Civil Engineering Support for Telemetered Traffic Monitoring Sites

Final Report

Project No. BD-543-12

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16. Abstract

This project was aimed at providing various civil engineering support services for the telemetered traffic monitoring sites operated by the Statistics Office of the Florida Department of Transportation. This was a companion project to the one that provided electrical engineering support services for the same sites. The results of two main tasks undertaken in this project are reported herein. The first main task was aimed at evaluating a traffic sensor used for measuring vehicle lengths. The second main task was aimed at researching dual-tire sensor by developing optimal segment length and developing classification algorithm that includes a dual-tire variable as one of the classification variables. The results of the studies provided the Statistics Office with performance evaluation of length-based vehicle sensor and the efficacy of dual-tire sensing and algorithm development.

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EXECUTIVE SUMMARY

Background

The Florida Department of Transportation (FDOT) monitors traffic operations on the state highway system using permanent and temporary count stations. The permanent count stations are divided into classification sites and weighing sites. All permanent count stations collect volume and speed data but the weigh-in-motion (WIM) sites additionally collects vehicle weights. FDOT continues to experience a number of challenges in operating the permanent sites, commonly known as telemetered traffic monitoring sites (TTMS), and in assuring the quality of data collected by these sites.

One of the challenges is the minimization of errors in the classification of vehicles. The vehicle attributes used in the FDOT classification algorithm are the number of axles and axle spacing with a few WIM sites using overall gross weight as a discriminating variable. The problem of misclassification is particularly pronounced in urban areas where tailgating vehicles are grouped with the preceding vehicle. Also, in both urban and rural settings, vehicles towing trailers are invariably thrown in a wrong category. FDOT has come to recognize that additional variables may be needed in the classification table. One of the variables suggested is the number of tires on an axle. A segmented, portable axle sensor-based system capable of distinguishing the number of tires a vehicle has was proposed and had to be evaluated in the field. The ability of the proposed sensor to recognize the tire footprint's length (as relative duration) will also allow for the detection of changing rate of speed through a two sensor array. The development of the system being proposed would provide FDOT a level of identification resolution and benchmarking for quality assurance.

In addition, the inclusion of overall vehicle length in the classification scheme has the potential of further reducing classification errors. The FDOT Transportation Statistics Office sponsored a project that evaluated intrusive and non-intrusive sensors capable of collecting individual vehicle lengths. The project was aimed at collecting vehicle length data throughout the state highway system and testing various algorithms and thresholds for classifying vehicles using length as the criterion. These efforts were continued in this project with the purpose of revising the algorithm, optimizing it, and validating the optimized thresholds in the field.

Objectives

This project had multiple objectives. The first objective was to develop prototype the tire foot print sensor to produce field testable, 8 ft. units and to create an interface circuit and new vehicle classification software program that can take advantage of the additional information provided by the segmented sensor. The second objective of this project was to continue field evaluation of sensors and algorithms related to length-based classification scheme. The third objective of this project is to continue providing support for FDOT Statistics Office in evaluating length-based sensors.

Findings and Conclusions

The results showed that the length-based sensor that was evaluated using short-term and long-term data comparison with loop sensors had a tendency of overestimating vehicle lengths by an average of approximately 12 percent resulting in overcounting single and multi-unit trucks. It should, however, be noted that the volumes and average speeds reported by the evaluated sensor were fairly close to those reported by ADR. The analysis of optimal segment length involved the determination of maximum actuations caused by singles and the minimum actuations caused by duals for different positions on the segments of different segment lengths. The results showed a length of less than 0.9 inch will cause clear discrimination between single and dual tires on a vehicle's axle. It is also possible to get segment lengths greater than 0.9 inch with clear or minimum error discrimination if shorter lengths are not technically viable.

Benefits

The results of this study were beneficial to the FDOT Statistics Office as it improved the understanding of length-based data collection using non-intrusive sensors. The performance review of the subject sensor reported herein and other sensors revealed strengths and weaknesses of side-fired sensors in classifying vehicles in three length bins. The results of this study also revealed the efficacy using a dual tire variable in further improving vehicle classification using Scheme F.

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PART ONE—EVALUATION OF WAVETRONIX TRAFFIC SENSOR

1.1 Scope of the Study

The study reported herein was conducted by the FAMU-FSU College of Engineering for the Florida Department of Transportation Statistics Office. This study was part of larger ongoing study aimed at determining the efficacy of non-intrusive traffic sensors in collecting length-based vehicle classification data. Currently, FDOT employs a combination of loop detectors and piezos in the collection of traffic data. However, the intrusive nature of loops and piezos poses installation and maintenance difficulties leading to the desire of the Statistics Office of the Florida Department of Transportation to explore other sensor systems to supplement the current loop-piezo combination sensors. The Wavetronix sensor, Model SS125 ITS Radar, manufactured by Wavetronix LLC was one of the sensors that were evaluated in this project. According to the manufacturer's data sheet, Model SS125 ITS Radar is capable of measuring traffic volume, individual vehicle speeds, average headway, lane occupancy as well as vehicle classification. The data sheet indicated that this sensor has a detection range of 250 feet and the ability to detect up to 10 lanes of traffic simultaneously.

1.2 Methodology of Evaluation

The Wavetronix Model SS125 ITS Radar traffic sensor unit was installed on May 2, 2007 on Crawfordville Highway (US 319) in Wakulla County, just south of the City of Tallahassee, Florida. The sensor was installed at exactly where the continuous telemetered traffic monitoring site (TTMS) is located. The site, numbered as TTMS # 590296, employs loop detectors and piezoelectric axle sensors to measure speed and determine axle spacing, number of axles, and overall vehicle lengths. The US 319 roadway at this location is a two-lane highway with one lane in each direction.

The methodology employed in evaluating the Wavetronix sensor was to compare its outputs of speed, volume, and vehicle lengths to those reported by the automatic data recorder (ADR) and to those reported by the video data and radar speed gun. Since video data were to be used as ground truth, vehicles lengths were extracted from frozen video images and the number of vehicles per period were counted from video. In collecting video data, the video camera was set plumb and level with its principal axis perpendicular to the road. The camera was positioned a known distance from two ranging poles spaced apart along a line parallel to the road. The distance between these ranging poles and that from the camera to the line formed by the poles was used to obtain the field of view of the video camera. To avoid taking incorrect measurements from distorted images, the vehicle images were frozen still so that the axis of the camera bisected the overall vehicle length. Vehicle types were visually extracted from images frozen by the software named Pinnacle Studio 8 by Pinnacle Systems, Inc. The video image analysis software used was Astroart 3.0 by MSB Software, Inc. The video image analysis software was used to extract the overall length—i.e., distance from the front bumper to the rear bumper—of the vehicle. To determine the vehicle length, the software requires two inputs: the perpendicular distance of a vehicle from the video camera and the field of view of the camera. The average distance from the camera to the target vehicle was set based on passing a vehicle of known length several times on the road in the camera visual zone.

The laser-guided radar speed gun was used to capture the speeds of individual vehicles, which was then used as ground truth in speed comparisons. Given that the extraction of video images was cumbersome and time consuming, the study was divided into two terms. The short term study involved comparing Wavetronix sensor outputs to those collected by ADR, video, and radar speed gun. The video data were collected for a period of 6 hours. The long term study involved comparing Wavetronix sensor data to those collected by the ADR only. The long term study covered a period of thirty days. The long term study compared only aggregated data on speed, length-based classification, and volume. The Wavetronix data were downloaded at the site whereas FDOT supplied the study team with ADR data.

1.3 Data Collection

Data for a short term study were collected over a period of three days from May 21, 2007 to May 23, 2007. On each day, data were collected during peak hours (7:00 am – 9:00 am, 1:00 pm – 3:00 pm, and 4:00 pm – 6:00 pm) continuously for two hours. The data collected were individual vehicle records from Wavetronix and ADR sensors, video images of traffic, and vehicle speeds using a laser-guided radar speed gun. Data were collected from both northbound lane and southbound lane.

For the long-term study, initially data from Wavetronix and ADR sensors were collected over a period of thirty days from May 3, 2007 to June 3, 2007. After a thorough examination of the Wavetronix data, it was discovered that the sensor was not capturing data over certain periods of the day due to insufficient solar power supply at the site. The problem was resolved by installing a second 85-watt solar panel and the 30-day long term data collection resumed on July 28, 2007 and ended on August 28, 2007.

1.4 Analysis of Results

The analysis of results is divided into short-term results and long-term results. As indicated earlier, the short term analysis was mainly on a microscopic level in which individual vehicle's length and speed were compared on one-to-one basis among the equipments whereas the long-term study was at a macroscopic level in which aggregated data on speed, volume, and length-based class were compared between Wavetronix sensor and ADR output. Since the video data captured the actual vehicle lengths, the data were used in the short term study to validate data collected by ADR's loops and piezos. Following the validation, the long term study used the results of ADR as a benchmark for comparison with the Wavetronix data.

Short-term study

The variables of interest in the comparative analysis were speed, length, and volume. The data obtained through video were used as ground truth in determining vehicle class and overall vehicle length. The video camera was set plumb and level with its principal axis perpendicular to the road, it was positioned a known distance from two ranging poles spaced apart along a line parallel to the road. The distance between these ranging poles and that from the camera to the line formed by the poles was used to obtain the field of view of the video camera. The calibration of the video camera was accomplished by passing a vehicle of known length in the field of view of the camera several times for the estimation of the distance between the vehicles and the camera. The overall vehicle length (bumper to bumper) was then extracted from the frozen images captured from the video. In comparing speeds, the data collected by radar speed detector were used as ground truth. Table 1.1 compares vehicular volumes as counted from video and as reported by both ADR and Wavetronix. The data were collected on May 21, 2007 for one hour from 2 p.m. to 3 p.m. The results in Table 1.1 shows that both Wavetronix and ADR sensors were very accurate in capturing volume data for the one-hour period analyzed.

Table 1.1: Volume Comparison

Vehicle Count			Percentage Error	
Video	ADR	Wavetronix	ADR	Wavetronix
464	465	464	0.2%	0.0%

Table 1.2 compares the individual speed data collected using the laser-guided speed equipment to those reported by ADR and Wavetronix. The data were collected on May 21, 2007 for one hour from 2 p.m. to 3 p.m. The results in Table 1.2 show that the speed data capture error rate was 4.1 percent for the ADR and 5.4% for the Wavetronix sensor. It is noteworthy that the speed limit on this roadway was 55 miles per hour. The graphical distribution of speeds is displayed in Appendix 1A.

Table 1.2: Speed Comparison

Average Speed (mph)			Percentage Error	
Lasergun	ADR	Wavetronix	ADR	Wavetronix
44.2	46	46.6	4.1	5.4

Table 1.3 compares individual vehicle lengths among data collected by video, ADR, and the Wavetronix sensor. The vehicle lengths data were extracted from video collected on May 21, 2007 for one hour from 2 p.m. to 3 p.m. The results in Table 1.3 show that the ADR on average underestimated vehicle lengths by 10.5 percent while the Wavetronix sensor tended to overestimate vehicle lengths by an average of 11.8 percent. The distribution of the collected vehicle lengths is shown in Appendix 1B.

Table 1.3: Length Comparison

ADR		Wavetronix	
Mean % Error	Σ	Mean % Error	Σ
-10.5%	0.83	+11.8%	0.73

Table 1.4 shows the comparison of vehicle lengths in three bins. As part of length-based vehicle classification project, the Florida Department of Transportation is currently experimenting with thresholds used to determine three length classes. The thresholds are:

Passenger Cars ≤ 0 ft. – 21.5 ft.
Single Unit Truck ≥ 21.5 ft. – 42.5 ft.
Multi-Unit Truck ≥ 42.5 ft.

Table 1.4: Length-Based Classification

	Video	ADR		Wavetronics	
Class	**Total**	**Total**	**%Error**	**Total**	**% Error**
Passenger Vehicles	432	442	+2.3	420	-2.7
Single Unit Trucks	29	20	-31.0	39	+34.4
Multi Unit Trucks	3	2	-33.3	5	+66.6
Unmatched Vehicles		1		0	

But because the Wavetronix SS125 ITS Radar sensor software does not accept decimal points in specifying the thresholds, the following thresholds were used in classifying vehicles by length as shown in Table 1.4.

Passenger Cars ≤ 0 ft. – 22 ft.
Single Unit Truck ≥ 23 ft. – 42 ft.
Multi-Unit Truck ≥ 43 ft.

The results in Table 1.4 show that both ADR and Wavetronix produced significant errors in vehicle classification, particularly because they are substantially underestimating and overestimating vehicle lengths, respectively.

Long-term study

The long term study involved comparing ADR data to those reported by the Wavetronix sensor for a period of 30 days. The comparative analysis discussed below is based on the total volume comparison, average vehicle speeds comparison, and how both ADR and Wavetronix sensor classified vehicles by length into three bins comprising of passenger cars, single-unit trucks, and multi-unit trucks. The volume, speed, and vehicle classification data were aggregated hourly and daily during the 30-day period.

The 30-day daily and hourly volume results are shown in Appendix 1C. The figures are stratified by direction of movement, i.e., northbound and southbound. The data displayed in Appendix 1C reveals that the Wavetronix volume counts on daily basis were within ±1 percent of ADR volume counts in the northbound direction and within ±1.5 percent in the southbound direction.

The 30-day average speed data are shown in Appendix 1D. The results show that the daily average speeds reported by Wavetronix were in the range of 4 to 7 percent above those reported by ADR in the northbound direction and from 2 to 9 percent above ADR in the southbound direction.

The 30-day classification results are shown in Table 1.5. The results show that the Wavetronix sensor grossly overestimated single-unit and multi-unit trucks. This could be due to Wavetronix overestimating vehicle lengths and ADR underestimating vehicle lengths. As indicated earlier in Table 1.3, Wavetronix was overestimating vehicle lengths by an average of 11.8 percent whereas the ADR underestimated vehicle lengths by an average of 10.5 percent.

Table 1.5: Long Term Length-Based Classification

	Southbound			**Northbound**		
Vehicle Class	**ADR**	**Wavetronix**	**%Error**	**ADR**	**Wavetronix**	**% Error**
Passenger cars	232,930	199,257	-14.5	241,587	226,136	-6.4
Single Unit Trucks	7,037	39,428	+460.3	7,175	21,189	+195.3
Multi-Unit Trucks	3,025	4,630	+53.1	2,725	3,844	+41.1
Total	242,992	243,315		251,487	251,169	

1.5 Conclusions

This study was aimed at evaluating the efficacy of the Wavetronix Model SS125 ITS Radar sensor in collecting length-based vehicle classification data. The ground truth length data used in the study were extracted from video images while the ground truth speed data were collected manually using a handheld laser-guided radar speed gun. The Wavetronix sensor was installed at a permanent telemetered traffic monitoring sites so that the loop and piezo data collected by the ADR at the site can also be compared to the Wavetronix and ground truth data. The results showed that the Wavetronix sensor had a tendency of overestimating vehicle lengths by an average of approximately 12 percent resulting in overcounting single and multi-unit trucks. It should be noted, however, that the volumes and average speeds reported by the Wavetronix sensor were fairly close to those reported by ADR.

PART TWO—REPORT ON TIRE PRINT MEASUREMENTS AND OPTIMAL SEGMENT LENGTH

2.1 Scope of the Study

Minimization of errors in classification of vehicles is a challenge facing many highway agencies as they try to improve their HPMS programs. The vehicle attributes commonly used in classification algorithms are the number of axles and axle spacing with a few WIM sites using overall gross weight as an additional discriminating variable. The problem of misclassification is particularly pronounced in urban areas where tailgating vehicles are grouped with the preceding vehicle. Also, in both urban and rural settings, vehicles towing trailers are invariably thrown in a wrong category. FDOT has come to recognize that additional variables may be needed in the classification table. One of the variables suggested is the number of tires on an axle. This study was supposed to evaluate in the field a proposed segmented, portable axle sensor-based system capable of distinguishing the number of tires a vehicle has. The ability to recognize the tire footprint's length (as relative duration) will also allow for the detection of changing rate of speed through a two sensor array. The development of the system being proposed would provide FDOT a level of identification resolution and benchmarking for quality assurance. This research study was aimed at determining the population characteristics of tire print widths in order to build optimum axle sensor segment that will be able to determine the profile of the majority of dual tires on the road.

2.2 Methodology

Following consultation with the FDOT Project Manager and the subcontractor, it was decided that tire print data should be collected directly in the field. The plan was to capture as many tires from different vehicle classes as possible. Since the current FDOT classification table has difficulty in distinguishing motor homes pulling trailer from Class 8 vehicles, special efforts were to be made to capture these types of vehicles. Data were collected at two truck stops and at Emerald Coast RV Center in Midway, Florida. The variables recorded were the tire type, width, the gap between the tires, and the total width of the two wheels.

2.3 Analysis of Results

All the tire print data that were collected are shown in Appendix 2. The analysis of tire print results involved determining the descriptive statistics including the minimum, average, and maximum values of variables recorded. Confidence intervals were also determined using the following formula:

$$\overline{X} - t_{\alpha/2,n-1} S/\sqrt{n} \le \mu \le \overline{X} + t_{\alpha/2,n-1} S/\sqrt{n}$$

where μ is the population mean, $\overline{X}$ is the sample mean, S is the standard deviation, n is the sample size, t represents the t distribution, and α is the significance level. Three confidence levels were chosen, i.e., 90%, 95%, and 99%. The results discussed below are stratified by vehicle class type and all vehicles.

Table 2.1: Vehicle Class 3

	Tire Width	Gap	Total Width
No. of Observations	6	6	6
Minimum	6 1/8	2 7/8	16 1/8
Average	6 6/8	3 4/8	17 1/8
Maximum	7 7/8	3 7/8	18 6/8
90% Confidence Interval	6 2/8 to 7 2/8	3 2/8 to 3 7/8	16 2/8 to 18 0/8
95% Confidence Interval	6 0/8 to 7 4/8	3 1/8 to 3 7/8	16 0/8 to 18 2/8
99% Confidence Interval	5 5/8 to 7 7/8	3 0/8 to 4 1/8	15 2/8 to 19 0/8

Table 2.2: Vehicle Class 4

	Tire Width	Gap	Total Width
No. of Observations	29	29	29
Minimum	7 0/8	3 1/8	17 2/8
Average	8 3/8	4 2/8	20 7/8
Maximum	9 2/8	5 2/8	23 1/8
90% Confidence Interval	8 1/8 to 8 4/8	4 0/8 to 4 4/8	20 2/8 to 21 4/8
95% Confidence Interval	8 0/8 to 8 5/8	4 0/8 to 4 4/8	20 1/8 to 21 5/8
99% Confidence Interval	7 7/8 to 8 6/8	3 7/8 to 4 5/8	19 7/8 to 21 7/8

Table 2.3: Vehicle Class 5 (Mainly RVs)

	Tire Width	Gap	Total Width
No. of Observations	50	43	43
Minimum	5 4/8	2 4/8	15 0/8
Average	7 5/8	4 2/8	19 2/8
Maximum	9 1/8	5 6/8	22 4/8
90% Confidence Interval	7 3/8 to 7 6/8	4 0/8 to 4 3/8	18 5/8 to 19 6/8
95% Confidence Interval	7 3/8 to 7 7/8	3 7/8 to 4 4/8	18 4/8 to 19 7/8
99% Confidence Interval	7 2/8 to 7 7/8	3 7/8 to 4 4/8	18 2/8 to 20 1/8

Table 2.4: Vehicle Class 8

	Tire Width	Gap	Total Width
No. of Observations	9	8	8
Minimum	6 4/8	4 4/8	21 1/8
Average	7 7/8	5 0/8	21 4/8
Maximum	8 5/8	5 2/8	22 0/8
90% Confidence Interval	7 4/8 to 8 3/8	4 7/8 to 5 2/8	21 3/8 to 21 6/8
95% Confidence Interval	7 3/8 to 8 4/8	4 6/8 to 5 2/8	21 2/8 to 21 6/8
99% Confidence Interval	7 2/8 to 8 5/8	4 5/8 to 5 3/8	21 1/8 to 21 7/8

Table 2.5: Vehicle Class 9

	Tire Width	Gap	Total Width
No. of Observations	73	57	51
Minimum	6 7/8	3 6/8	18 1/8
Average	8 3/8	4 7/8	21 4/8
Maximum	9 4/8	6 0/8	22 4/8
90% Confidence Interval	8 3/8 to 8 4/8	4 6/8 to 4 7/8	21 2/8 to 21 5/8
95% Confidence Interval	8 3/8 to 8 4/8	4 5/8 to 5 0/8	21 2/8 to 21 6/8
99% Confidence Interval	8 2/8 to 8 5/8	4 5/8 to 5 0/8	21 1/8 to 21 6/8

Table 2.6: Vehicle Class 10

	Tire Width	Gap	Total Width
No. of Observations	7	5	5
Minimum	6 6/8	4 5/8	18 7/8
Average	9 2/8	5 0/8	21 0/8
Maximum	12 6/8	5 3/8	22 3/8
90% Confidence Interval	7 4/8 to 11 0/8	4 6/8 to 5 3/8	19 7/8 to 22 1/8
95% Confidence Interval	7 0/8 to 11 4/8	4 5/8 to 5 3/8	19 5/8 to 22 3/8
99% Confidence Interval	5 7/8 to 12 5/8	4 4/8 to 5 5/8	18 7/8 to 23 1/8

Table 2.7: Vehicle Class 11

	Tire Width	Gap	Total Width
No. of Observations	4	4	4
Minimum	7 5/8	4 4/8	21 2/8
Average	8 1/8	5 0/8	21 5/8
Maximum	8 4/8	5 3/8	22 0/8
90% Confidence Interval	7 6/8 to 8 5/8	4 4/8 to 5 4/8	21 2/8 to 22 0/8
95% Confidence Interval	7 5/8 to 8 6/8	4 2/8 to 5 5/8	21 1/8 to 22 2/8
99% Confidence Interval	7 0/8 to 9 2/8	3 6/8 to 6 1/8	20 5/8 to 22 5/8

Table 2.8: All Vehicles

	Tire Width	Gap	Total Width
No. of Observations	177	152	146
Minimum	5 4/8	2 4/8	15 0/8
Average	8 1/8	4 4/8	20 4/8
Maximum	12 6/8	6 0/8	23 1/8
90% Confidence Interval	8 0/8 to 8 2/8	4 3/8 to 4 5/8	20 2/8 to 20 6/8
95% Confidence Interval	8 0/8 to 8 2/8	4 3/8 to 4 5/8	20 1/8 to 20 6/8
99% Confidence Interval	8 0/8 to 8 3/8	4 3/8 to 4 5/8	20 1/8 to 21 0/8

2.4 Dimensioning

The determination of an optimal dimension of a single individual segment of the sensor for discriminating between single and dual tires requires the consideration of either the number of actuated segments under the two types of tires or the detection of a gap between singles of a dual set. The number of actuated segments under any category of tires depends on the position of the sensor the tire stamps. For a certain position a single tire may actuate number of segments equal to those actuated by a dual tire on another position making identification of the dual tires difficult. Discrimination between a single and dual tire is simple if the maximum number of actuations caused by the single tire is less than the minimum number of actuations caused by the dual tire.

The determination of optimum segment length was done through building a model that calculates the number of actuated segments for the two types of tires on different positions of one segment whose dimension was varied from 0.5 inch to 4 inches at an increment 0.05 inch. For each length of a sensor the model calculates the maximum number of actuations made by a single tire and compares with minimum the actuations caused by a dual tire. The model was run on the inferential statistics of tires of vehicle classes 3 to 11 and the following points were noted:

- the number of segments actuated by a tire decreases with increase in segment length,
- the discriminability decreases with increase in segment length,
- there is poor discrimination between a single and dual tire if the segment is long enough to bridge the gap between singles of a dual set, and
- Figure 2.1 suggests any segment length except 2.25 , 2.85 and >3.60 in. (where red and green lines intersect or the blue line touches the horizontal axis).

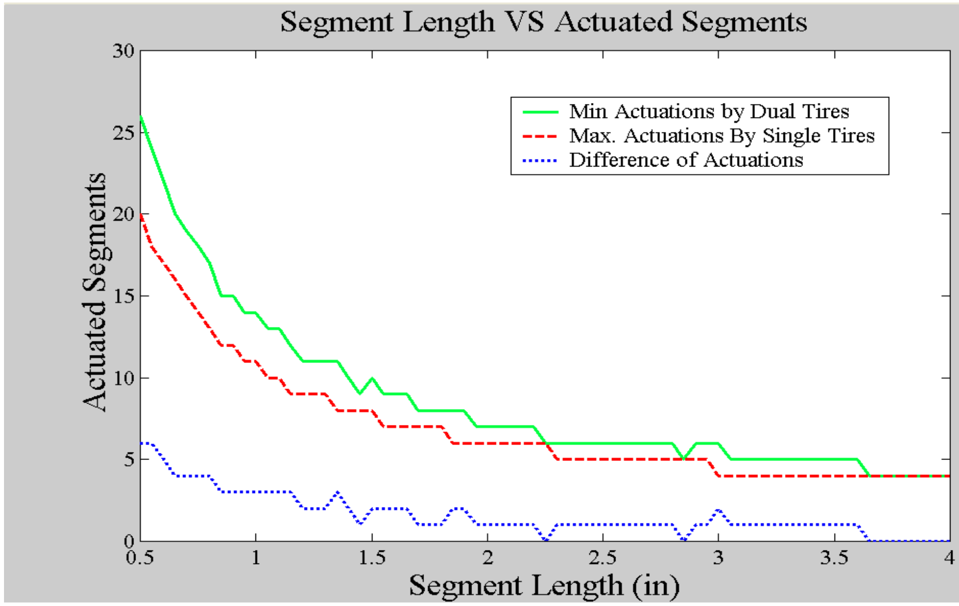


Figure 2.1: Optimal lengths of a segment based on inferential statistics of raw data

Since the inferential statistics form just a few data points as compared to the raw data, it was worth running the model on the whole raw dataset as a means of counterchecking the results obtained by the use of inferential statistics in determining the optimal segment length. The result showed a length of less than 0.9 inch can result in 100% discrimination between single and dual tires. However, there are intermittent feasible regions in the range 0.9-2.40 inches in case a length less than 0.9 inch won’t be technically viable (Figure 2.2).

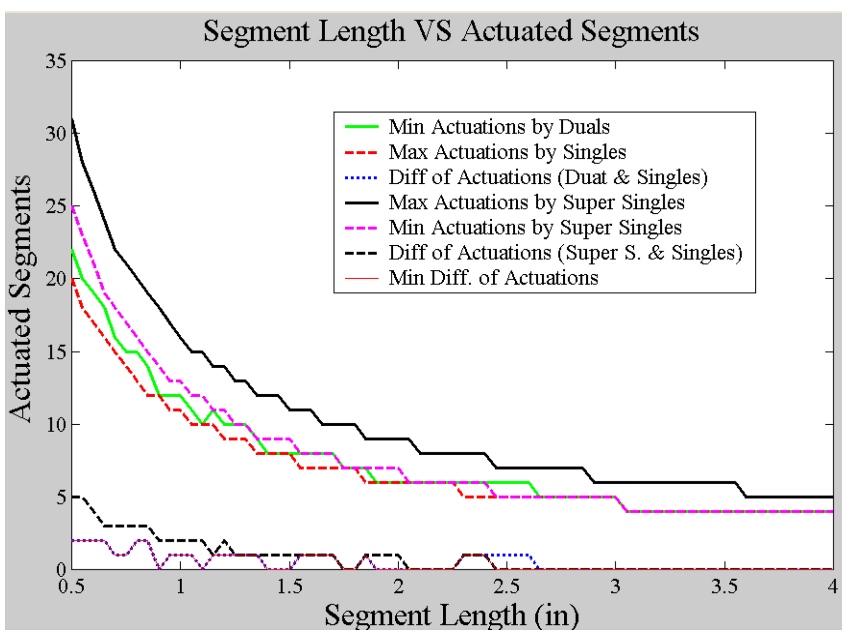


Figure 2.2: Optimal lengths of a segment based on raw data

It was worth determining the types of tire configurations for which the number of actuations by singles and duals was equal and hence misclassification duals. The analysis showed for a segment less than 3 inches there were 7 misclassified dual tires that had total width between 15 inches and 16 inches inclusive and they belonged to Class 5 of Scheme F. For the segment lengths greater than 3 inches the misclassified points formed four clusters belonging to class 3 and 5 as shown in the Figure 2.3 below. Figure 2.3 shows feasible lengths and their respective actuations thresholds for which discrimination on the representative sample is 100% accurate.

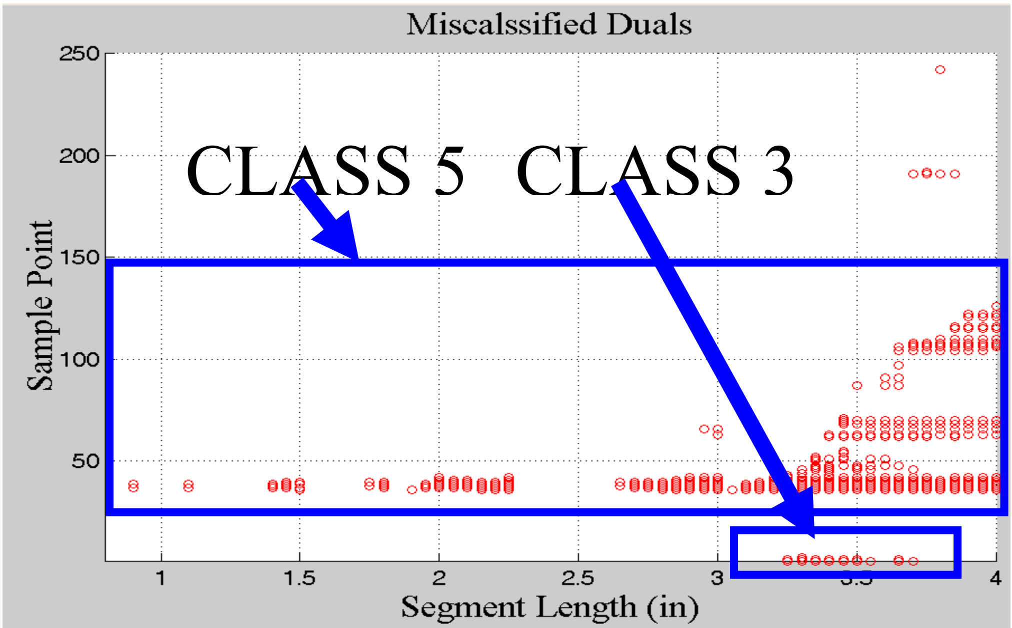


Figure 2.3: Misclassified dual tire samples for specific segment lengths

2.5 Conclusions and Recommendations

The determination of the optimal segment dimension for the segmented dual tire sensor required collection of truck tire tread widths with different conditions ranging from new to worn out tires. The data were collected from different truck stops and recreation vehicle parks. The analysis of optimal segment length involved the determination of maximum actuations caused by singles and the minimum actuations caused by duals for different positions on the segments of different segment lengths. The results showed a length of less than 0.9 inch will cause clear discrimination between singles and duals. It is also possible to get segment lengths greater than 0.9 inch with clear or minimum error discrimination if shorter lengths are not technically viable.

PART THREE—THE VEHICLE GRADATION ALGORITHM USING DUAL TIRE VARIABLE FOR VEHICLE CLASSIFICATION

3.1 Introduction

Vehicle classification is the grouping together of vehicles with similar predefined physical or operational characteristics. The vehicle classification data are required for different transportation analyses. The accuracy of the classification data depends on the accuracy of the algorithm used to collect the data which in turn depends on the type and accuracy of equipments used to collect the variables. The current equipment used to collect vehicle class data are inductive loops and piezoelectric sensors.

Currently, the Florida Department of Transportation collects vehicle classification data from its highway system using Scheme F. The scheme has been in use by transportation agencies since 1985. The scheme classifies vehicles into non-commercial and commercial vehicles; the commercial vehicles are further classified according to the number of units and the number of axles. The vehicles defined by the Scheme F are automatically collected from the highways using the number of axles and axle spacings. The problem with these features is that the equipments fail to differentiate between different vehicle types with equal number of axles and axle spacings**.**

The addition of the number of tires per axle increases the level of understanding vehicle features. Where the number of axles and axle spacings explain a vehicle in the dimension along the direction of travel, the number of tires per axle tries to explain the dimension of the vehicle perpendicular to the direction of travel: vehicle width. The combination of these vehicular features explains the two dimensions of a vehicle: length and width. This is advancement in the modeling of manual vehicle classification. Future addition of vehicle profile will even advance more this modeling by gathering the features extracted when performing manual classification. With the maturity of axle sensing technologies to a resolution of reporting number of tires per axle, classification errors can be reduced to an acceptable level.

This report describes the development of a new algorithm -Vehicle Gradation Algorithm, VGA- for automatic classification of vehicles as defined by the Scheme F shown in Table 3.1. The algorithm adds in the dual tire variable to the two variables used by the current algorithm. The algorithm assumes a truck class to have a relationship with the number and position of axles having dual tires. The algorithm identifies reasonably well the vehicles operating on the Florida highway system. The algorithm has high accuracy in separating passenger vehicles and reducing the number of unidentified vehicles.

Table 3.1: Scheme F Vehicle Classification

Class	Description of Class
1	**Motorcycles:** All two or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles. This vehicle type may be reported at the option of the state.
2	**Passenger Cars:** All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers.
3	**Other Two-axle, Four-tire Single unit vehicles:** All two-axle, four-tire, vehicles other than passenger cars. Included in this classification are pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single unit vehicles pulling recreational or other light trailers are included in this classification.
4	**Buses:** All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses (including school buses) functioning as passenger-carrying vehicles. Modified buses should be considered to be trucks and be appropriately classified.
5	**Two-Axle, Six-Tire, Single Unit Trucks:** All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., having two axles and dual rear wheels.
6	**Three-axle Single unit Trucks:** All vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., having three axles.
7	**Four or More Axle Single Unit Trucks:** All trucks on a single frame with four or more axles.
8	**Four or Less Axle Single Trailer Trucks:** All vehicles with four or less axles consisting of two units, one of which is a tractor or straight truck power unit.
9	**Five-Axle Single Trailer Trucks:** All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
10	**Six or More Axle Single Trailer Trucks:** All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
11	**Five or Less Axle Multi-Trailer Trucks:** All vehicles with five or less axles consisting of three or more units, one of which is a tractor or straight truck power unit.
12	**Six-Axle Multi-Trailer Trucks:** All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
13	**Seven or More Axle Multi-Trailer Trucks:** All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit.

3.2 Limitations of Current Algorithm

The current algorithm classifies vehicles based on the patterns exhibited by the combination of number of axles and separations between axles. The algorithm picks these features - the number of axles and axle spacings - and matches them with a classified series of a set of ranges of axle spacings in the look up table. A class is assigned to a set of axle spacings after they get a positive match with those in the lookup table or assigned into the misidentified bin. The algorithms major problem is its inability to differentiate vehicles types that have equal number of axles and separation between these axles. Specifically, the vehicles of Class 3 are misclassified as truck Class 5, 8 or 9 and single unit trucks – Class 5, Class 6, and Class 7 - towing light trailers are wrongly classified as semi-trailers. This limitation may be caused by limited number of variables used for automatic classification vehicles which in turn depend on the available current traffic sensing technology. Both the current algorithm and the equipments produce truck classification error that may be intolerable to some data users. Increasing the number of variables for classification requires an equipment that can extract the additional variable from vehicles and rebuilding classification algorithm to accommodate the additional variable.

This research deals with the building of vehicle classification algorithm that is capable of identifying almost all vehicles after the addition of the new variable. The added variable is the number of tires per axle. The number of tires per axle can be collected by equipments that can detect number of tires on an axle and actually count the number of axles having dual and wide tires. The overall vehicle weight or individual axle weight were not considered as additional variables because of the costs and inconveniences to install the weigh-in-motion systems on more than 15,000 temporary data collection sites. Furthermore, the vehicle weight of any vehicle is variable depending on whether it is loaded or not. Avoiding the use of vehicle weight avoids the error of misclassifying empty light trucks.

3.3 Relationship Between Tire Configuration and Truck Class

Observation of vehicles operating on the Florida highway system showed that high class trucks of Class 8 to Class 13 generally have axles with dual or wide tires except the steering axle and sometimes one axle of their tridem axle groups. The buses and single-unit trucks -- Class 5 to Class 7 -- generally have axles with dual tires on their driving axles and occasionally on axles of their light trailers. The general trend observed was that the number of dual-tired axles increases with increase in truck class. The following points were noted and used in the building of VGA:

- the majority of vehicles of classes 2 and 3 have single tires on all axles,
- one of axles on the tandem axle of 3 axle-buses or motor homes has single tires,
- the majority of light trailers have their axles with single tires,
- some tridem axles have one axle with a single tire,
- all the tires on mobilehome trailers are singles, and
- the truck super single tires are wider than the tires of passenger vehicles.

3.4 The New Algorithm, VGA

The number of axles and axle spacings in the current table are extracted along a vehicle in the direction of travel. After the data on total axles, location of each axle and the number of tires on each axle are collected, they are fed into the algorithm for determining the class of a vehicle. The rule governing the algorithm is that the class of a vehicle increases as the number of axles with dual tire does. Each vehicle class has its own axle and tire configuration.

The VGA algorithm first removes passenger vehicles (Class 1 to Class 3) by checking that they don't have dual tires on any of their axles. These vehicles are classified using only their first axle spacings regardless of the total number of axles and units they have. All vehicles with at least one axle with dual tires are considered as trucks. All trucks with the same number of total axles are then directed into the same channel where they can be discriminated by the major criterion: the number and position of axles with dual tires. All the trucks with equal number of axles having dual tires are further discriminated according to the location (the i^{th} position from the front) of the axles having dual tires and part of a set of axle spacings. The axle spacings only differentiate vehicles that have equal number of axles with dual tires at the same position.

Though full axle spacing information is extracted from a vehicle, only part of it is used to perform classification. The use of partial axle spacing information is possible since a lot of discrimination task is first done by the number of axles and axles with dual tires. One of the advantages of the algorithm is that only the unidentified vehicles are expected to be trucks. A passenger vehicle having axle configuration equal to those of trucks are no more classified as trucks and vice versa. Figure 3.1 shows the central decision logic of the algorithm. In this figure, DT stands for dual tires and C for class. Other sub-decision trees for vehicles having different number of axles are shown in figures in Appendix 3. The vehicles sketched in red are scarce in the state. This decision tree was tested on 1,770 samples from TTMS 304, Westbound outside lane. The results showed that 100% accuracy was achieved in separation of trucks from non-trucks. The overall misclassification of trucks was reduced from 23% to 2.0%. The 2% error was caused by 2-axle Class 4 vehicles being mixed with Class 5 vehicles. Further work that is required includes building two more decision trees, analyze axle spacing followed by the dual-tire question, analyzing dual-tires followed by axle spacings question, and analyzing the influence of super single tires on the overall classification performance.

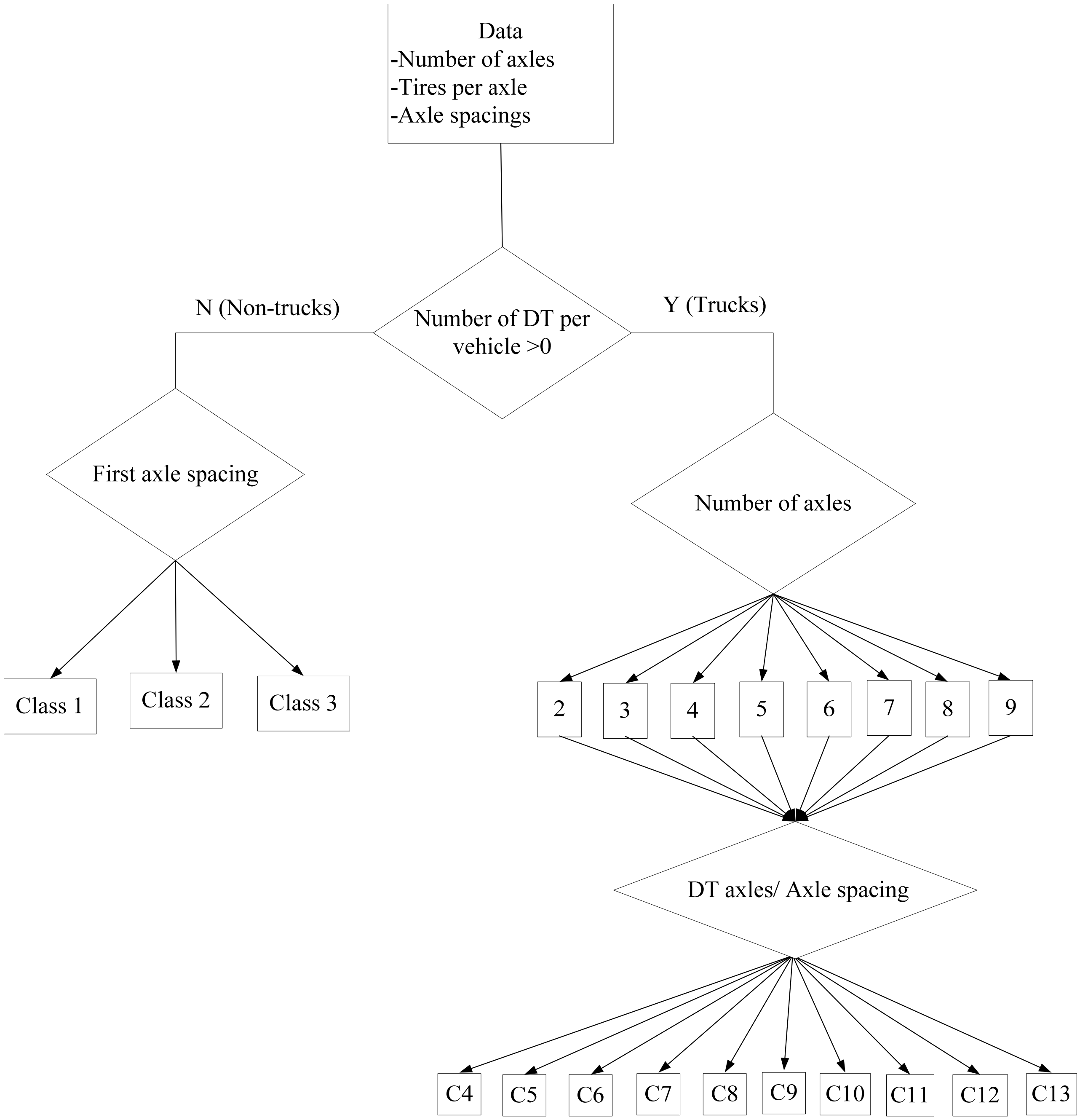
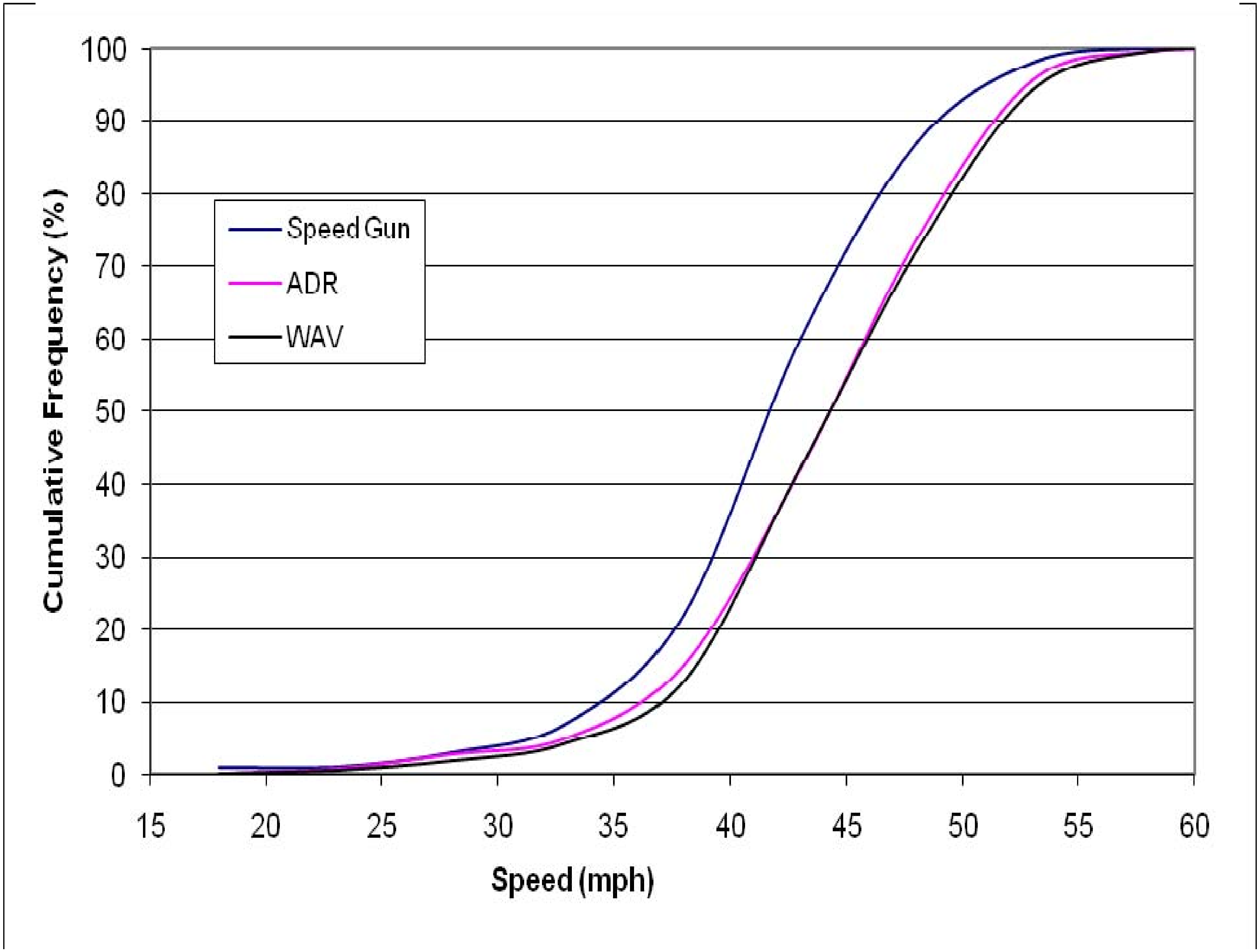


Figure 3.1: Algorithm Central Decision Logic

APPENDIX 1A. SHORT TERM SPEED DISTRIBUTION

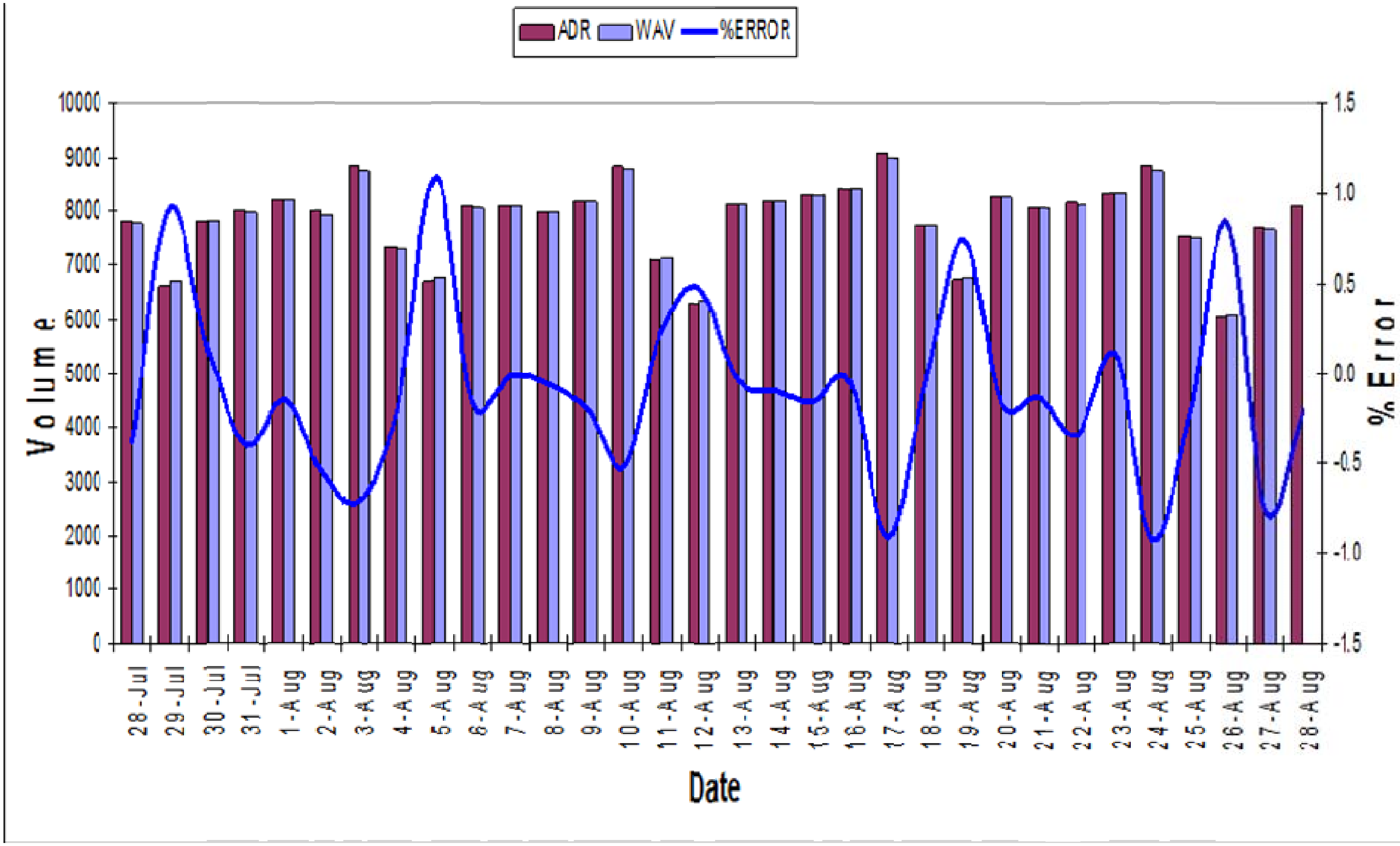


APPENDIX 1B. SHORT TERM LENGTH COMPARISON (Truncated)

Time span	ADR (length- Ft)	WAV Length(ft)	Video Lengths(ft)	Error (ADR)	Error (WAV)	%Error (ADR)	%Error (WAV)
14:12:01	0	9	7	-7.00	2	-100.0	28.6
	1	10	7.51	-6.83	2.49	-90.9	33.2
	1	13	12.15	-11.08	0.85	-91.2	7.0
	5	13	12.5	-7.24	0.5	-57.9	4.0
	9	14	12.6	-3.21	1.4	-25.5	11.1
	10	14	12.6	-2.89	1.4	-22.9	11.1
	11	14	12.6	-2.08	1.4	-16.5	11.1
	11	14	12.95	-2.14	1.05	-16.5	8.1
	11	14	12.95	-2.11	1.05	-16.3	8.1
	11	14	13.01	-2.16	0.99	-16.6	7.6
	11	14	13.05	-2.13	0.95	-16.3	7.3
	11	14	13.06	-1.94	0.94	-14.9	7.2
	11	14	13.1	-1.90	0.9	-14.5	6.9
	11	14	13.1	-1.85	0.9	-14.1	6.9
	11	15	13.15	-1.90	1.85	-14.4	14.1
	11	15	13.16	-1.83	1.84	-13.9	14.0
	12	15	13.2	-1.69	1.8	-12.8	13.6
	12	15	13.21	-1.69	1.79	-12.8	13.6
	12	15	13.25	-1.71	1.75	-12.9	13.2
	12	15	13.3	-1.76	1.7	-13.2	12.8
	12	15	13.3	-1.74	1.7	-13.1	12.8
	12	15	13.3	-1.71	1.7	-12.9	12.8
	12	15	13.4	-1.81	1.6	-13.5	11.9
	12	15	13.41	-1.78	1.59	-13.3	11.9
	12	15	13.46	-1.81	1.54	-13.4	11.4
	12	15	13.5	-1.79	1.5	-13.3	11.1
	12	15	13.5	-1.79	1.5	-13.3	11.1
	12	15	13.55	-1.78	1.45	-13.1	10.7
	12	15	13.55	-1.69	1.45	-12.5	10.7
	12	15	13.56	-1.70	1.44	-12.5	10.6
	12	15	13.6	-1.74	1.4	-12.8	10.3

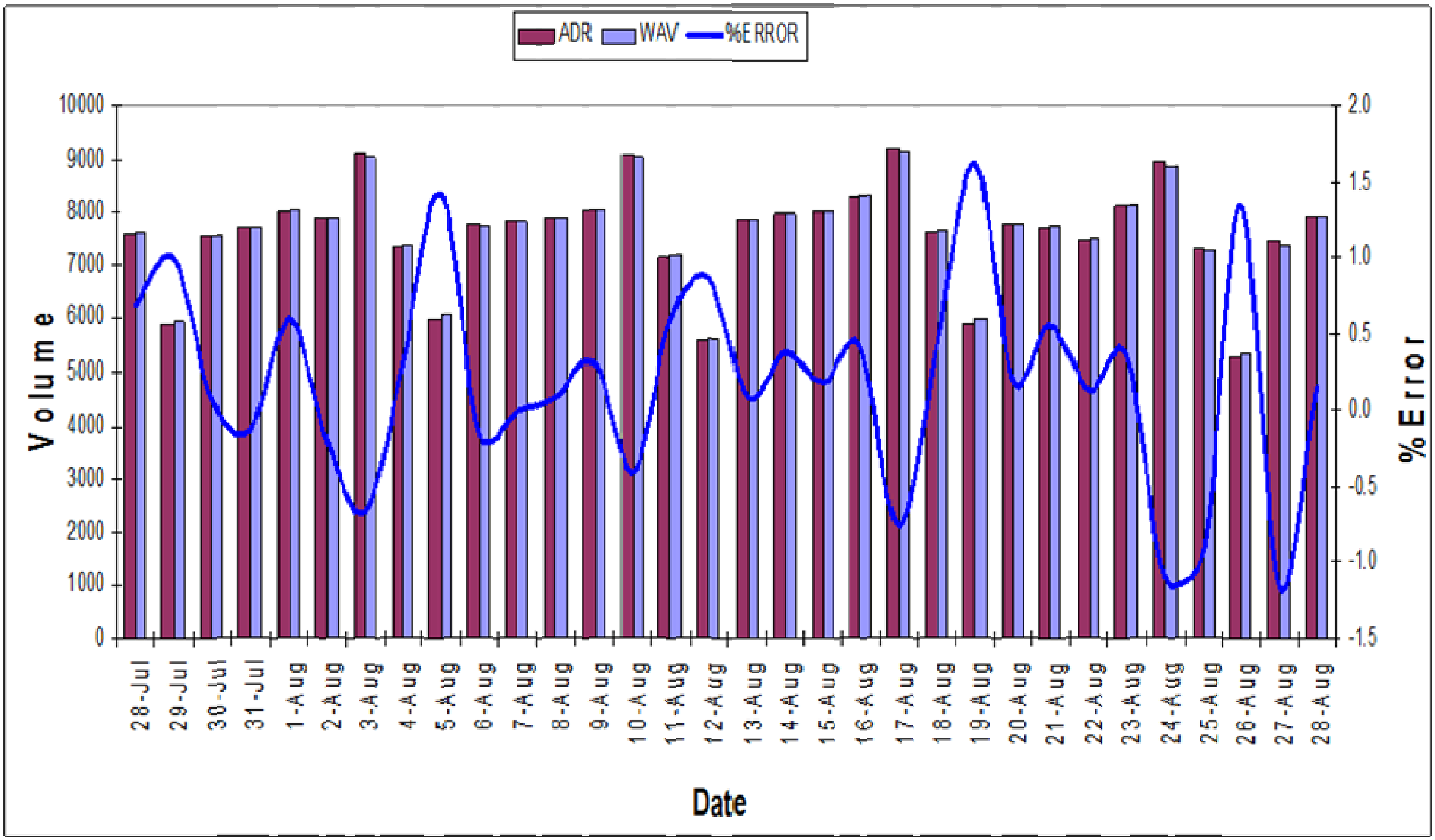
APPENDIX 1C. 30-DAY VOLUME DISTRIBUTION

Daily Traffic Volume – NB

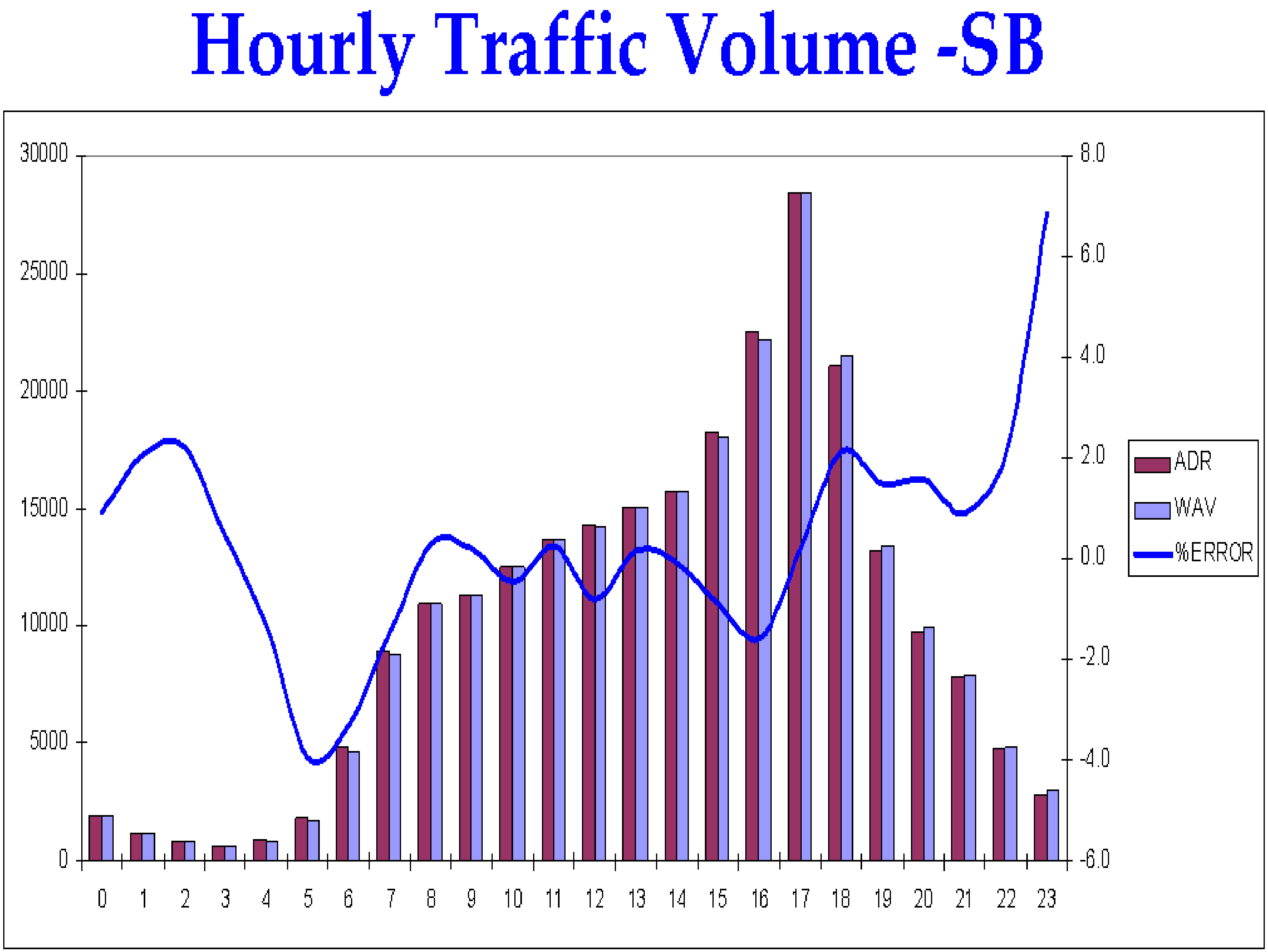


APPENDIX 1C. (Cont'd)

Daily Traffic Volume – SB

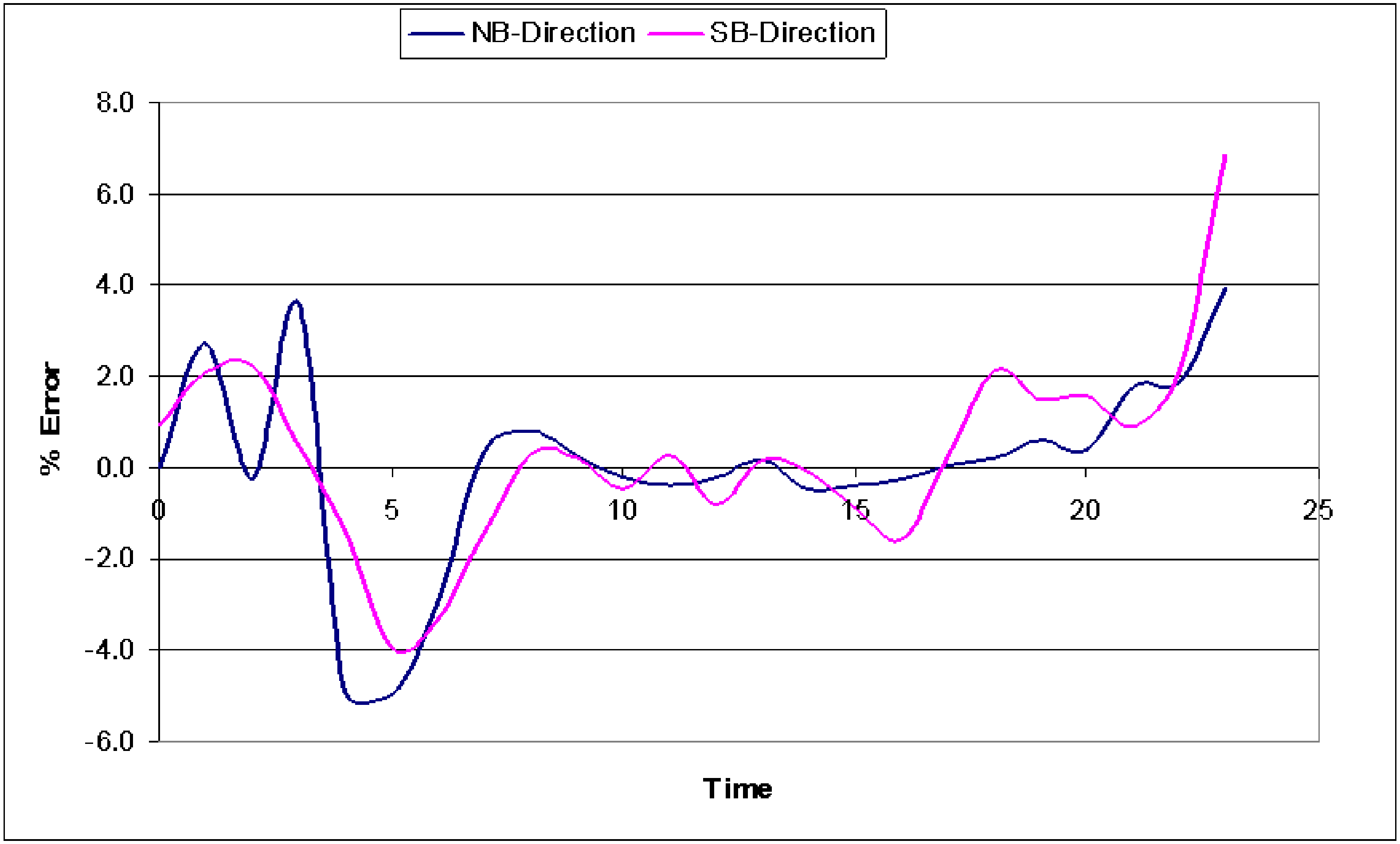


APPENDIX 1C. (Cont'd)



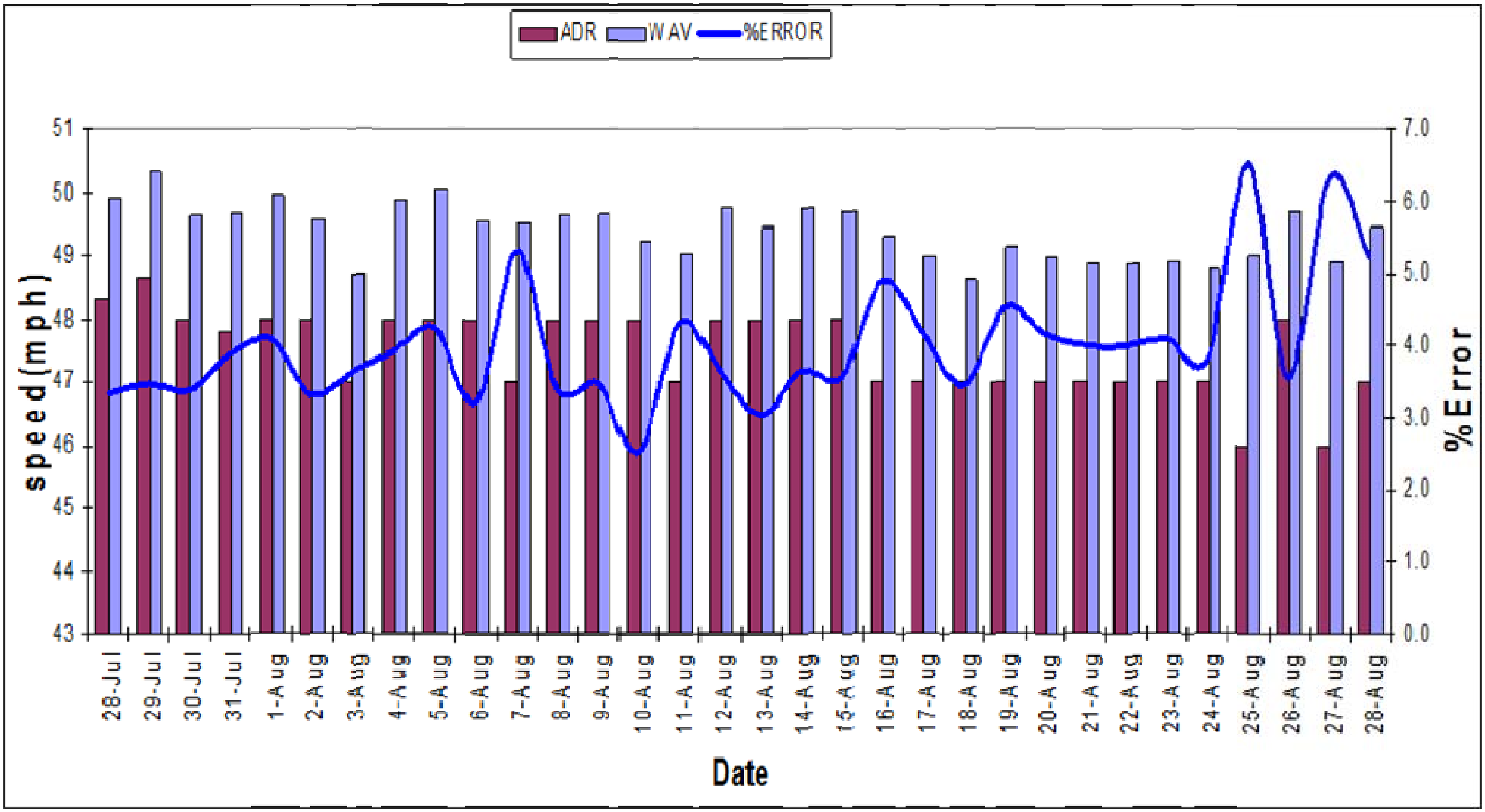
APPENDIX 1C. (Cont'd)

Hourly Volume Percentage Error Wavetronix Vs ADR

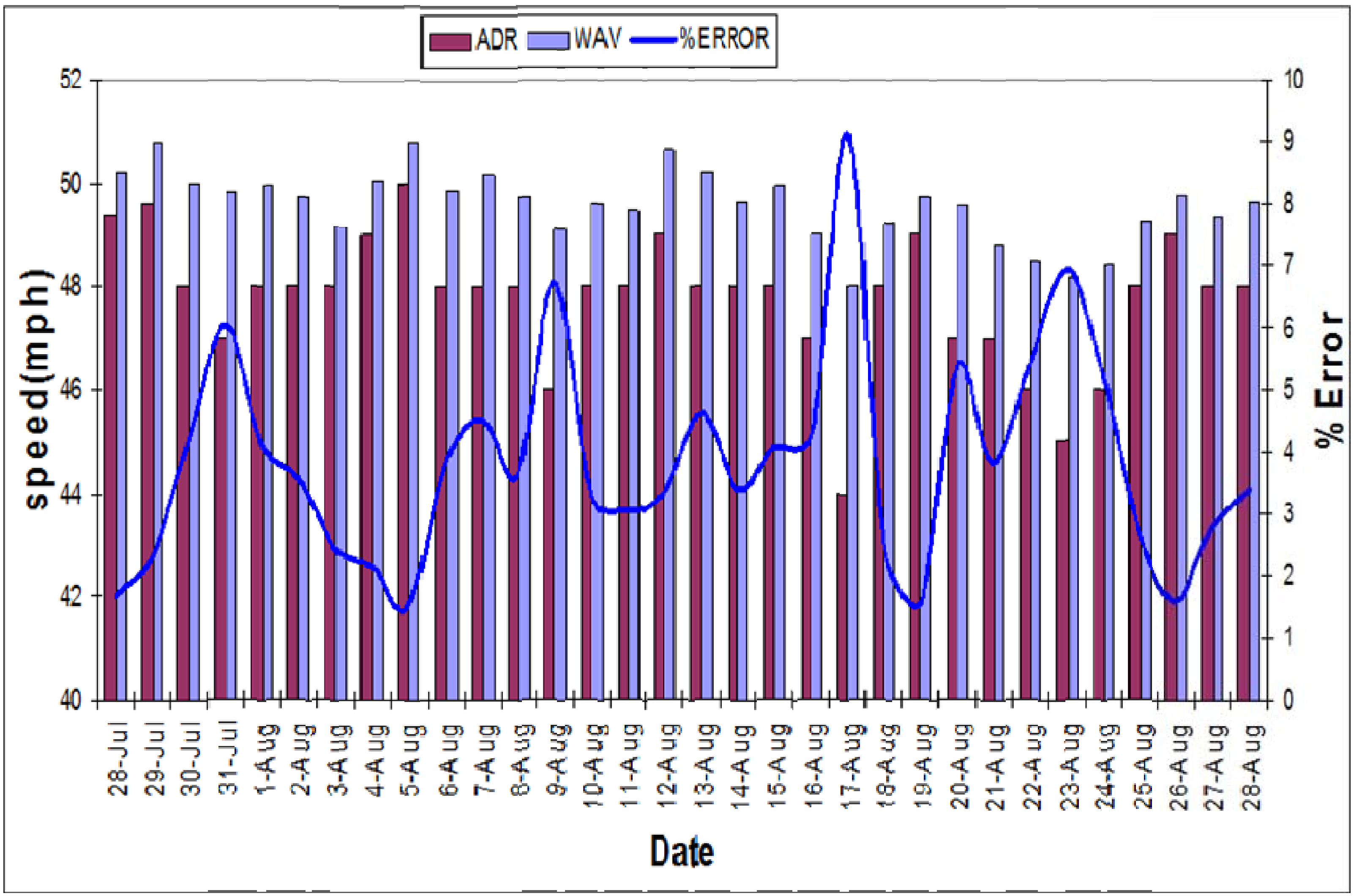


APPENDIX 1D. 30-DAY AVERAGE SPEED DISTRIBUTION

Daily Average Speed – NB



Daily Average Speed – SB



APPENDIX 2. VEHICLE TIRE WIDTH RAW DATA

No.	Class	Tire Make	Brand	Size	Axle	Width	Gap	Total
1	9	Bridgestone	R227	295/75R22.5	R	8 1/2	4 7/8	21 5/8
2	9	Bridgestone	M726	295/75R22.5	R	8 1/2	5	22
3	5	Bridgestone	R250	11/R22.5	F	8 3/8		
4	5	Bridgestone	MIX711	11/R22.5	R	8 1/4	4 3/4	21 3/8
5	9	Toyo	M147	11/R24.5	F	8 1/2		
6	9	Dunlop	SP431	11/R24.5	R	8 1/4	5 1/4	21 3/4
7	9	Firestone	FT455	11/R22.5	R	7 5/8	5 3/4	
8	5[R]	Dynatrac	Highway plus	9.00R20	F	7 3/8		
9	5[5]	Steelmark		9.00R20	R	7 5/8	4 1/4	20
10	10	Bridgestone	M844	425/65R22.5	F	12 3/4		
11	10	Michelin	XZE	11/R22.5	R	8 3/4	4 5/8	22 3/8
12	9	Aurora		285/75R24.5	R	8 5/8	4 3/4	
13	9	Bridgestone		R185/75R22.5	R	8 3/4	4 3/4	
14	9	Michelin	XZA2	275/80/R22.5	R	9 1/4	4 3/4	
15	9	Goodyear	G314	295/7522.5	F	8 3/4		
16	9	Goodyear	G395	295/275R22.5	F	8 3/8		
17	9	Goodyear	G372	295/275R22.5	R	8 3/4	4 1/2	
18	9	Bridgestone	R299	295/275R22.5	R	8 1/4	5 1/8	
19	5	Goodyear	G357	11R22.5	F	8 1/8		
20	5	Goodyear	G362	11R22.5	R	8	5 3/8	21 1/8
21	9	Hankook	ALO1	11R24.5	R	8 5/8	4 3/4	22
22	9	Steelmark	AHD II	11R24.5	R	8 1/8	5 1/8	21 1/2
23	9	Triangle	TR 686	11R24.5	R	8 1/2	4 5/8	21 3/4
24	9	Michelin	XZA2	11R22.5	F	9 3/8		
25	9	Michelin	XDA-HT	11R22.5	R	8 3/4	4 1/2	22
26	9	BFGoodrich	TR 134	275/80R22.5	R	7 5/8	5 5/8	21
27	9	Dunlop	SP 160	11R22.5	R	7 1/4	6	20 5/8
28	9	Bridgestone	R 287	295/75R22.5	F	8 3/4		
29	9	Bridgestone	R 227	295/75R22.5	R	8 1/2	4 7/8	21 1/2
30	9	Goodyear	G 314	295/75R22.5	R	8 1/2	4 7/8	21 1/2
31	9	Bridgestone	M 726	295/75R22.5	R	8 7/8	4 3/4	21 5/8
32	9	Bridgestone	R 280	295/75R22.5	F	9 1/2		
33	9	Michelin	PILOT XT1	275/80R22.5	R	8 7/8	4 3/8	22 1/4
34	9	Bridgestone	R 195	295/75R22.5	R	8 3/4	4 1/2	22
35	9	Michelin	XDA 3	275/80R22.5	R	8 3/4	4 5/8	22
36	9	Bridgestone	M726 EL	295/75R22.5	R	9 1/8	4 1/4	22 1/2
37	9	Toyo	M 147	285/75R24.5	F	8 5/8		

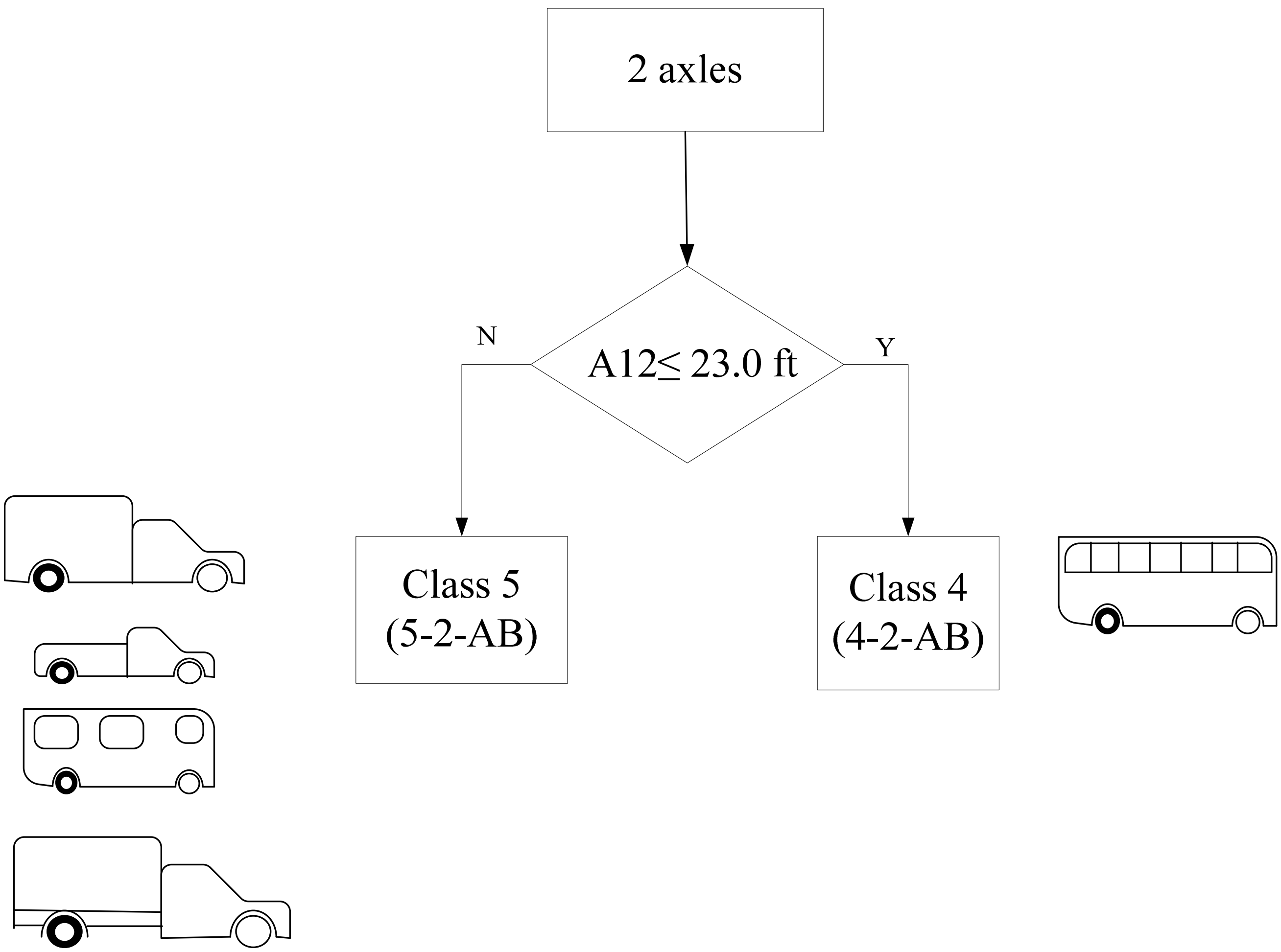
No.	Class	Tire Make	Brand	Size	Axle	Width	Gap	Total
38	9	Bridgestone	R 194	295/75R22.5	R	8 3/8	4 7/8	21 3/8
39	9	Bridgestone	R 299	295/75R22.5	R	8 3/8	4 5/8	22 1/8
40	9	Bridgestone	R 195	295/75R22.5	R	8 7/8	4 1/4	22 1/8
41	9	Michelin	XZA 3	275/80R22.5	R	8 3/8	4 7/8	21 1/2
42	9	Michelin	M 720	295/75R22.5	R	8 5/8	4 3/4	22
43	5[R]	Michelin	XZA	8R19.5	F	5 5/8		
44	5[R]	Michelin	XZA	8R19.5	R	5 1/2	4	15
45	9	Goodyear	G 159	11R22.5	R	8 3/8	4 3/4	21 1/4
46	9	Firestone	FS 590	295/75R22.5	F	8 7/8		
47	9	Yokohama	SuperSteel TY 303	295/75R22.5	R	8 3/4	4 5/8	22 1/8
48	9	Dynatrac	PD- 880	295/75R22.5	R	9	4 1/2	22 1/4
49	9	Leopard	OOCL	10.00-20	R	7 3/4	5 5/8	21 3/8
50	9	Hi-way	OOCL	11-22.5	R	7 3/8	5 5/8	20 3/8
51	9	Goodyear	G 159	265/70R22.5	R	8 1/4	4 3/8	20 3/4
52	9	Michelin	XZE	255/70R22.5	R	8 1/4	4 7/8	21 3/4
53	9	Dunlop	SP 381	11R22.5	R	8 1/2	4 5/8	22
54	9	Michelin	XDA- HT	11R22.5	R	8 5/8	4 5/8	22
55	5	Toyo	Hyparadial	11R22.5	R	8 5/8	4 3/8	21 3/8
56	8	Galaxy	Trailerspecial	8-14.5	R			
57	9	Toyo	M 147	11R22.5	F	8 1/2		
58	9	Goodyear	G 372 LHD	295 /75R22.5	R	8 5/8	4 3/4	22 1/8
59	10	Yokohama	SuperSteel RY103	255/70	R	8	5	21 1/8
60	9	Kumho	Power Fleet 961A		R	7 7/8	5 3/8	21
61	9	General	D 460	11R24.5	R	8 1/2	4 5/8	21 7/8
62	9	Hercules	S-307	11R24.5	R	8 3/8	5	21 3/4
63	9	Yokohama	RY 617	11R24.5	F	8 7/8		
64	9	Bridgestone	R 250	285/75R24.5	F	8 7/8		
65	9	Goodrich	ST 230	275/80R22.5	F	8 3/4		
66	9	Superior	M 144	295/75R22.5	R	9 1/4	3 3/4	22 1/4
67	9	General	S 580	285/75R24.5	F	8 3/4		
68	9	Kumho	967	285/75R24.5	R	8 3/8	4 7/8	21 1/2
69	9	General	D 460	285/75R24.5	R	8 3/8	5 1/8	21 7/8
70	9	Firestone	Steel Tex Rad R45	LT235/85/12.6	R	7	4	18 1/4
71	10	Goodyear	G 114	215/75R17.5	R	6 3/4	5 3/8	18 7/8
72	10	GT Radial	GT 688	11R24.5	R	8 1/4	4 3/4	21 1/2
73	10	Kumho	943	11R24.5	R	7 3/4	5 3/8	21 1/8
74	10	Sumitomo	ST 720	425/65R22.5	F	12 1/2		
75	9	Michelin	XDZ	255/70R22.5	R	8 1/4	4 7/8	21 1/2

No.	Class	Tire Make	Brand	Size	Axle	Width	Gap	Total
76	9	Michelin	XTA 2	265/70R19.5	R	8 1/2	4	21 1/8
77	9	Continental	HSL	11R24.5	F	8 7/8		
78	9	Yokohama	RY 587	285/75R24.5	R	8 1/4	4 7/8	21 1/2
79	9	Steel Mark	AHS	295/75R22.5	F	8 3/4		
80	9	Kumho	982	295/75R22.5	R	8 7/8	4 3/8	22 1/4
81	9	General	S 380A	295/75R22.5	F	8 7/8		
82	9	Firestone	FD 663	11R24.5	R	7 3/4	5 1/4	21 1/8
83	9	Michelin	XDHT	11R24.5	R	8 1/8	5	21 3/8
84	9	Goodyear	Wingfoot	11R24.5	R	7 1/2	5 3/4	20 3/4
85	9	Armosteel	Kelly KDA	11R22.5	R	8 1/4	4 5/8	21 1/8
86	9	Michelin	M+S4	11R22.5	R	8	5 1/4	21 7/8
87	9	Goodyear	Workhorse	9.50-16.5LT	R	7 1/8	4 1/8	18 1/8
88	5	Cooper	CXMT 340	295/75R22.5	F	8 7/8		
89	5	Hankook	235A	295/75R22.5	R	8 1/8	5 1/8	21 5/8
90	5	Bridgestone	M773	LT235/85R16	R	7 1/8	3 1/2	17 5/8
91	5	General	Ameristeel	8.25R20	R	6 7/8	5 1/4	18 7/8
92	9	Diamond	Matador	11R24.5	R	8 5/8	4 3/4	22
93	9	Remington	R 499	11R24.5	R	8 1/8	4 3/4	21 1/4
94	9	Continental	HTK	215/75R17.5	R	6 7/8	5	19 3/8
95	5	Sears	Mileage Rib	8.25-20	R	7	4 1/4	17
96	5	General	SRF	8.25-20	F	7		
97	5	Goodyear	G 357	11R22.5	R	8 3/8	5 3/8	21 1/4
98	5	Cooper	CXMA 354	11R22.5	F	8 5/8		
99	8	Good year	G 114	295/75R22.5	R	8	5 1/8	21 1/2
100	8	Good year	G 314	295/75/R22.5	R	8 5/8	4 5/8	22
101	8	Good year	Wingfoot	295/75R22.5	R	7 5/8	5 1/8	21 1/4
102	8	Good year	G 314	11R24.5	R	7 3/4	5 1/4	21 1/8
103	8	Good year	G 338	295/75R22.5	R	8 1/2	4 1/2	21 5/8
104	8	Good year	Wingfoot	295/75R22.5	R	7 5/8	5 1/4	21 3/8
105	8	Good year	G 357	295/75R22.5	R	8 1/2	5 1/4	21 3/8
106	11	General	D 460	295/75R22.5	R	8 1/4	4 1/2	21 7/8
107	11	Bridgestone	R194	295/75R22.5	R	8 1/2	5 1/4	21 1/2
108	11	Good year	G 328	295/75R22.5	R	7 5/8	5 3/8	21 1/4
109	11	Yokohama	Sup.Steel TY303	295/75R22.5	R	8 1/4	4 3/4	22
110	8	Good year	G 357	295/75R22.5	R	8 1/4	5 1/8	21 3/4
111	3	Bronco	Radial APE	LT225/75R16	R	6 1/2	3 1/2	16 1/4
112	5[R]	Good year	G 670 RV	245/70R19.5	R	8 1/8	2 7/8	19 1/4
113	5[R]	Michelin	XRV	235/80R22.5	R	6 7/8	5 3/4	19 1/8
114	5[R]	Good year	G 670 RV	275/70R22.5	R	8 1/4	5	21 3/8
115	5[R]	Michelin	XRV	255/80R22.5	R	7 1/2	5 3/4	19 1/8

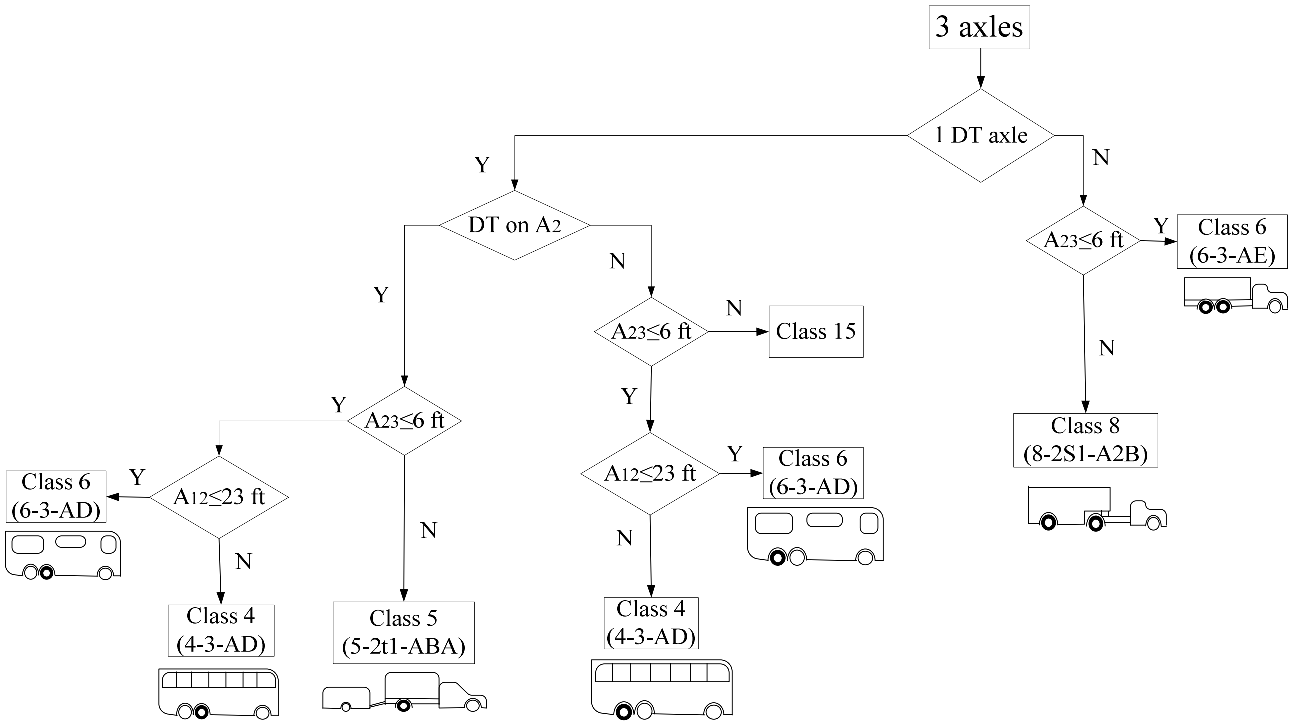
No.	Class	Tire Make	Brand	Size	Axle	Width	Gap	Total
116	5[R]	Good year	G 670 Rv	255/70R22.5	R	8	5 1/8	21
117	5[R]	Michelin	LTX M/S	255/75R16	R	6 7/8	3 1/2	17 1/8
118	5[R]	Uniroyal	Laredo	255/75R16	R	6 3/4	3 1/4	16 7/8
119	5[R]	Michelin	XRV	255/80R19.5	R	7	3 1/8	17 1/8
120	5[R]	Bridgestone	R 187	225/70R19.5	R	7 1/4	2 3/4	17 1/8
121	3[R]	Good year	Wragler	LT235/80R17	R	7 7/8	2 7/8	18 3/4
122	5[R]	MasterCraft	Courser R/D	225/75R16	R	6 3/4	3 3/8	16 3/4
123	3[R]	Dominator	Radial T/D	215/85R16	R	6 1/8	3 7/8	16 1/8
124	5[R]	Michelin	XZA	255/70/R19.5	R	7 3/8	2 1/2	17 3/8
125	5[R]	Kelly	Safari	235/80/R16	R	6 3/4	3 7/8	17 1/2
126	3[R]	Uniroyal	Laredo AWT	235/85R16	R	7 1/8	3 1/2	17 7/8
127	4	Firestone	City Trans	12R22.5	R	9 1/4	4 3/4	22 5/8
128	4	Firestone	City Trans	12R22.5	R	8 1/2	4 7/8	22
129	4	Firestone	City Trans	12R22.5	R	9 1/8	4 1/4	22 5/8
130	4	Bridgestone	R250	295/75R22.5	R	8 1/2	4 1/2	21 7/8
131	4	Goodyear	G159	295/75R22.5	R	9 1/8	4 1/8	22 1/2
132	4	Goodyear	G159	295/75R22.5	R	9	4 1/4	22 3/8
133	4	Firestone	City Trans	12R22.5	R	9 1/8	4 1/2	22
134	4	Firestone	City Trans	12R22.5	R	9 1/8	4 1/4	22 3/8
135	4	Michelin	X	275/70R22.5	R	9 1/4	3 3/4	23 1/8
136	4	Goodyear	G159 Unisteel	LT215/85R16	R	7 1/8	3 1/4	17 3/8
137	4	Goodyear	G159 Unisteel	LT215/85R16	R	7 1/4	3 3/8	17 5/8
138	4	Goodyear	G159 Unisteel	LT215/85R16	R	7 1/8	3 1/8	17 1/4
139	4	Goodyear	G159 Unisteel	LT215/85R16	R	7	3 3/8	17 1/4
140	4	Goodyear	G159 Unisteel	LT215/85R16	R	7 1/8	3 1/4	17 3/8
141	4	Goodyear	G159 Unisteel	LT215/85R16	R	7 1/8	3 1/8	17 3/8
142	4	Goodyear	G169	255/70R22.5	R	8	5 1/8	21 3/8
143	4	Goodyear	G149	11R22.5	R	8 1/2	4 5/8	21 5/8
144	4	Bridgestone	R260	11R22.5	R	9 1/8	3 7/8	22
145	4	Goodyear	G159	11R22.5	R	8 1/4	5	21
146	4	Bridgestone	R295	255/70R22.5	R	8 1/8	4 7/8	21 3/8
147	4	Goodyear	G159	10R22.5	R	7 7/8	5 1/8	20 5/8
148	4	Bridgestone	R294	255/70R22.5	R	8	5 1/8	21
149	4	Bridgestone	R260	11R22.5	R	9 1/8	3 3/4	22 1/8
150	4	Goodyear	G159	10R22.5	R	7 5/8	5 1/4	20 1/8
151	4	Goodyear	RSA	11R22.5	R	8 3/8	4 7/8	21 5/8
152	4	Bridgestone	R260	11R22.5	R	9	4	22 1/4
153	4	Goodyear	G149	11R22.5	R	8 1/2	4 3/8	21 3/8
154	4	Goodyear	G159	11R22.5	R	8 1/2	4 3/8	21 3/8
155	4	Goodyear	G149	11R22.5	R	8 1/2	4 3/4	21 3/4

No.	Class	Tire Make	Brand	Size	Axle	Width	Gap	Total
156	5	General	LMT 400	225/70R19.5	R	7 3/8	3 3/8	18 1/8
157	3	Uniroyal	Laredo	LT235/85R16	R	6 3/4	3 5/8	17 5/8
158	3	BFGoodrich	Commercial T/A	LT215/85R16	R	6 1/8	3 3/4	16 1/8
159	5	Michelin	XZE	245/70R19.5	R	8	3 1/4	19 1/8
160	5	Michelin	XZE	245/70R19.5	R	8 1/4	3	19 3/8
161	5	Bridgestone	V-Steel	LT225/75R16	R	7 1/8	3 1/4	17 1/4
162	5	Bridgestone	V-Steel	LT215/85R16	R	6 5/8	3 1/2	16 5/8
163	5	Bridgestone	R250	295/75R22.5	R	8 3/4	4 3/8	22
164	5	Bridgestone	M726 EL	295/75R22.5	R	9 1/8	4 3/8	22 1/2
165	5	Bridgestone	V-Steel	LT215/85R16	R	6 3/8	3 7/8	16 1/2
166	5	Bridgestone	V-Steel	LT215/85R16	R	6 3/8	3 3/4	16 5/8
167	5	Bridgestone	M726	295/75R22.5	R	8 1/4	5	21 1/2
168	5	Michelin	XZA	275/80R22.5	R	8	5 3/8	21 1/2
169	5	Bridgestone	V-Steel	LT215/85R16	R	6 1/2	3 5/8	16 3/4
170	5	Bridgestone	R250	295/75R22.5	R	8 3/8	5	21 5/8
171	5	Bridgestone	R250	295/75R22.5	R	8 1/4	4 3/4	21 1/4
172	5	Bridgestone	R187	245/70R19.5	R	7 1/2	3 3/4	18 3/4
173	5	Bridgestone	R299	295/75R22.5	R	8 3/4	4 1/2	22 1/8
174	5	Bridgestone	M726	295/75R22.5	R	8 1/2	4 3/4	21 7/8
175	5	Michelin	LTX L-S	LT225/75R16	R	7	3 1/4	17 1/4
176	5	Bridgestone	V-Steel	LT215/85R16	R	6 1/2	3 5/8	16 3/4
177	5	Bridgestone	M726	295/75R22.5	R	8 1/8	5	21 3/8
178	5	Bridgestone	R195	295/75R22.6	R	8 1/4	5 1/4	21 1/2

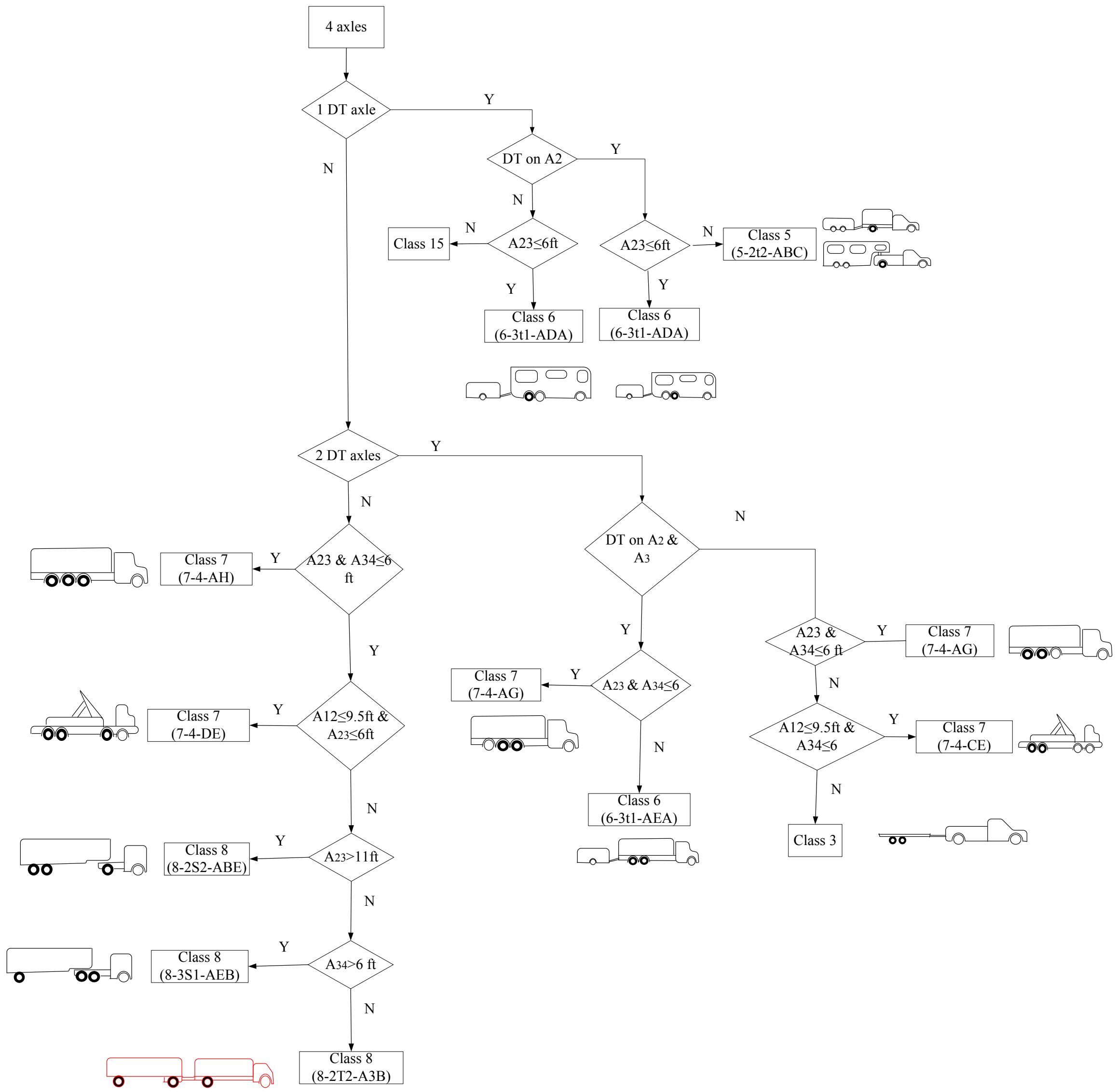
APPENDIX 3A. 2-AXLE ALGORITHM



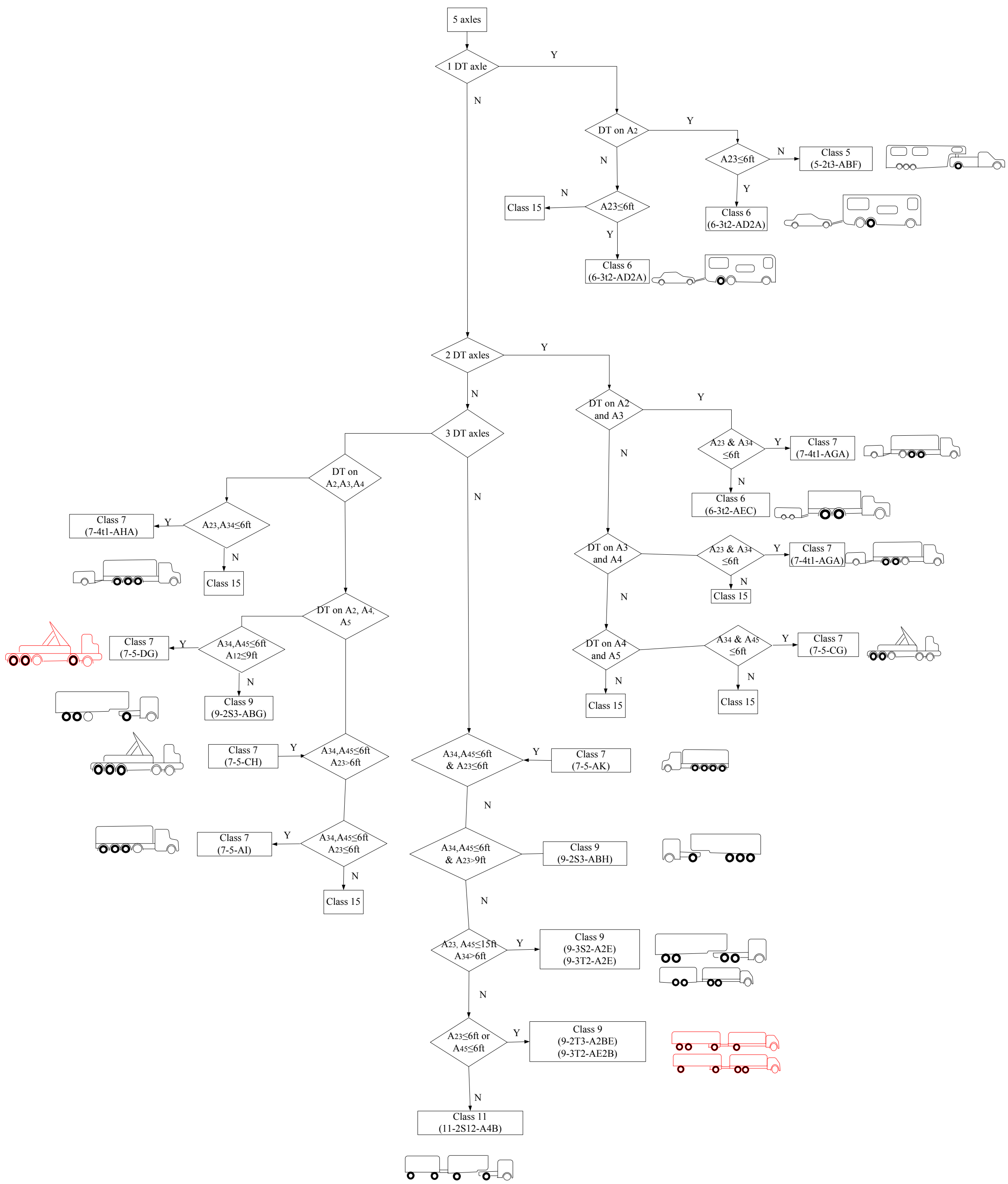
APPENDIX 3B. 3-AXLE ALGORITHM



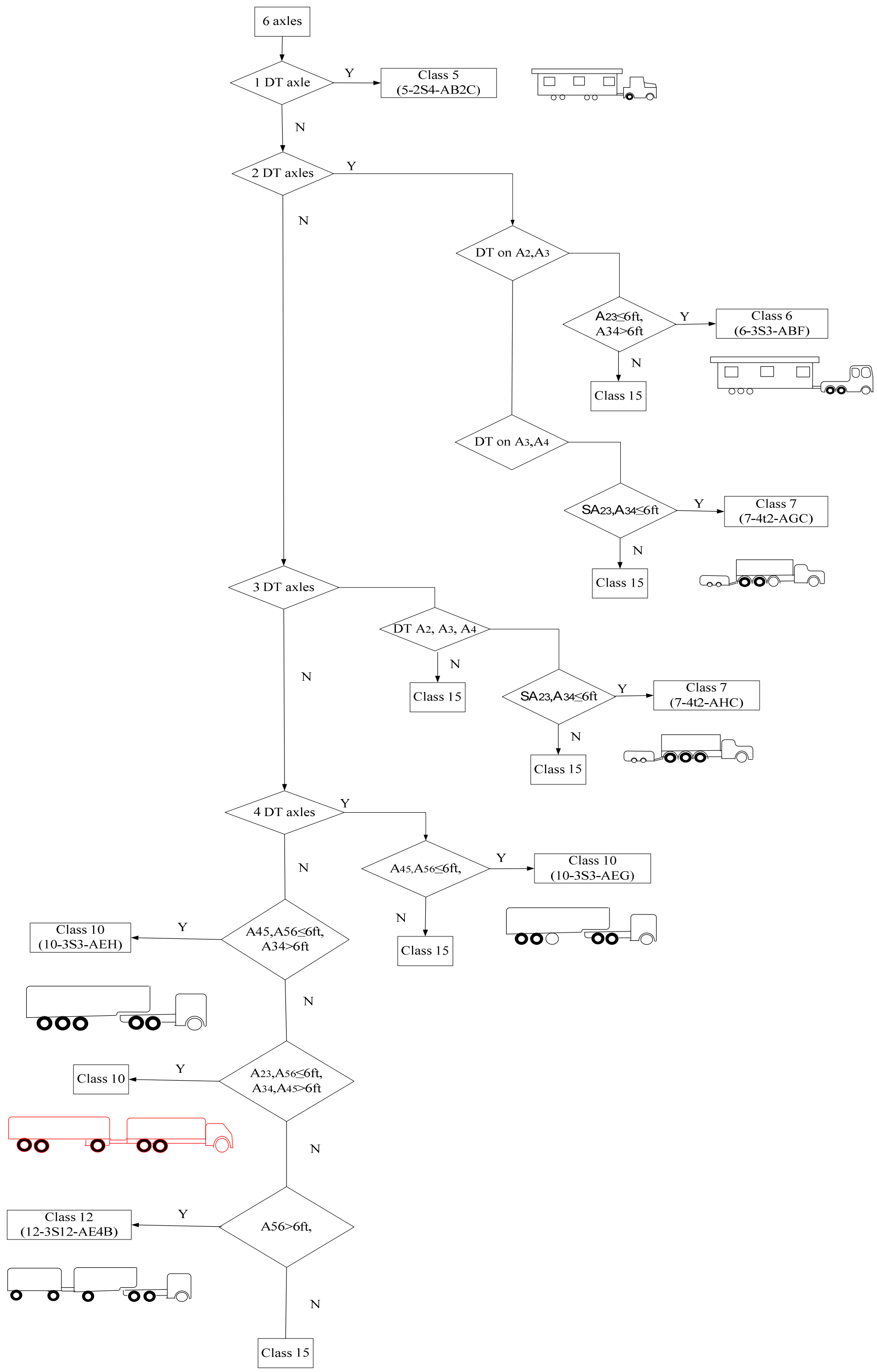
APPENDIX 3C. 4-AXLE ALGORITHM



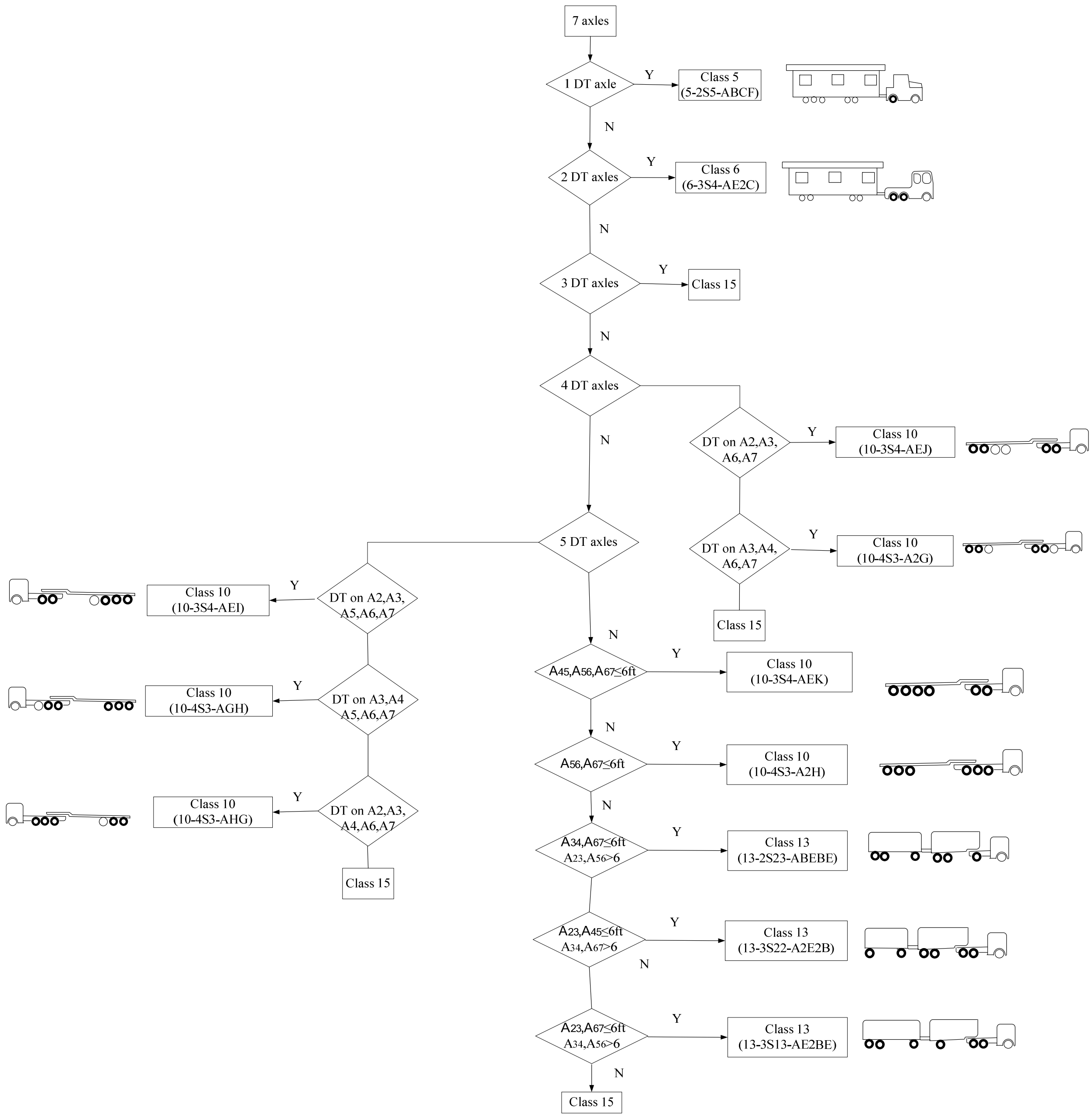
APPENDIX 3D. 5-AXLE ALGORITHM



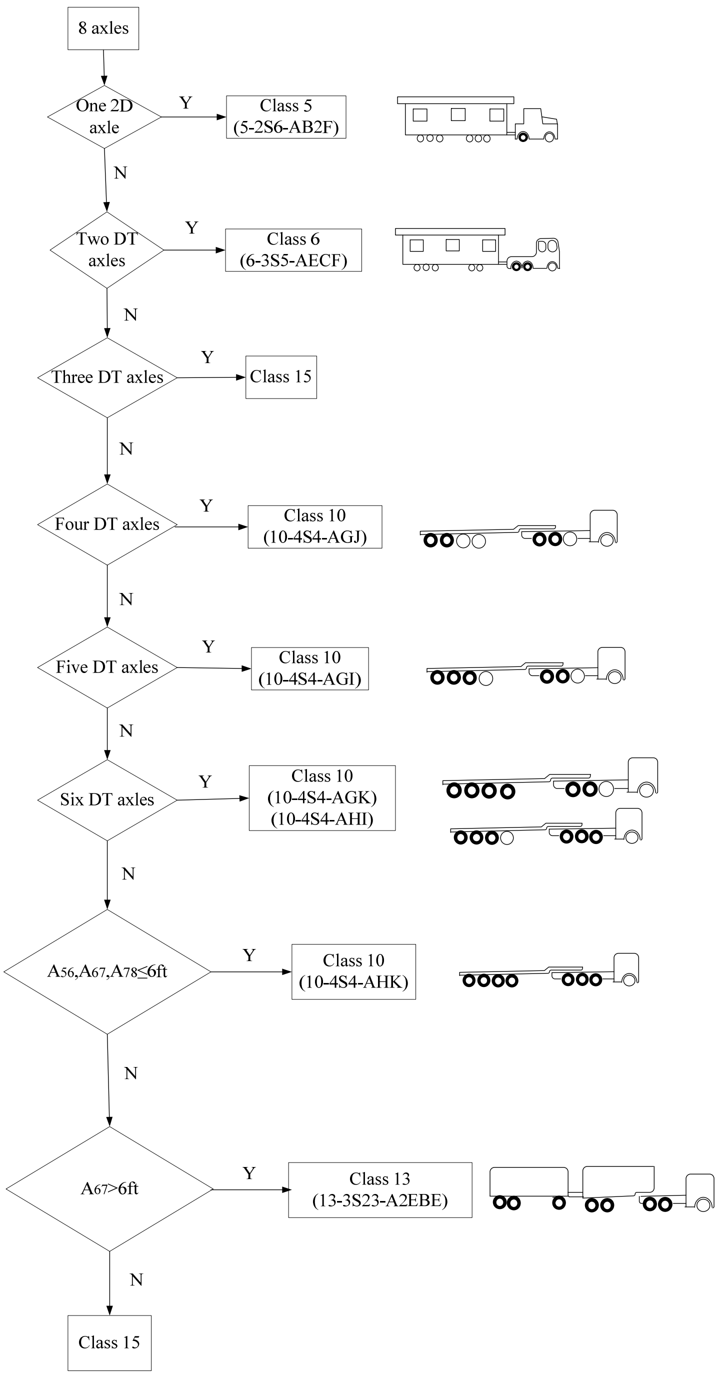
APPENDIX 3E. 6-AXLE ALGORITHM



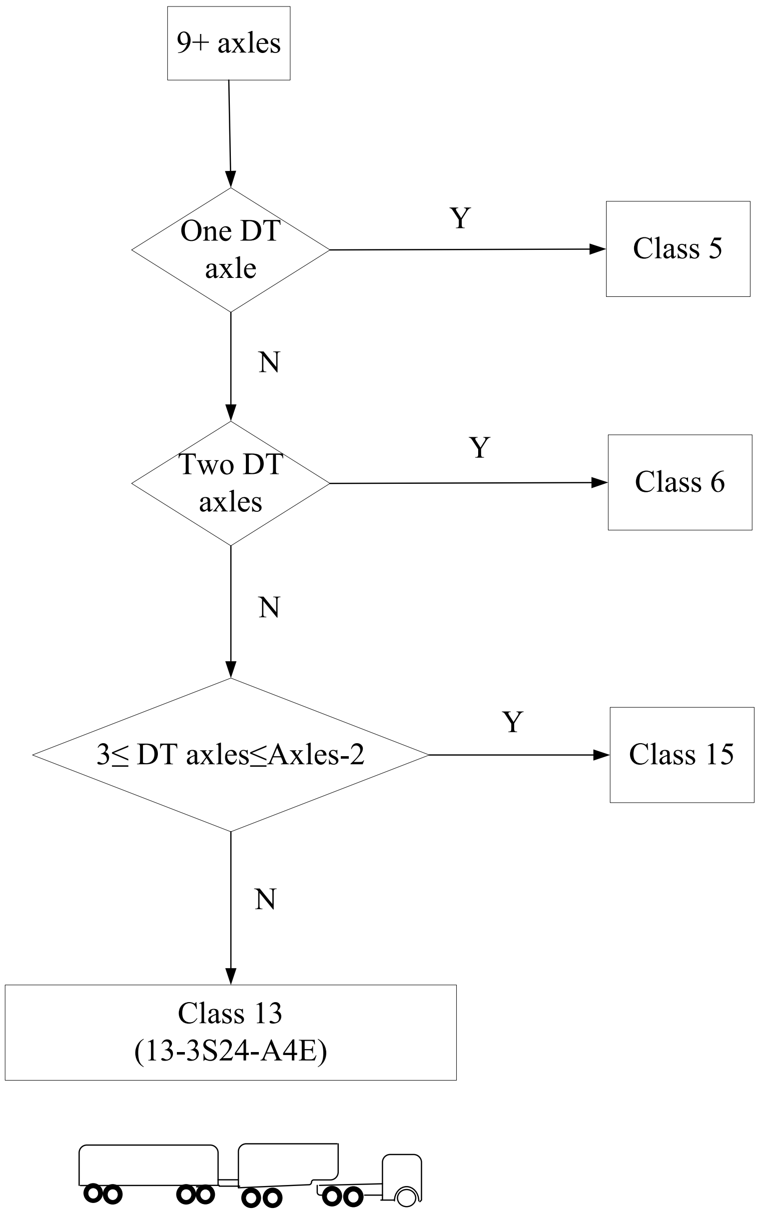
APPENDIX 3F. 7-AXLE ALGORITHM



APPENDIX 3G. 8-AXLE ALGORITHM



APPENDIX 3H. 9+ AXLE ALGORITHM



APPENDIX 4 – EVALUATION OF WAVETRONIX AND SENSYS SLIDES

Evaluation of Wavetronics and Sensys Traffic Sensors

Presentation

Purpose and Scope

- Compare Wavetronics and Sensys outputs with ground truth data
- Use video camera as ground truth to capture vehicle lengths and class
- Use laser-guided radar speed gun to capture vehicle speeds
- Download individual vehicle records from ADR at Site 550304 for short and long term study comparison

Methodology

Short Term Study (24-hr)

- Compare PVR of speed, length, and volume for four equipment—Sensys, Wavetronics, ADR, and video
- Compare data only from the WB outside lane

Long Term Study (30-day)

- Compare hourly summaries of speed and volume for three equipment—Sensys, Wavetronics, and ADR
- Compare data for all 4 travel lanes

Data Collection

- 24- hr data were collected over 8 days starting from 09/11/2006 to 09/19/2006
- Video data was collected in 3 to 4 hr periods for a total of 24 hours
- Sensys data were downloaded from Sensys server in California
- Wavetronics data were downloaded at the site using a laptop
- ADR data were supplied by FDOT
- 30-day data were collected starting from 09/20/2006 to 11/2/2006

Overview of ADR Performance

- ADR does not record vehicle lengths ≥ 80 ft
- Sometimes the ADR erroneously recorded all the vehicles in a certain lane as having lengths ≥ 80 ft (denoted by >Range)
- There were some ghost vehicles recorded by the ADR
- Some multi-unit trucks were split into two

Overview of Wavetronics Performance

- Some trucks were recorded as a sequence of different shorter vehicles
- Connection was randomly lost and re-established during downloading causing loss of vehicle records
- Speed data were not recorded for a number of vehicles.

Overview of Sensys Performance

- Some of the vehicle lengths recorded were unrealistically high, e.g.:
  - 1240.4 ft recorded on 09/12/2006 at 08:23 a.m. with corresponding speed of 1551.5 mph.
  - 307.2 ft recorded on 09/14/2006 at 11:18 a.m.
- The frequency of occurrence of these errors was small

Traffic Parameters Analyzed

- Volume
- Speed
- Length
- Classification

Volume Analysis

30-min Period No.	Vehicle Count				Percentage Error		
	Video	ADR	Wavetronics	Sensys	ADR	Wavetronics	Sensys
1	441	448		424	1.6		-3.9
2	439	443	492	453	0.9	12.1	3.2
3	432	435	561	435	0.7	29.9	0.7
4	459	463	591	460	0.9	28.8	0.2
5	461	464		457	0.7		-0.9
6	377	379		382	0.5		1.3
7	395	402	563	398	1.8	42.5	0.8
8	448	452	597	433	0.9	33.3	-3.3
9	505	514	622	497	1.8	23.2	-1.6
10	413	419	565	405	1.5	36.8	-1.9
11	405	409	570	397	1.0	40.7	-2.0
12	443	448	606	441	1.1	36.8	-0.5

Volume Analysis

30-min Period No.	Vehicle Count				Percentage Error		
	Video	ADR	Wavetronics	Sensys	ADR	Wavetronics	Sensys
13	468	472	596	460	0.9	27.4	-1.7
14	420	424	507	412	1.0	20.7	-1.9
15	392	393	551	382	0.3	40.6	-2.6
16	435	438	597	437	0.7	37.2	0.5
17	565	570	641	566	0.9	13.5	0.2
18	411	417	517	410	1.5	25.8	-0.2
19	345	351	480	338	1.7	39.1	-2.0
20	352	364	471	347	3.4	33.8	-1.4
21	497	501	626	495	0.8	26.0	-0.4
22	404	410		407	1.5		0.7
23	394	399	541	393	1.3	37.3	-0.3
24	371	371	468	365	0.0	26.1	-1.6
Mean Percentage Error					1.1	30.6	-0.8

Summary of Volume Analysis

- ADR consistently erred on the positive side
- Sensys mostly erred on the negative side
- However, both ADR and Sensys had a good match with ground truth (within $\approx \pm 1\%$)
- Wavetronics greatly overcounted number of vehicles possibly due to splitting multi-unit trucks
- On the average, Wavetronics created $\approx$ 30% more vehicles with Max = +43% and Min = +12%

Speed Analysis

30-min Period No.	Average Speed				Percentage Error		
	Laser gun	ADR	Wavetronics	Sensys	ADR	Wavetronics	Sensys
2	67.7	68.0	69.4	67.2	0.4	2.5	-0.7
5	66.7	65.7	68.0	63.9	-1.5	1.9	-4.3
10	64.4	64.5	68.1	65.7	0.2	5.7	2.0
13	66.6	66.1	66.8	66.5	-0.8	0.2	-0.2
17	67.6	67.2	68.9	67.8	-0.7	1.9	0.3
21	66.8	66.5	68.6	66.1	-0.4	2.6	-1.1
Mean Percentage Error					**-0.5**	**2.5**	**-0.7**

Summary of Speed Analysis

- All 3 sensors recorded speeds fairly close to the ground truth
- Wavetronics recorded slightly higher speed averages probably due to missing data (18% of the vehicles did not have speed recorded by Wavetronics)

Length Analysis (by 30-min Periods)

30-min Period No.	ADR		Wavetronics		Sensys	
	Mean % Error	SD	Mean % Error	SD	Mean % Error	SD
1	-11.5	8.8	-15.8	40.0	-10.2	24.4
2	-12.7	7.9	-13.2	38.0	-11.2	23.3
3	-16.1	8.8	-15.7	32.2	-15.9	20.8
4	-14.2	6.5	-13.5	41.1	-11.2	23.2
5	-14.2	6.5	-5.5	16.5	-12.8	26.2
6	-15.6	6.1	-17.1	33.6	-13.3	17.7
7	-12.9	7.9	-16.9	37.9	-12.8	23.7
8	-14.9	6.3	-17.0	43.9	-12.4	20.7
9	-14.4	8.0	-16.2	31.9	-13.8	16.6
10	-12.9	8.8	-13.2	34.9	-12.8	20.2
11	-16.3	6.4	-16.5	29.8	-14.5	20.9
12	1.5	6.2	-0.7	32.1	1.0	20.7

Length Analysis (by 30-min periods)

30-min Period No.	ADR		Wavetronics		Sensys	
	Mean % Error	SD	Mean % Error	SD	Mean % Error	SD
13	-13.0	7.4	-15.8	33.6	-13.3	21.8
14	-13.4	7.5	-13.1	39.4	-14.0	19.9
15	-12.7	6.2	-13.6	35.9	-12.3	23.8
16	-14.3	6.3	-17.6	35.2	-12.4	22.0
17	-14.2	6.9	-13.0	28.8	-14.2	19.7
18	-15.4	9.5	-10.2	40.4	-12.6	25.8
19	-14.3	7.0	-16.1	41.5	-12.0	23.3
20	-14.7	8.6	-16.1	35.9	-11.3	22.3
21	-14.2	7.3	-16.3	37.8	-13.2	21.4
22	-15.3	7.0	-14.8	49.9	-14.1	21.7
23	-15.5	7.5	-15.9	37.5	-15.9	25.6
24	-15.8	6.9	-17.0	34.5	-13.7	22.9
MEAN	-13.6	7.3	-14.2	35.9	-12.4	22.0

Length Analysis (by Class)

Class	Video	ADR		Wavetronics		Sensys	
	Total	Total	% Error	Total	% Error	Total	% Error
Passenger Vehicles	8077	8407	4.1	9234	14.3	7785	-3.6
Single Unit Trucks	887	705	-20.5	860	-3.0	1278	44.1
Multi Unit Trucks	1263	1178	-6.7	406	-67.9	805	-36.3
Unmatched Vehicles		29		1455		209	

Passenger Vehicles ≤ 21.5 ft
Single Unit Trucks 21.6 ft to 42.5 ft
Multi Unit Trucks > 42.5 ft

ADR Length Analysis

Class	Video	Original Length		Modified Length (+14%)	
	Total	Total	% Error	Total	% Error
Passenger Vehicles	8,077	8,407	4.1	8,300	2.8
Single Unit Trucks	887	705	-20.5	786	-11.4
Multi Unit Trucks	1,263	1,178	-6.7	1,204	-4.7
Mean Percentage error			-7.7		-4.4

Passenger Vehicles ≤ 21.5 ft
Single Unit Trucks 21.6 ft to 42.5 ft
Multi Unit Trucks > 42.5 ft

Length Analysis (by F-Scheme)

Class	Video	ADR		Wavetronics		Sensys	
	Avg	Avg	% Error	Avg	% Error	Avg	% Error
1	7.1	2.65	-62.7	9.7	36.6	12.8	80.3
2	16.25	14.6	-10.2	15.95	-1.8	14.3	-12.0
3	21.8	17.25	-20.9	16.25	-25.5	18.1	-17.0
4	35.7	29.35	-17.8	21.3	-40.3	31.75	-11.1
5	31.55	24.8	-21.4	20.9	-33.8	28.7	-9.0
6	32.9	25.15	-23.6	19.2	-41.6	31.45	-4.4
7	30.9	24	-22.3	17.85	-42.2	31.9	3.2
8	60.25	50.05	-16.9	20.5	-66.0	52.25	-13.3
9	74.1	63.45	-14.4	22.55	-69.6	60.1	-18.9
10	83	65.4	-21.2	23.75	-71.4	65.45	-21.1
11	80.3	70.9	-11.7	21.9	-72.7	74.05	-7.8
12	88.3	74.3	-15.9	38	-57.0	78.9	-10.6
13	103.25	75.1	-27.3	39.3	-61.9	68.85	-33.3
Unmatched				1,455		209	

Summary of Length Analysis

- All 3 sensors undermeasured vehicle lengths
- ADR sensor consistently undermeasured all vehicles
- Sensys overmeasured some vehicles, particularly Class 7 and Class 1 vehicles

ADR Errors

Date	Time	Lane		Speed (mph)	Length (ft)	Class
18-09-2006	07:37:19	Lane 1	Fwd	44	14	1
18-09-2006	07:37:19	Lane 3	Fwd	72	>Range	2
18-09-2006	07:37:20	Lane 3	Fwd	71	>Range	2
18-09-2006	07:37:20	Lane 3	Fwd	76	>Range	2
18-09-2006	07:37:22	Lane 3	Fwd	72	>Range	2
18-09-2006	07:37:22	Lane 1	Fwd	47	12	2
18-09-2006	07:37:22	Lane 3	Fwd	76	>Range	2
18-09-2006	07:37:23	Lane 4	Fwd	62	14	2
18-09-2006	07:37:24	Lane 4	Fwd	62	16	2
18-09-2006	07:37:24	Lane 3	Fwd	74	>Range	2
18-09-2006	07:37:24	Lane 4	Fwd	61	14	2
18-09-2006	07:37:24	Lane 1	Fwd	45	16	2
18-09-2006	07:37:25	Lane 3	Fwd	71	>Range	2
18-09-2006	07:37:26	Lane 4	Fwd	61	13	2

Wavetronics Errors - 1

Date	Time	Lane04	Length	Speed	Class	Range	Sensor time
9/19/2006	10:20:37	Lane04	16	71	1	55	10:20:26
9/19/2006	10:20:37	Lane04	26	69	2	55	10:20:26
9/19/2006	10:20:37	Lane04	7	62	1	55	10:20:26
9/19/2006	10:20:37	Lane04	6	67	1	55	10:20:26
9/19/2006	10:20:37	Lane04	13	68	1	54	10:20:26

See Actual vehicle

9/11/2006	9:35:44	Lane04	8		1	55	9:35:38
9/11/2006	9:35:44	Lane04	11	66	1	55	9:35:38
9/11/2006	9:35:45	Lane04	7	69	1	50	9:35:38
9/11/2006	9:35:45	Lane04	11		1	55	9:35:38
9/11/2006	9:35:45	Lane04	6		1	50	9:35:38
9/11/2006	9:35:45	Lane04	7	73	1	55	9:35:38

Long truck recorded as 5 shorter vehicles

Wavetronics Errors - 2

Date	Time	Lane04	Length	Speed	Class
9/14/2006	9:05:01	Lane04	17	65	1
9/14/2006	9:05:03	Lane04	11	63	1
9/14/2006	9:05:05	Lane04	16	67	1
9/14/2006	9:08:18	Lane04	6	86	1
9/14/2006	9:08:19	Lane04	15	80	1

3min

Date	Time	Lane04	Length	Speed	Class
9/12/2006	9:17:46	Lane04	9		1
9/12/2006	9:17:53	Lane04	14	68	1
9/12/2006	9:17:55	Lane04	13	57	1
9/12/2006	9:43:04	Lane04	20	61	1
9/12/2006	9:43:04	Lane04	16	56	1
9/12/2006	9:43:05	Lane04	6	68	1

25min

Wavetronics Errors - 3

Missing Speed Data

Date	Time	Lane04	Length	Speed	Class
9/11/2006	10:00:20:093	Lane04	9	70	1
9/11/2006	10:00:20:015	Lane03	10	64	1
9/11/2006	10:00:20:250	Lane04	20		1
9/11/2006	10:00:21:968	Lane03	19	73	1
9/11/2006	10:00:21:890	Lane04	16	71	1
9/11/2006	10:00:23:375	Lane04	17		1
9/11/2006	10:00:23:609	Lane01	18	62	1
9/11/2006	10:00:25:015	Lane02	13	76	1
9/11/2006	10:00:25:171	Lane04	15	77	1
9/11/2006	10:00:25:796	Lane03	36		2
9/11/2006	10:00:25:718	Lane04	51		3
9/11/2006	10:00:27:671	Lane01	18	66	1
9/11/2006	10:00:28:453	Lane01	11	65	1
9/11/2006	10:00:28:921	Lane04	19	68	1
9/11/2006	10:00:29:000	Lane03	16	70	1