is detected and allowed.
- Bit1—Vehicle length greater than the maximum length (150 feet) is detected and allowed.

If two types of errors occur in a 20-second interval, the value of the number used to indicate these two errors should be the sum of the two numbers indicating the corresponding errors. For instance, in Table 1, the number "80" (corresponding to the binary value of 01010000) represents two types of errors, "64" (bit 7 is set) and "16" (bit 5 is set).

Flag 2 has only two values, 0 when no vehicle is detected, and 8 when vehicles are found.

PRELIMINARY TESTS

Since a dual-loop detector consists of two single loops (M and S), if a dual-loop detector functions well, the volume data collected by the dual-loop system should be consistent with the volumes collected by the two corresponding single loops. To check this consistency, ten dual-loop detectors were randomly chosen from I-5, I-90, I-405, and SR 520 freeways by the author to perform preliminary tests. Dual-loop volume data (T) and corresponding single-volume loop data (M and S) for a 60-minute period were compared to get general descriptive statistics for these dual-loop systems.

As can be seen in Table 2, although the volume difference between each pair of individual M and S loop measurement was not significantly large, the volume difference between the single-loop measurements and the corresponding dual-loop measurement was considerable. While in some cases the difference was small (3 percent or less), in many cases the discrepancies were serious (differences of 60 percent or more). Volume data collected by the dual loop systems were consistently lower than the corresponding volumes measured by the corresponding single loops.

Table 2. Single-Loop Data and Dual-Loop Data Volume Comparison

Loop ID	Date	Time Period	M loop	S Loop	T Loop	M vs. S (%)	T vs. S (%)
ES-163R: GP Lane 3	5/13/99	5:00-6:00 pm	1550	1557	1515	-0.4	-2.7
ES-520D: GP Lane 2	1/20/00	9:00-10:00 am	1348	1386	1230	-2.7	-11.3
ES-855D: GP Lane 2	3/10/00	4:30-5:30 pm	1808	1771	1570	2.1	-11.3
ES-940D: GP Lane 3	2/24/00	5:00-6:00 pm	282	275	239	2.5	-13.1
ES-074D: GP Lane 2	2/7/00	1:00-2:00 pm	1247	1271	1020	-1.9	-19.7
ES-651D: GP Lane 2	3/10/00	4:30-5:30 pm	1697	1695	1354	0.1	-20.1
ES-136R: GP Lane 3	9/20/99	9:00-10:00 am	1459	1450	1147	0.6	-20.9
ES-924D: GP Lane 2	3/10/00	4:30-5:30 pm	1101	1099	737	0.2	-32.9
ES-168R: GP Lane 3	3/10/00	4:30-5:30 pm	1626	1604	961	1.4	-40.1
ES-516R: GP Lane 2	3/10/00	4:30-5:30 pm	579	577	209	0.3	-63.8

GP: General-purpose lane

To check how accurately dual-loop detectors estimate vehicle lengths and distribute them into corresponding categories (bins), the Washington State Transportation Center (TRAC) performed some tests to compare dual-loop data and video data collected in the HOV Evaluation Project (Ishimaru, 2000). The comparisons indicated that the loop-based truck percentage consistently underestimated the truck percentage observed in the HOV study by degrees varying from 1 percent to 100 percent or more.

Because the distinction between Bin 1 and Bin 2 is difficult for the current dual-loop system to detect, TRAC tried revising the truck-length definition by excluding Bin 2 vehicles from the truck count and compared “big trucks” only (Bin 3 and Bin 4) to improve the match. Results showed that the resulting loop-based big truck percentage still underestimated the truck percentage observed in the HOV Evaluation Project by degrees varying, from 1 percent to 50 percent. However, because the dual-loop data were for specific days and times, while the HOV Evaluation data were averaged for a number of days, the tests performed were only based on an approximate match of background conditions.

PROBLEM STATEMENT

Given the preliminary tests performed above, the problems of dual-loop data could be summarized as follows:

- The total volume of vehicles detected and assigned to bins by the dual-loop system for a given time interval was consistently lower than the total volume of vehicles detected by the corresponding single loops for the same interval. I.e., the volume of classified vehicles was consistently lower than the volume of actual vehicles detected, reflecting vehicles that were dropped by the dual-loop system during the classification step.
- The existing dual-loop detector systems had problems measuring vehicle lengths; hence the vehicle bin volume distribution for any time period might differ significantly from the actual distribution. Therefore, the detected trucking information did not reflect the true trucking activities during that period at that location.

RESEARCH OBJECTIVES

This study quantitatively evaluated the accuracy of WSDOT dual-loop data using video ground truth data and investigated the types and potential causes of dual-loop data inaccuracies. It also sought and recommended methods to improve the quality of dual-loop data. The objectives of the research are summarized below:

- Identify dual-loop detectors in the FLOW system in good working condition to serve as representatives of WSDOT dual-loop detectors for analysis.
- Quantitatively evaluate the accuracy of the sample dual-loop measurements of vehicle volumes and vehicle classifications.
- Identify and interpret the potential causes of dual-loop data inaccuracies.
- Recommend strategies for improving dual-loop data quality.

STATE OF THE ART

Due to heavy weights and large turning radii, truck movements have characteristics very different from those of passenger cars and smaller vehicles. These differences make the collection of reliable and continuous vehicle classification data and truck volume data very important for reliable freeway performance monitoring. Of course, such data are critical to the specific monitoring of regional freight movements. To date, several different technologies have been used for vehicle detection and classification. These include single-loop detectors, dual-loop detectors, classification with vehicle acoustic signatures, video imaging systems, and laser and night vision systems. Each of these technologies has its own advantages and disadvantages.

Dual-loop detectors are often used to collect vehicle classification data. As previously described, a dual-loop detector consists of two consecutive single loops that are only a few feet apart. An algorithm is applied to calculate vehicle speed and vehicle length on the basis of the information that these two single loops provide. The inductive loops are relatively cheap to install but at the cost of some inconvenience, as traffic has to be stopped. The loops can be damaged or broken and, thus, become unreliable.

Vehicle classification can also be achieved using single-loop detectors. Wang and Nihan (Wang and Nihan 2000a) analyzed vehicle-length distributions and developed a nearest-neighbor algorithm to classify vehicles into a short-vehicle (SV) category and a large-truck (LT) category by using only single-loop measurements. This research development is especially useful in practice because most highway systems are, to date, equipped only with single-loop detectors. Comparison of the estimated large-truck volumes with dual-loop observed large-truck volumes showed that this algorithm worked well, especially when traffic volume was low. However, the method tended to underestimate large truck volumes under heavy traffic conditions. This was due to the fact that when traffic volume is heavy, speed is very unstable, and the uniform speed assumption, on which the algorithm is based, is violated.

Nooralahiyan *et al.* (1997) investigated the feasibility of developing a novel traffic sensor for reliable vehicle classification based on audio monitoring of road traffic. The approach was centered around neurocomputing classification based on digital signal processing of the acoustic signature of traveling vehicles. The advantages of this technology are that the equipment can be installed without stopping traffic; and it can be easily maintained as it is above ground; and the cost of a microphone and associated digital signaling facilities is not high. Despite all these advantages, the equipment can only classify vehicles into four broad categories consisting of buses or lorries, small or large saloon cars, various types of motorcycles, and light-goods vehicles or vans. It cannot distinguish single-unit trucks from multi-trailer trucks.

Video imaging systems are growing in popularity as the cost of video technology diminishes. However, these systems tend to be badly affected by adverse weather conditions. Laser and night vision systems overcome this problem but they are more expensive. Other technologies such as microwaves and active infrared beacons are also popular but used mainly for vehicle detection rather than vehicle classification.

Among all these technologies, the video camera offers more unique signature information about vehicles than other technologies (Nihan et al., 1995). This system was used only to collect short period ground-truth data for the current research effort. The ground-truth data were collected manually from video images on a frame-by-frame basis.

In effect, this technology provides a video emulation of loop detectors because it can be used to record real-time traffic flow on the roadway section where loop detectors exist. Therefore, it is currently an appropriate way to collect ground truth data.

RESEARCH APPROACH/PROCEDURES

In general, the research approach was to compare ground truth data collected by video camera with dual-loop data to determine the accuracy of the dual-loop data with respect to vehicle volume and vehicle classification measurements.

STUDY SITE

A suitable site for data collection had to consist of a section of roadway in which a video camera could be placed directly over the roadway travel lanes, with the dual loops in the camera's field-of- view. This meant that an overpass, on which the video camera could be positioned, had to exist nearby. Additionally, the height of the overpass used for locating the camera should not be too low. Also, the dual loops in the field-of-view had to be working well. For this project, the working condition of dual loops could be checked on the Traffic Data Acquisition and Distribution (TDAD) website, where real-time dual-loop data are shown online.

Given all these considerations, the NE 45th street overpass perpendicular to Interstate 5 was chosen as a suitable place on which to position a video camera. Four dual-loop detectors about 300 feet away from the overpass were chosen as study samples for this research. (See Figure 1) The sample site consisted of four general-purpose (GP) lanes in each direction. Data were collected from the four northbound GP lanes, with the video camera located directly over the middle of the two median lanes.

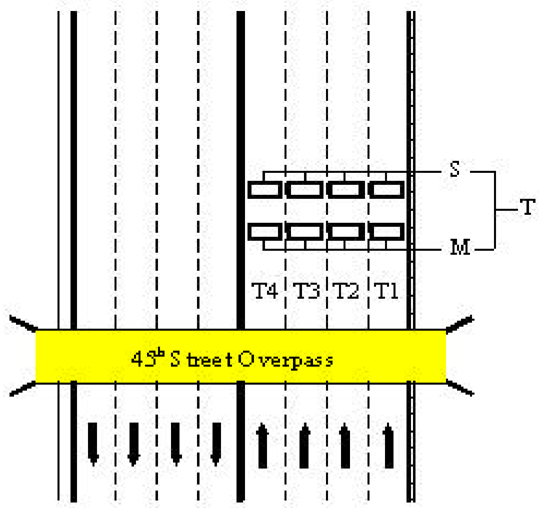

Figure 1. Data Collection Location

DATA COLLECTION

Data were collected on both a weekday and weekend, and at different times of day (peak vs. off-peak) to check the variation of loop data accuracy under different traffic conditions. Table 3 lists the data collection dates and time periods.

Table 3. Data Collection Date and Time

Date	Time Period	Weather	Type of Data
March 23, 2000	2:30-4:30 PM	Cloudy	Weekday Peak hour
March 25, 2000	8:10-10:00 AM	Cloudy	Weekend Off-peak hour

Video Data Collection

Before the data collection began, the clock of the camera operator was synchronized with official Pacific Standard Time. Once the video recording had started, a time-stamp from the synchronized clock was spoken into the microphone. The Canon L2 camera placed a digital time-stamp on the video; thus, the actual clock time could be determined at any point on the video. This made for easy synchronization of the video system clock and the dual-loop detector system clock.

It was necessary to use a shutter speed that was capable of providing clear images of the vehicles during a “frozen” camera image. The appropriate shutter speed depends on the speed of vehicles. Because the traffic to be recorded was on the I-5 freeway, and the traffic traveling speed was between 55 and 65 mph at low congestion periods, shutter speeds over 1/500 second were expected to provide adequate results for freeway free-flow speeds. Because there was no disadvantage to using a higher shutter speed in this research, a shutter speed of 1/1000 second made sense for recording the traffic data.

Loop Data Collection

Regular-loop and dual-loop data are available in electronic form at the University of Washington’s ITS website (http://www.its.washington.edu/). Loop data are downloaded from the Traffic Data Acquisition and Distribution (TDAD) Query Interface which provides a web-based front-end to the Traffic Management System. The TDAD database on the ITS website collects the output of the Traffic Management System over time. Every 20 seconds, a new “snapshot” of the current highway conditions is added to the database for a total of 4,320 20-second intervals each day.

Three separate measurements are stored along with each daily volume to explain the state of the underlying 20-second data. For each sensor, let n = the number of available samples in a day, and v = the number of those samples that are valid, with $v = n$ and $n = 4320$. Then the following useful ratios exist:

- count_quality is $v/4320$

- data_completeness is $n/4320$
- sensor_validity is v/n

To trust a daily count, count_quality must be close to 100 percent. If that isn't the case, the explanation is either that the data set was incomplete (low data_completeness) or that the sensor was reporting itself invalid (low sensor_validity).

Table 4 shows the three measurements that explain the state of the underlying 20-second data on the study dates for the selected study site. The count_quality, data_completeness, and sensor_validity of the data for the two study dates were very good; therefore it is reasonable to conclude that the sample dual-loop detectors were excellent representatives of the WSDOT dual-loop detectors that were in good working order.

Table 4. Dual-Loop Data State

Sensor No.	Date	Count_quality	Data_completeness	Sensor_validity
ES-137R NB	03/23/2000	99.98%	99.98%	100%
ES-137R NB	03/25/2000	99.98%	99.98%	100%

METHOD OF ANALYSIS

Synchronization of Two System Clocks

Because dual-loop data and video data were to be compared for concurrent 20-second intervals, exact synchronization of the two system clocks was required for accurate comparison. Also, since no official documentation described the settings of the dual-loop system clock, the dual-loop data and video data had to be analyzed before the error calculations in order to identify information that could help synchronize the two system clocks.

As shown in Table 5, two 20-second intervals in the dual-loop data contained no passing vehicles. Correspondingly, a 44-second gap was found in the video data for that period. Therefore, by matching the starting time of the observed video gap with the starting time of the initial dual interval containing a zero volume, the two system clocks could be roughly matched with an estimated error of ± 4 seconds. Another 20-second gap was also observed about 20 seconds later, after a Bin 3 truck had passed by, providing additional information with which to further synchronize the two system clocks. After trial –and error, the two system clocks were synchronized, making accurate 20-second data comparison possible.

Table 5. Dual-Loop Data Used to Synchronize System Clocks

SENSOR_ID	DATA_TIME	Speed	Length	Flag1	Flag2	BIN1	BIN2	BIN3	BIN4
ES-137R:_MN__T1	20000325081611000	63	15	0	8	1	0	0	0
ES-137R:_MN__T1	20000325081631000	0	0	0	0	0	0	0	0
ES-137R:_MN__T1	20000325081651000	0	0	0	0	0	0	0	0
ES-137R:_MN__T1	20000325081711000	65.5	16.2	0	8	4	0	0	0
ES-137R:_MN__T1	20000325081731000	61	44	0	8	0	0	1	0
ES-137R:_MN__T1	20000325081751000	0	0	0	0	0	0	0	0
ES-137R:_MN__T1	20000325081811000	75	19	0	8	2	0	0	0

Process Video Data

After the system clocks had been synchronized, video data were manually processed for analysis by aggregating the video data output into the same 20-second intervals observed for the dual-loop data. Observed vehicles were classified based on the criteria of bin classification adopted by WSDOT (Hallenbeck, 1993 and USDOT, 1998). This classification was based on manually identified vehicle types so that classification errors due to inaccurate vehicle length measurements were virtually eliminated. Special traffic conditions were also marked for later analysis.

FINDINGS/DISCUSSION

A digital camcorder was used to record real-time traffic data during each simultaneous loop-data collection period, providing a visual representation of traffic flows and parameters on the same roadway section where the loop detectors existed. Two independent researchers manually inspected the video images of the vehicles passing over the loops on a frame-by-frame basis to identify vehicle types and classify them into the correct bins. A system was set up so that any differences in the two researchers' independent classifications would be reviewed by the research team for mutual agreement. Hence the method of extracting bin-volume data from videotapes was a painstaking and carefully monitored process, and we stand by resulting classification data as being true ground truth data. It represents a 100% sample of the vehicles observed passing over the loops for the study period. The extracted data were used as ground-truth data to determine the accuracy of the observed dual-loop measurements. Volume and vehicle classification data were compared for peak and off-peak periods. For convenience, the letters V, T, M, and S were used to represent video data, dual-loop data, the first single-loop data, and the second single-loop data, respectively.

OFF-PEAK HOUR DATA COMPARISON

Volume Comparison

Comparison of 20-Second Volume Data

First, video and dual-loop volume data were compared for each 20-second interval for each of the four lanes. If the total number of vehicles or the number of vehicles in each category counted by dual-loop detectors did not match the video data for particular intervals, the intervals were marked incorrect. For each of the four lanes, 180 20-second intervals were examined during the 60-minute period. Table 6 summarizes the 20-second data comparison, as well as the general descriptive statistics for each of the four lanes.

Table 6. Summary of 20-Second Volume Data Comparison

Lane No.	Number of Intervals	Number of Incorrect Intervals	Percentage of Incorrect Intervals	Total Volume (Video Data)
Lane 1	180	24	13.3	464
Lane 2	180	46	25.6	822
Lane 3	180	58	32.2	916
Lane 4	180	31	17.2	629
Total	720	159	22.1	2831

As can be seen in Table 6, the percentage of incorrect intervals for each of the four lanes is larger than 10 percent, and the number of incorrect intervals increases from 13.3 percent to 32.2 percent, with the increase in traffic volume from 1,866 to 3,683.

60-Minute Volume Data Comparison

Table 7 shows the percentage difference between the same video ground truth data (V) and dual-loop data (T) for a 60-minute interval. As expected, the percentage difference decreased with the increase in time interval. Although the volumes recorded using single-loop detectors M and S were consistently higher than the video ground truth volumes, all the percentage differences were less than 5 percent, indicating that video ground truth volume data and the volume data collected using the individual loops in the dual-loop system were not seriously different.

Table 7. A 60-Minute Volume Data Comparison

Lane No.	V	T	S	M	T vs. V (%)	S vs. V (%)	M vs. V (%)	S vs. M (%)	S vs. T (%)
Lane 1	464	460	469	473	-0.9	1.1	1.9	-0.8	2.0
Lane 2	822	801	840	837	-2.6	2.2	1.8	0.4	4.9
Lane 3	916	892	931	943	-2.6	1.6	2.9	-1.3	4.4
Lane 4	629	615	636	637	-2.2	1.1	1.3	-0.2	3.4
Total	2831	2768	2876	2890	-2.2	1.1	2.1	-0.2	3.4

As can be seen from Figure 2, the classified vehicle volumes collected using dual loops (i.e., the sum of volumes assigned to the four bins) were consistently lower than the corresponding video ground-truth volumes, whereas the vehicle volumes detected by the M or S loop were usually larger than the corresponding video ground-truth volumes.

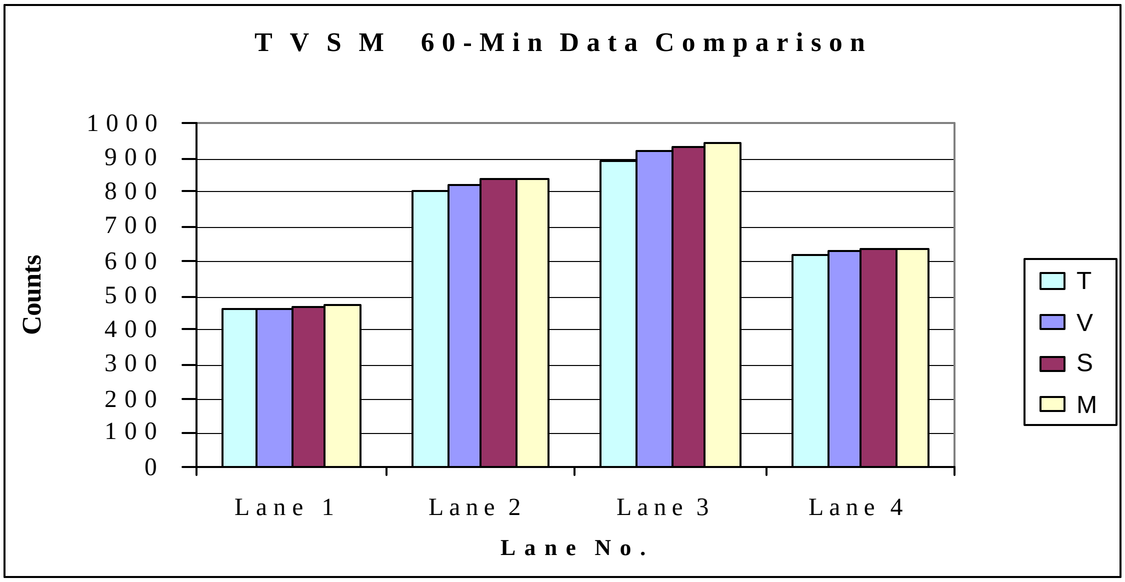

Figure 2. Volume Data Comparison for a 60-Minute Interval

Vehicle Classification Comparison

To estimate how accurately dual-loop detectors measure vehicle lengths, the bin volumes recorded for the 60-minute interval by the dual-loop systems and the corresponding ground-truth data were compared. Table 8 gives the comparison results.

Table 8. Comparison of T and V Bin Volumes

Lane No.	Bin 1			Bin 2			Bin 3			Bin 4		
	T	V	T vs. V (%)	T	V	T vs. V (%)	T	V	T vs. V (%)	T	V	T vs. V (%)
Lane1	447	446	0.2	7	12	-41.7	4	5	-20.0	2	1	100.0
Lane2	750	765	-2.0	27	33	-18.2	12	19	-36.8	12	5	140.0
Lane3	851	870	-2.2	21	31	-32.3	8	11	-27.3	12	5	140.0
Lane4	607	622	-2.4	3	3	0	4	4	0.0	1	0	---

--Data not applicable

As shown in Table 8, the percentage differences between dual-loop data and video data for Bin 1 volumes were all less than 5 percent, indicating that the differences were not large. However, the percentage differences between ground-truth data and dual-loop data for the other three bins were substantial.

Table 9 shows how vehicles belonging to each bin (according to the ground-truth data) were actually classified by the dual-loop system.

Table 9. Summary of Vehicle Assignments by Dual-Loops

TRUE BIN	TOTAL NO. VEHS	DUAL-LOOP BIN ASSIGNMENT	NO. VEHS	PERCENT
Bin2	79	To Bin1	19	24%
		To Bin2	55	70%
		To Bin3	5	6%
		To Bin4	0	0%
Bin3	39	To Bin1	0	0%
		To Bin2	0	0%
		To Bin3	23	59%
		To Bin4	16	41%
Bin4	11	To Bin1	0	0%
		To Bin2	0	0%
		To Bin3	0	0%
		To Bin4	11	100%

As shown in Table 9, dual-loop detectors sometimes incorrectly distributed Bin 2 vehicles into Bin 3. But more frequently, they failed to distinguish Bin 2 vehicles from Bin 1 vehicles. Among the 79 Bin 2 vehicles, 55 (70 percent) were correctly assigned, 19

(24 percent) were incorrectly assigned to Bin 1, and 5 (6 percent) were incorrectly assigned to Bin 3 during the 60-minute period. Dual-loop detectors had serious problems in correctly identifying Bin 3 vehicles. Among the 39 Bin 3 vehicles, only 23 (59 percent) were properly distributed into Bin 3; the other 16 (41 percent) were incorrectly distributed into Bin 4. Although dual-loop detectors had problems correctly recognizing Bin 2 and Bin 3 vehicles, they correctly recognized all the Bin 4 vehicles and distributed them into their appropriate long-length category during the 60-minute period.

Summary of Dual Loop Errors

Dual-loop errors recorded by the video camera during the 60-minute period were classified into five error types. There were 720 20-second data intervals altogether, with 180 for each of the four lanes. Table 10 summarizes the number of 20-second intervals for each error type.

Table 10. Summary of Dual-Loop Errors by Error Type

	No. of 20-second Intervals with Each Error Type					
Lane No.	Total Volume Underestimated	Total Volume Overestimated	Bin 2 vehicles assigned to Bin 1	Bin 2 vehicles assigned to Bin 3	Bin 3 vehicles assigned to Bin 4	Total
Lane 1	15	6	5	0	1	27
Lane 2	27	9	8	0	7	51
Lane 3	34	8	6	4	7	59
Lane 4	23	7	0	1	1	32
Total	99	30	19	5	16	169

As shown in this table, 129 of the 720 intervals for the period had incorrect estimates of vehicle volumes, and 40 of the 720 intervals had incorrect bin assignments. Volume counts were more likely to be underestimated than overestimated. This would be expected since the dual-loop detectors tend to discard vehicle data with error flags before making bin assignments. Therefore, the sum of volumes for the four bins should have been less than or equal to the true volume for that lane during the 60-minute period.

Summary of Off-Peak Hour Data Analysis

1. Dual loop detectors counted fewer vehicles than those identified by video ground truth data during the 60-minute period. As previously mentioned, because dual loop detectors implement various checks on the reasonableness of measurements, some intervals with uncertain lane-occupancies or long elapsed times are discarded before the number of vehicles detected can be archived. This explains why the dual-loop detectors consistently underestimated total vehicle volumes.
2. M and S loop detectors counted more vehicles than those identified by video ground truth data during the 60-minute period. Because the video data showed many vehicles changing lanes at the study location during this period, some vehicles could have been counted twice by the individual loops, i.e., one count by the M loop in one lane, and a second count by the S loop in the adjacent lane to which the vehicle switched.
3. Dual-loop detectors failed to correctly distinguish some Bin 3 vehicles from larger vehicles and incorrectly assigned them to Bin 4. The reverse type of error did not occur; i.e., there were <u>no</u> incorrect assignments of Bin 4 vehicles to Bin 3 during the 60-minute period.
4. Dual-loop detectors failed to correctly recognize Bin 2 vehicles. At times, they failed to distinguish Bin 2 vehicles from Bin 1 vehicles, and at other times, they incorrectly assigned Bin 2 vehicles to Bin 3. No Bin 3 vehicles were incorrectly assigned to Bin 2 during the 60-minute period.

PEAK HOUR DATA COMPARISON

Volume Comparison

20-Second Volume Data Comparison

As was previously done for off-peak hour data, video and dual-loop interval data were compared for each of the four lanes during a portion of the peak period. Incorrect 20-second intervals were marked. There were ninety 20-second intervals for each of the four lanes during the 30-minute period of data selected. Table 11 summarizes the 20-second data comparison.

Table 11. Summary of 20-Second Volume Data Comparison

Lane No.	Number of Intervals	Number of Incorrect Intervals	Percentage of Incorrect Intervals	Total Volume (Video Data)
Lane 1	90	15	16.7	516
Lane 2	90	24	26.7	836
Lane 3	90	42	46.7	865
Lane 4	90	40	44.4	1001
Total	360	121	33.6	3218

As can be seen in Table 11, the percentage of incorrect intervals of peak hour data increased from 16.7 percent to 44.4 percent for Lane 1 to Lane 4, which was much higher than the corresponding increase for off-peak hour data. This indicates that if more vehicles pass during a given time interval, the dual-loop data will be less accurate.

30-Minute Volume Data Comparison

Since 30 minutes of data collected during the peak period produced a large enough sample for comparison, this shorter period was used for the peak-hour comparisons. Table 12 gives the results of the 30-minute comparisons. The percentage difference for each compared data pair decreased with the increase of the time interval from 20 seconds to 30 minutes. All the percentage differences were less than 5 percent, indicating no significant difference between each data pair.

Table 12. A 30-Minute Volume Data Comparison

Lane No.	V	T	S	M	T vs. V (%)	S vs. V (%)	M vs. V (%)	S vs. M (%)	S vs. T (%)
Lane 1	516	524	533	532	1.6	3.3	3.1	0.2	1.7
Lane 2	836	853	865	849	2.0	3.5	1.6	1.9	1.4
Lane 3	865	861	873	903	-0.5	0.9	4.4	-3.3	1.4
Lane 4	1001	1004	1014	1028	0.3	1.3	2.7	-1.4	1.0
Total	3218	3242	3285	3312	0.7	2.1	2.9	-0.8	1.3

As can be seen from Figure 3, the number of vehicles counted by dual-loop detectors was slightly higher than the number counted using video camera. This was caused by some abnormal dual-loop data collected during a 1-minute stretch of time, which will be discussed later. The number of vehicles detected by the M and S loops were also larger than those of the video ground truth data.

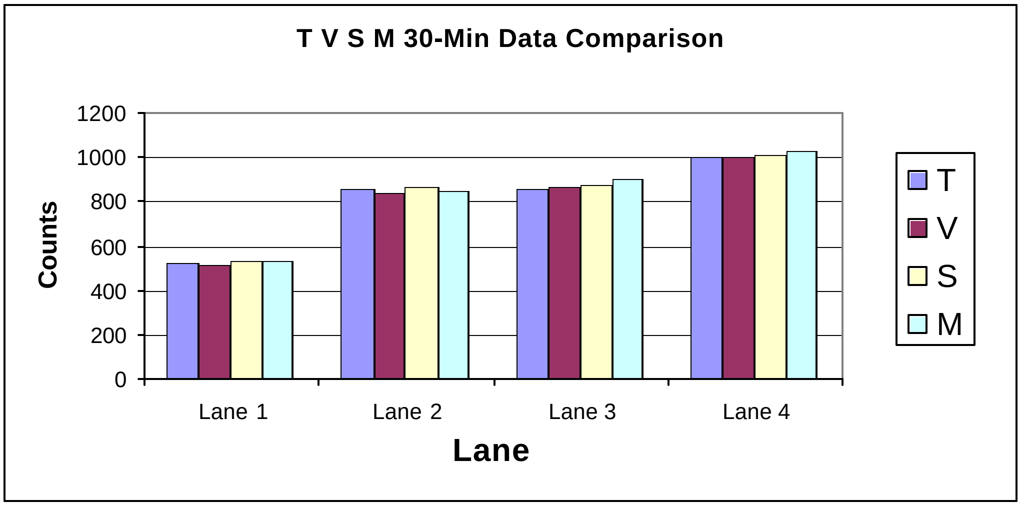

Figure 3. 30-Minute Volume Data Comparison

VEHICLE CLASSIFICATION COMPARISON

As with the off-peak hour vehicle classification comparison, dual-loop and video bin volume data collected during the 30-minute period were compared to determine how accurately dual-loop detectors estimate vehicle lengths. Table 13 shows these results.

Table 13. Comparisons of T and V Bin Volumes

Lane No.	Bin 1			Bin 2			Bin 3			Bin 4		
	T	V	T vs. V (%)	T	V	T vs. V (%)	T	V	T vs. V (%)	T	V	T vs. V (%)
Lane 1	518	508	0.2	5	7	-28.6	1	1	0.0	0	0	0
Lane 2	824	805	2.4	15	18	-16.7	8	9	-11.1	6	4	50
Lane 3	821	826	-0.6	11	15	-26.7	11	21	-47.6	18	3	500
Lane 4	994	991	0.3	7	8	-12.5	2	2	0.0	1	0	--

--- *Data not applicable*

As shown in Table 13, the percentage differences between dual-loop measurements and video data for Bin 1 volumes were all less than 5 percent, indicating that the differences were not serious. However, the percentage differences for the other three bins were substantial.

Table 14 shows how vehicles belonging to each bin (according to the ground-truth data) were actually distributed by the dual-loop systems.

Table 14. Summary of Vehicle Assignments by Dual Loops

TRUE BIN	TOTAL NO. VEHS	DUAL-LOOP BIN ASSIGNMENT	NO. VEHS	PERCENT
Bin2	48	To Bin1	10	20.8%
		To Bin2	32	66.7%
		To Bin3	6	12.5%
		To Bin4	0	0%
Bin3	33	To Bin1	0	0%
		To Bin2	0	0%
		To Bin3	15	45.5%
		To Bin4	18	54.5%
Bin4	7	To Bin1	0	0%
		To Bin2	0	0%
		To Bin3	0	0%
		To Bin4	7	100%

As shown in Table 14, dual-loop detectors sometimes incorrectly distributed Bin 2 vehicles into Bin 3. But more frequently, they failed to distinguish Bin 2 vehicles from Bin 1 vehicles. Among the 48 Bin 2 vehicles, 32 (66.7 percent) were correctly assigned, 11 (20.8 percent) were incorrectly assigned to Bin 1, and 6 (12.5 percent) were incorrectly assigned to Bin 3 during the 30-minute interval. Dual-loop detectors had serious problems in correctly identifying Bin 3 vehicles. Among the 33 Bin 3 vehicles, only 15 (45.5 percent) were properly distributed into Bin 3; the other 18 (54.5 percent) were incorrectly assigned to Bin 4. Although dual-loop detectors had problems correctly identifying Bin 2 and Bin 3 vehicles, they correctly identified all the Bin 4 vehicles and distributed them into their appropriate long-length category during the 30-minute period.

Summary of Dual Loop Errors

Dual-loop errors recorded by the video camera during the 30-minute period were classified into five types. The number of 20-second intervals that had each type of error for this period is shown in Table 15.

Table 15. Summary of Dual-Loop Errors by Error Type

	No. of 20-second Intervals with Each Error Type					
Lane No.	Total Volume Underestimated	Total Volume Overestimated	Bin 2 vehicles assigned to Bin 1	Bin 2 vehicles assigned to Bin 3	Bin 3 vehicles assigned to Bin 4	Total
Lane 1	8	5	2	0	0	15
Lane 2	10	8	3	1	2	24
Lane 3	22	6	2	4	15	49
Lane 4	31	6	3	1	1	42
Total	71	25	10	6	18	130

Summary of Peak Hour Data Analysis

1. M and S loop detectors counted more vehicles than those identified by video ground truth data during the 30-minute period. Because many vehicles changed lanes at the sample location during this period, some vehicles could have been counted twice by the individual loops; i.e., one count by the M loop in one lane, and a second count by the S loop in the adjacent lane to which the vehicle switched. The video ground truth data, did not count any vehicle twice.
2. Dual-loop detectors failed to correctly distinguish Bin 3 vehicles from Bin 4 vehicles as they sometimes distributed Bin 3 vehicles into Bin 4., whereas, dual-loop detectors never distributed Bin 4 vehicles into Bin 3 during the 30-minute period.
3. Dual-loop detectors failed to correctly recognize Bin 2 vehicles. They sometimes failed to distinguish Bin 2 vehicles from Bin 1 vehicles. At other times they distributed Bin 2 vehicles into Bin 3. The dual-loop detectors never distributed Bin 3 vehicles into Bin 2 during the 30-minute period.
4. Dual-loop detectors counted many more vehicles than warranted for one particular minute (three consecutive 20-second intervals) during the 30-minute period. The cause of this abnormal phenomenon needs further research.

DUAL-LOOP ERROR INTERPRETATION

According to the sketch of the TSMC vehicle classification algorithm described in the section “dual-loop background information,” dual-loop detectors implement various checks on the reasonableness of the data. Thus some sample intervals with uncertain occupancy ratios or long elapsed times are discarded before they are archived. This explains why dual-loop detectors consistently underestimate true vehicle volumes.

By comparing true vehicle classification counts with those collected by dual loops in the field, the current study found that dual-loop detectors also fail to accurately estimate vehicle lengths and distribute them into their corresponding length categories

Although the WSDOT dual-loop detectors measure vehicles individually, the data are aggregated into 20-second intervals for output. This makes the individual vehicle length measurements unavailable when more than one vehicle is detected per interval. Wang and Nihan (2000b) developed a computer program to extract 20-second intervals containing only one vehicle detected per interval from a 14-day data sample to check vehicle length distribution. Their results showed two peaks in the vehicle length distribution histogram, one at about 17 feet (std deviation 2.86) and the other at about 77 feet (std deviation 11.79). This vehicle length distribution indicated that vehicle lengths are concentrated at two different levels, and vehicles can be naturally divided into two classes according to their lengths: SV (vehicle length less than 39 feet) class and LT (vehicle length more than 39 feet) classes. Therefore, if the vehicle-length distribution from that research represents real vehicle-length distribution on the freeway system, the 4-Bin categories used in the TSMC dual-loop algorithm to classify vehicles may not be practical. The impractical vehicle classification tends to induce more assignment errors.

The potential causes of other errors identified in the study data comparison are hard to determine solely from the comparison outputs. Further examination of the dual-loop detector systems and the underlying dual-loop algorithm is needed to identify the causes.

CONCLUSIONS

The conclusions drawn from off-peak-hour and peak-hour data comparisons can be summarized as follows:

- Normally, dual-loop detectors tend to underestimate total vehicle volumes
- Dual-loop detectors often fail to correctly distinguish Bin 3 vehicles from Bin 4 vehicles as they sometimes assign Bin 3 vehicles into Bin 4. The reverse incorrect assignment (Bin 4 vehicles into Bin 3) never occurs.
- Dual-loop detectors often fail to correctly recognize Bin 2 vehicles. They assign Bin 2 vehicles to Bin 1 and sometimes distribute Bin 2 vehicles into Bin 3. The reverse error (Bin 3 vehicles into Bin 2) never occurs.

In general, the WSDOT dual-loop data system is not reliable for vehicle classification, given the analysis performed in this research. Errors in vehicle volume and classification data may be due to hardware, software, or the underlying algorithm. The current study controlled for hardware malfunctions, but further research is needed to pin down the major causes of dual-loop data errors. Although a few of the causes of dual-loop errors can be conjectured by examining the differences between dual-loop data and ground truth data, most of them are hard to identify and interpret without scrutinizing the underlying algorithm and the implementation code. More detailed information regarding this study is available from Zhang (2000).

RECOMMENDATIONS/APPLICATION/IMPLEMENTATION

FURTHER ANALYZE TRAFFIC DATA COLLECTED UNDER CONGESTED TRAFFIC CONDITIONS

Dual-loop data collected under congested traffic flow conditions must be further analyzed. According to the TSMC algorithm previously mentioned, if the second single-loop detector does not detect a vehicle in a reasonable amount of time, or the occupancy of the first loop detector does not equal that of the second detector plus or minus 10 percent, the dual-loop detector flags an error and the sample is discarded. Thus, under congested traffic conditions short of stop-and-go, dual-loop detectors have a greater tendency to flag errors and discard vehicle samples. Therefore it is desirable to analyze dual-loop data collected under heavily congested traffic conditions.

FURTHER ANALYZE ABNORMAL DUAL-LOOP DATA

As mentioned in the section on peak-hour data analyses, during the 30-minute period dual-loop detectors counted far more vehicles than those in video ground truth data during a 1-minute (three 20-second intervals) period. As shown in Table 16 the differences between the volumes detected by dual-loop detectors and ground truth data ranged from –37.5 percent to 200.0 percent. This abnormal phenomenon, or dual-loop mistake, needs to be addressed, and possible causes should be investigated.

Table 16. Lane 1 Abnormal 20-Second Dual-Loop Data

DATA_TIME	Lane No.	Video true data (V)	Dual-loop data (T)	M-loop data (M)	S-loop data (S)	Percentage difference (V vs. T)
20000323154431000	Lane 1	3	5	4	4	66.7%
20000323154451000		8	5	4	4	-37.5%
20000323154411000		5	13	6	4	160.0%
20000323154431000	Lane 2	10	17	10	10	70.0%
20000323154451000		10	17	10	10	70.0%
20000323154411000		11	21	9	8	90.9%
20000323154431000	Lane 3	10	19	12	14	90.0%
20000323154451000		12	19	12	14	58.3%
20000323154411000		5	15	8	8	200.0%
20000323154431000	Lane 4	9	22	10	11	144.4%
20000323154451000		15	22	10	11	46.7%
20000323154411000		10	25	10	11	150.0%

IMPROVE TSMC DUAL-LOOP ALGORITHM

As mentioned previously, the average vehicle speed detected by the dual-loop detector is calculated by dividing the distance between the M and S loops by the elapsed time. After the speed is calculated, it is used with the lane-occupancy detected by the single-loop detector to calculate vehicle length. Obviously, the TSMC algorithm partly determines how accurately the dual loops measure vehicle travel speeds, vehicle lengths, and vehicle categories. Theoretically, if the dual loops are in good working condition, the lane-occupancy detected by the M and S single loops is accurate, the applied algorithm is correct, and the program used to implement the algorithm is appropriate, then the dual-loop data should be accurate and reliable. Therefore, to radically solve the dual-loop data problem and to improve the quality of dual-loop data on the FLOW system, improvements to the WSDOT dual-loop algorithm and implementation program should be the emphasis of future research.

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