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DEVELOPMENT OF A LOW-COST AUTOMATIC VEHICLE CLASSIFICATION (AVC) SYSTEM

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16. Abstract

The main objectives of this research were to review and evaluate the current automatic vehicle classification (AVC) systems and operating procedures and to design and recommend a modified AVC system that utilizes weights for improved performance.

Recommendations: tubes should be used for all AVC installations as they typically had a lower frequency of missed axles/vehicles compared to piezoelectric sensors; Tubes should be installed about 6" from the edge of the inside lane marking, which would minimize the potential for stray vehicles from and adjacent lane to activate the sensors; use of inductive loops generally would not be advantageous, except for relatively congested facilities and should be used in urban facilities that experience recurring congestion.

The field test results show that overall accuracy for all vehicles was greater than 90%, although accuracy for trucks was generally site specific. Using a different binning scheme for different sites might improve performance on individual sites. Typically, about 1 to 4% of the vehicles were missed, thus not classified by the system. Passenger vehicles are generally most affected, and proportion was typically higher when a loop was used.

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Executive Summary

The main objectives of this research project were to review and evaluate the current automatic vehicle classification (AVC) systems and operating procedures used by the Nevada Department of Transportation (NDOT), and to design and recommend a modified AVC system that utilizes vehicle weights for improved performance. The modified system should be inexpensive, readily adaptable to the current AVC system being used by NDOT, and provide the accuracy of vehicle classification information required for the purposes of NDOT.

The tasks that were performed to carry out these objectives were divided into three categories, namely, 1) Evaluation of NDOT's current AVC systems and procedures, 2) Modification of the current systems and procedures to improve performance, and 3) Design of a weight based system.

NDOT's current AVC systems use traffic counters that classify vehicles based on axle configuration and spacing. The axle sensors used can be portable or permanently installed on a site. At permanent sites, two 6′ piezoelectric sensors are typically embedded in the pavement 12′ to 14′ apart with a 6′x6′ inductive loop between them. The portable system uses two pneumatic tubes firmly taped onto the pavement surface. A portable loop may also be installed between the sensors.

A number of field tests were conducted to evaluate the performance of these systems on a freeway site. It was found that while the overall vehicle classification accuracy was over 95%, the accuracy rate for heavy vehicles (including trucks, buses, and recreation vehicles) was well under 90%. The systems particularly overestimated the single 4 axle trucks by mis-classifying several 2-axle vehicles with 2-axle trailers as single 4 axle trucks. This was especially the case with passenger cars and recreation vehicles (RVs) with trailers. Occasionally, some 5 axle trucks (3S2s) were also mis-classified as single 4 axle trucks if the axle sensors fail to detect one of the axles. However, when detected with the correct number of axles, trucks with 5 axles or more were generally classified at accuracy rates of over 90%.

Most of the classification errors were due to axle sensors failing to detect one or more axles of a vehicle, combining two or more closely spaced vehicles into one, and splitting vehicles with wide axle spacing into two or more vehicles. The latter two types of errors were a result of the maximum axle spacing which the user specifies for the system. The higher the maximum spacing, the more the likelihood of combining vehicles, while a lower maximum spacing would increase the likelihood of splitting vehicles. These errors can easily be minimized by using inductive loops. However, it was observed that using loops generally causes an increase in the frequency of missed axles to such an extent as to offset the reduction in the errors due to combining/splitting of vehicles.

Failure by axle sensors to detect some axles of vehicles was generally a function of the sensitivity of the sensors. Piezoelectric sensors were found to be more prone to this problem than tubes because of their sensitivity to temperature and other environmental conditions. As a result, tubes were found to be more suitable for application in an axle spacing-based AVC system. The binning scheme used is also responsible for some mis-classification errors. This is due to overlaps in the distributions of axle spacings for different classes of vehicles which results in cross-classification of vehicles across adjacent vehicle classes. In summary, results of evaluations of the AVC systems conducted for this study, the following modifications are recommended to the current NDOT's AVC procedures:

- Tubes should be used for all AVC installations. They typically have a lower frequency of missed axles/vehicles compared to piezoelectric sensors.
- The tubes should be installed about 6" away from the edge of the inside lane marking. This will minimize the potential for some stray vehicles from an adjacent lane to activate the sensors.
- The use of inductive loops is generally not advantageous, except for relatively congested facilities. It is therefore recommended that they be used only in urban facilities experiencing recurring congestion. If used, the loop should be placed in between the axle sensors such that it is within 6" of either sensor.

- It is recommended to specify a maximum axle spacing of 40 feet. This tends to minimize the potential for the system to combine/split vehicles, especially when a loop is not used.
- The modified binning scheme evaluated in this project should be used.

Results of this study have shown that the performance of an axle spacing-based AVC system is site specific, depending on the relative proportions of the different vehicle classes in a traffic stream. Further improvement in performance can best be achieved with a weight-based system to supplement the spacing-based system. A separate electronic unit was therefore designed for this purpose to detect and process vehicle weights. The new unit would process signals from piezoelectric axle sensors and would output vehicle weight measures for all vehicles of interest. This weight-based data would be combined with the axle spacing data for more accurate vehicle classification. This process is especially designed to improve classification accuracy for vehicle classes with 2, 3, and 4 axles, where most of the inaccuracies were observed to occur with the current AVC system.

The hardware and software design of the electronic unit is complete. The unit is designed to collect axle weights, spacing and speeds, for classification of the vehicles. It consists of a Motorola microprocessor that processes detected axle signals from piezoelectric sensors and stores the data in a memory chip in the unit. The data is stored by axles, with each record consisting of the axle number, time detected, height and width of the pulse detected, speed of the axle, and time spacing between axles. This data is to be downloaded onto a laptop computer for laboratory post-processing into vehicle classifications. Since the unit is capable of collecting vehicle speeds and both axle spacing and weight data, it can be used as a stand-alone unit or together with an existing counter.

The unit has been successfully tested in the laboratory. However, time and funds ran out before field tests and calibration of the unit and the binning schemes could be completed. The software programs for post-processing of the data have been written and are awaiting field data for calibration. It is recommended that these remaining activities be considered for completion in a future phase of the project or in-house by NDOT with the assistance of the UNLV Transportation Research Center.

Chapter 1

Introduction

Automatic vehicle classification (AVC) devices currently used by NDOT are designed to count the number of axles on an individual vehicle and to measure the axle spacings. The AVC system utilizes a built-in "binning" algorithm to process the axle data, to assign the vehicle to one of several classification categories or "bins", and to maintain counts of each classification bin. Embedded (permanent) or surface-mounted (portable) sensors are used to determine the axle-related data.

Vehicle classification data are used to calculate the percent trucks and the distribution of truck types in the traffic streams of individual highway and street sections in Nevada. Such data are needed by NDOT for a variety of purposes: to compute vehicle mile tables; to forecast equivalent axle loadings; and to distinguish commodities by vehicle type. The number of trucks and their distribution are important inputs for the structural design of pavements. Typically, forecasts of trucks and their distribution are used to compute a structural number, a valuable input to pavement thickness design and pavement rehabilitation. Gross errors in the estimation of the structural number lead to the waste of scarce resources.

However, data currently collected on axle number and spacing only tell part of the story. A group of vehicles with the same axle configuration may actually belong to several different classification categories if the weight of each vehicle were simultaneously considered. A problem of special concern in Nevada is that pickups and motorhomes towing trailers are being classified as two and three axle single unit trucks with trailers and vice versa. Additionally, these types of vehicles sometimes have axle configurations similar to three and four axle truck/semi trailer vehicle rigs. The overall impact is that a number of vehicles and vehicle combinations are being misclassified and the validity of the data is being compromised.

The AVC system must include gross vehicle weight as an additional input to the classification algorithm (i.e., binning scheme). Vehicle weight together with the number and spacing of axles will permit a more accurate vehicle classification system and subsequently, more useful planning and design information. A portable weight sensor coupled with a modified AVC system that is capable of recording weight-based axle sensor signals will provide the needed additional data.

There are a number of portable Weigh-In-Motion (WIM) systems on the market that could be used for this purpose. However, WIM systems are in general quite expensive and provide a level of accuracy not required for typical AVC applications. For AVC applications, the weight data is required only to supplement axle spacing data in order to improve the accuracy of vehicle classifications. Hence, it is preferable to design a low-cost weight-based AVC unit to use with one of several relatively inexpensive weight sensors available on the market.

Objective of Study

The main objectives of this research project are to review and evaluate NDOT's current AVC operating procedures, and to design and recommend a modified AVC system for improved performance. The system should be inexpensive, readily adaptable to existing AVC systems, and provide the accuracy of classification information required for the purposes of NDOT. To accomplish this, the following specific tasks were identified:

1. To document and evaluate NDOT's current AVC operating procedures.
2. To identify alternative operating procedures designed to improve performance.
3. To review available weight sensors and identify those with potential application to AVC systems.
4. To design an AVC system with weight sensors coupled with a modified algorithm providing classification by both axle configuration and weight.
5. To conduct field tests to evaluate the designed system(s).

6. Overall evaluation of the system(s) and preparation of recommendations.

The primary benefit of this project will be a revised and improved methodology for the collection of data important to the planning and design functions of NDOT. Specifically, the modified system will yield more accurate data on truck percentages and the distribution of vehicle classifications within the traffic streams of roadway sections throughout Nevada. These data combined with temporal trend information will provide better estimates of pavement design life in terms of both ESAL and chronological age. Application of the revisions recommended through this project should result in significant savings to NDOT in pavement construction and rehabilitation costs. Additionally, more accurate data related to vehicle classification should be of benefit to the planning, design, and economic analysis activities of NDOT.

Chapter 2

Evaluation of NDOT's Existing AVC Systems and Operating Procedures

NDOT currently uses two types of AVC systems, the portable system and the permanent system. The permanent system consists of piezoelectric Type II axle sensors (currently being replaced by the more accurate Type I sensors), while the portable system consists of a pair of road tubes. Both systems classify vehicles based on the number and spacing of axles. In this task, operating procedures for the current systems are documented and evaluated. Alternative procedures for improvement of performance are identified and evaluated in terms of accuracy and reliability. The evaluation is based on relevant ASTM (American Society for Testing and Materials) standards and the level of accuracy required for various NDOT purposes including pavement design, highway cost allocation, and maintenance planning. The AVC systems operated by NDOT are described below:

PORTABLE AVC:

- System components: The standard configuration for NDOT's portable AVC system consists of a pair of pneumatic tubes as axle sensors connected to the Diamond 2001 vehicle classifier. Inductive loops may also be connected in an integrated arrangement with the tubes, as described in the vehicle classifier field unit manual[1].
- Installation procedure: The procedure is described in an NDOT document included in the appendix to this report and in the recording unit's field unit manual. Some of the key considerations include:
  - The site selected for installation of the AVC unit should have appropriate physical characteristics, such as the roadway should be free from wear groves, there should be a sign or guardrail for chaining and locking the recording unit

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[1] Diamond Traffic Tally 2001, Field Unit Manual

- Two 1/4" pneumatic tubes of the same length (between 20 and 60 feet long) should be firmly and securely attached to the pavement. Shorter lengths are generally more accurate. The tubes should be placed perpendicular to the direction of flow, 5 to 25 feet apart. NDOT uses 40 foot-long tubes placed 12 feet apart.
- Other sensor configurations include installing an inductive loop between the two tubes, or installing two inductive loops on either side of a single tube.

- Calibration procedure: Apart from the tube specifications, no calibration procedure of any other parameters is described.
- Testing procedure: Once the recording unit has been connected to the sensors, manual observation of the traffic is made for a few minutes before leaving the site. Usually that would involve observing one or more trucks with several axles to ensure that the system obtains correct axle counts and vehicle classifications for known vehicles.

PERMANENT AVC:

- System components: The permanent AVC system consists of permanent piezoelectric Type II sensors (In future, the more accurate Type I sensors typically used for WIM systems will be used). As with the portable system, an inductive loop my also be placed between the pair of the piezoelectric sensors.
- Installation procedure: A detailed description of the installation procedure was provided by NDOT (see appendix). The piezoelectric sensors consist of two 6 ft long strips that are embedded half-way into the pavement perpendicular to direction of flow, 14 feet apart with a 6'x6' loop in between. During operation the loop may or may not be used.
- Calibration procedure: The Diamond 2001 has a procedure for manual adjustment of the sensitivity of the sensors. This helps to minimize the potential errors in axle detection.

- Testing procedure: As with the portable system, after the recording unit has been connected to the sensors, manual observation of the traffic is made for a few minutes to ensure correct axle count and vehicle classification by the system. If necessary the sensitivity of the sensors may be adjusted, as described in the calibration procedure.

Evaluation of the Performance of the AVC Systems

This task was accomplished by collecting raw vehicle data using the portable and permanent AVC systems, at the same site, and evaluating their performance in comparison to manual classification. The manual data was obtained by video recording the traffic at the site and performing the manual classification of the data later in the laboratory. Classification was done based on the binning scheme used by NDOT (See Appendix).

The location selected for the study was on the I-15 Interstate freeway about 17 miles south of Las Vegas, at Sloan (milepost 17). The site has permanent piezoelectric Type I sensors and a Diamond 2001 traffic counter already installed. The sensors are placed 14' apart with a 6'x6' inductive loop in the middle. A portable unit, consisting of pneumatic tubes and an inductive loop, was also installed within a few feet (about 40 feet) downstream of the permanent unit. The tubes were installed downstream so that they cannot affect operation of the piezoelectric sensors. They were placed perpendicular to the direction of flow, 12 feet apart, and about a foot away from the inside edge of the lane (in order to avoid possible detection of inside lane vehicles traveling very close to the edge of the lane). The tubes were securely fixed to the pavement.

One and a half to two hours of traffic classification data was collected from both units at the same time. The data was collected in raw format with bin classification, i.e., the information for each vehicle included the number and spacing of axles, speed and classification of the vehicle.

Discussion of Results

The performance of the two AVC systems is summarized below. Potential reasons for the errors are discussed, and recommendations are made on strategies for improved performance of the systems. Seven types of errors were observed, as described below:

1. The system completely fails to detect a vehicle, i.e., none of the sensors is able to detect any of the axles of the vehicle.
2. Discrepancy between sensors: when one sensor detects more axles than the other sensor for the same vehicle.
3. Detecting fewer axles than what are actually on a vehicle.
4. Detecting more axles than what are actually on a vehicle.
5. Combining closely spaced successive vehicles into one.
6. Splitting a vehicle into two or more vehicles whenever axle spacing exceeds the maximum specified.
7. A vehicle is wrongly classified even though the correct number of axles has been detected. This is a result of the deficiency of the binning algorithm.

Errors (1) to (4) are generally due to sensor characteristics. If the sensor is not sensitive enough, some axles passing over the sensor may not be detected. This is more likely to affect light vehicles, typically, passenger cars. On the other hand, if the sensors are too sensitive, false activation of the sensors may occur even when there is no axle passing over them. For the piezoelectric sensors, the sensitivity of the sensor can be adjusted to minimize these errors. However, the variability of the sensitivity of these sensors due to temperature changes make it difficult to maintain the sensitivity over time of day. For the portable system, consisting of road tubes, the sensitivity is generally affected by the length of the tubes. Another potential source of these errors, especially errors (2) and (3) is from vehicles changing lanes within the sensor location. This results in only some of the axles being detected.

Errors (5) and (6) are due to the specification of the maximum axle spacing. This is one of the parameters that is input by the user such that whenever axle spacing exceeds the maximum specified, the classifier should consider the axles to be of separate vehicles. If the maximum specified axle spacing is too short, vehicles with wider axle spacing may be split into two or more shorter vehicles. On the other hand, if the maximum axle specification is too large, closely spaced vehicles may be combined into one vehicle. Therefore, selection of the appropriate maximum axle spacing is very critical. Use of an inductive loop between the axle sensors may help reduce the potential occurrence of these errors.

The type (7) error is due to the defiecincy of the "binning" scheme used. The errors are normally caused by overlapping of the distribution of axle configurations between different vehicle classes (i.e., overlapping vehicle class boundaries). Also, "abnormal" vehicles, such as pick-ups with trailers or towing other vehicles may be misclassified into truck classes. This error may also be a result of wrong calculation of axle spacing by the counter, which, in this study, was observed to occur (very rarely, though) together with erroneous calculation of vehicle speeds.

Discussion of Results for the Portable System:

Table 1 below shows the performance results of the portable system, with two tubes placed 10 feet apart and a maximum axle spacing of 35 feet specified. It is observed from the table that the road tubes had an excellent sensitivity, having missed axles of only 2 of the 528 vehicles that were observed. The major errors were in splitting long vehicles, and errors due to the binning algorithm. Seven vehicles, all trucks, were split into shorter vehicles, representing 1.3% of all vehicles and 6.4% of the heavy vehicles. Error due to the binning algorithm (type 7) constituted 2.1% of all vehicles and 10% of heavy vehicles. The overall accuracy rate is 96.2%, well over the specified accuracy rate of 90%. However, since most of the errors are on heavy vehicles, which were about 20% of the total traffic, the accuracy rate among the heavy vehicles is just about 82%, which is below the desired 90% accuracy rate.

Table 1: Observed Errors for the Portable AVC

Type of Error	All vehicles		Heavy vehicles	
	No.	%-ge	No.	%-ge
1. Completely missing a vehicle				
2. Discrepancy between sensors	1	0.2%		
3. Detecting fewer number of axles	1	0.2%	1	1.0%
4. Detecting more axles for a vehicle				
5. Combining successive vehicles into one				
6. Splitting one vehicle into two or more vehicles	7	1.3%	7	6.4%
7. Correct # of axles, but wrong bin classification	11	2.1%	11	10.4%
Total Classification Errors*	19	3.6%	19	17.9%
Total Vehicles	528		106	

*Excludes missed vehicles (error types 1 and 2) since they are not classified by the system. The heavy vehicle category includes trucks, buses and recreational vehicles (RVs).

Table 2 shows the distribution of the errors for the different types of vehicles. The table shows, for example, that of the total of 60 observed 5-axle trucks (i.e., 3S2's, bin # 9), only 51 were correctly classified by the AVC system, for an accuracy rate of 85%. All the errors were due to the 7 vehicles that were split into 14 shorter vehicles, of which 2 were classified as passenger cars (bin #1), 1 as a 2-axle truck (2SD, bin #4), 6 as 3-axle trucks (O3S, bin #5), and 5 as other vehicles (bin #16). The 2 that were misclassified as single 4-axle trucks were a result of the classifier missing one of the axles. The last column of the table gives the accuracy of classification of each vehicle type. On the other hand, the bottom row gives the total error observed on each vehicle type by comparing the total number of vehicles manually observed to the total number reported by the system. This error takes into account compensated misclassifications between vehicle bins. For example, the 3S2's were under-estimated by 15%, while the single 4-axle trucks (bin #8) were over-estimated by 300%. It can be observed that bin #4, which consists of 2-axle trucks and RV's is the most misclassified, mostly due misclassification of the RVs.

Table 2: Performance of the Portable AVC System

AVC Bin => Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Mis	Split	Total	Accu-racy
1	421																1		422	99.8%
2																				
3																				
4	5	4		10				1											20	50.0%
5					4														4	100.0%
6																				
7	1						1												2	50.0%
8								1											1	100.0%
9	2			1	6			2	51							5		7	60	85.0%
10										3									3	100.0%
11																				
12												11							11	100.0%
13													2						2	100.0%
14																				
15															3				3	100.0%
16																				
Total AVC	429	4		11	10		1	4	51	3		11	2		3	5			534	
Total Manual	422	0		20	4		2	1	60	3		11	2		3	0	1	7	528	
Net Error	2%	####		-45%	150%		-50%	300%	-15%	0%		0%	0%		0%	####				

In summary, the potential for significant over-estimation of 2-axle buses (bin #2), 3-axle trucks (bin #5), single 4-axle trucks, and under-estimation of RV's/2SD's (bin #4) is quite apparent.

Discussion of Results for the Permanent System:

As previously presented, the permanent system consists of two piezoelectric sensors placed 14 ft apart, with a maximum axle spacing of 35 feet specified. The results are presented in Tables 3 and 4 below.

Table 3: Observed Errors for the Permanent AVC System

Type of Error	All vehicles		Heavy vehicles	
	No.	%-ge	No.	%-ge
1. Completely missing an entire vehicle	26	4.9%		
2. Discrepancy between sensors	38	7.2%	1	0.9%
3. Detecting fewer number of axles	4	0.8%	4	3.8%
4. Detecting more axles for a vehicle	2	0.4%	1	0.9%
5. Combining successive vehicles into one	1	0.2%	1	0.9%
6. Splitting one vehicle into two or more vehicles	5	0.9%	5	4.7%
7. Correct # of axles, but wrong bin classification	14	2.7%	13	12.3%
Total Classification Errors	**26**	**4.9%**	**24**	**22.6%**
Total Vehicles	**528**		**106**	

The main problem with the piezoelectric sensor system is the sensitivity of the sensors. The sensors failed to detect several axles for passenger cars. Although the sensitivity of the sensor can be adjusted, it tends to drift over time, mainly due to temperature changes. It needs frequent monitoring to ensure that it remains within the desired range throughout the period of data collection. This is difficult to achieve, making the use of the piezoelectric sensors potentially more error prone compared to the tubes, unless a suitable automated system for sensitivity correction can be devised. Preliminary research has shown that there are vendors who claim to have such devices available for use.

Table 4: Performance of the Permanent AVC System

AVC Bin =>	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Vehicles		Total	Accu-racy
Manual Bin																	Missed	Split		
1	356			1	1											1	64	1	422	84.4%
2																				
3																				
4	5	4		8				2									1		20	40.0%
5					4														4	100.0%
6																				
7	1						1												2	50.0%
8								1											1	100.0%
9	4			1	3				49		1	1				6		5	60	81.7%
10										2					1				3	66.7%
11																				
12								1				8					2		11	72.7%
13													2						2	100.0%
14																				
15															3				3	100.0%
16																				
Total AVC	366	4		10	8		1	4	49	2	1	9	2		4	7			467	
Total Manual	422	0		20	4		2	1	60	3	0	11	2		3	0			528	
Net Error	-13%	####		-50%	100%		-50%	300%	-18%	-33%	####	-18%	0%		33%	####				

Another problem that was observed with the piezoelectric sensor system is false computation of speeds, and hence vehicle spacing. Of the 528 vehicles observed, 7 were found to have recorded speeds much higher of lower than measured by the portable system. It is not clear whether the source of this problem are the sensors or the classifier unit. The manufacturer of the counter is aware of this problem but is not certain what causes it.

In general, the portable system performed better than the piezoelectric sensor based system. For both systems, vehicles that had the most misclassifications were RVs, which tended to be misclassified mostly as either passenger vehicles (bin #1), 2-axle buses (bin #2), or as single 4-axle trucks (bin #8). Hence, RVs were significantly underestimated, resulting over-estimation of 2-axle buses and the single 4-axle trucks. The most common type trucks, the 3S2's (i.e., 5-axle trucks), was significantly under-estimated because they were the most affected by splitting of vehicles by the classifiers.

Chapter 3

Identification of Alternative Procedures to Improve Performance.

From the results presented in the previous chapter, three key parameters were identified as having potential for improving the performance of the AVC systems. These are, the specified maximum axle spacing, the use of inductive loop between the sensors, and the binning algorithm. Inductive loops are designed to detect presence of a vehicle over the sensors, and hence avoid splitting or combining of vehicles. Due to the problems with the piezoelectric sensors, as discussed in Chapter 2, only tube sensors were used for all subsequent tasks of this project.

Different sets of vehicle classification data were collected for different parameter values and sensor configuration. Vehicle classification data was collected for different specified maximum axle spacings (35, 40 and 45 feet), with and without the use of inductive loops. The data was evaluated and parameter values that result in improved performance were identified. A modified binning scheme was also developed and evaluated. The performance of the modified AVC was evaluated at different sites (interstate freeway, 2-lane rural, and urban highway) to compare performance of the system at sites with different traffic patterns. Recommendations for suitable installation, calibration and testing procedures for the current AVC system are then recommended.

The following alternative installation configurations were initially evaluated for the portable system:

a) 35' maximum axle spacing, without loop (base case)
b) 35' maximum axle spacing, with loop
c) 45' maximum axle spacing, without loop
d) 45' maximum axle spacing, with loop

The following series of tables summarize the results obtained. Table 5 below presents results from the portable system, with the maximum axle spacing set at 35 feet, with and without an inductive loop between the sensors.

Table 5: Portable AVC at Maximum Axle Spacing of 35 feet

Type of Error	Without Loop				With Loop			
	All vehicles		Heavy vehicles		All vehicles		Heavy vehicles	
	No.	%-ge	No.	%-ge	No.	%-ge	No.	%-ge
1. Totally missing a vehicle								
2. Discrepancy between sensors	1	0.2%			13	2.1%		
3. Detecting fewer axles	1	0.2%	1	1.0%	8	1.3%	8	5.5%
4. Detecting more axles								
5. Combining vehicles					2	0.3%	2	1.4%
6. Splitting of vehicles	7	1.3%	7	6.4%				
7. Wrong bin classification	11	2.1%	11	10.4%	17	2.7%	15	10.3%
Total Classification Errors	19	3.6%	19	17.9%	27	4.3%	25	17.2%
Total Vehicles	528		106		630		145	

It is observed from the results that introduction of the loop eliminates all the errors due to splitting of vehicles with wide axle spacing (error type 6). However, as a result of the loop, there is a significant increase in the number of missed axles (both error types 2 and 3). There are two possible explanations for why the loop introduces additional errors. First, there is the potential for the loop to get stuck in the on position (hence detect non-existent vehicles) or off position (thus missing vehicles). This will conflict with detection by the axle sensors, and hence result in an error being reported by the system. The second possible cause of these errors is due to the placement of the loop relative to the axle sensors (Figure 1). It can be seen from this figure that some vehicles may leave the sphere of influence of the loops before the last axle activates the downstream sensor, resulting in an erroneous detection. As a result of these problems, the overall effect of the loop on performance of the classifier is negligible.

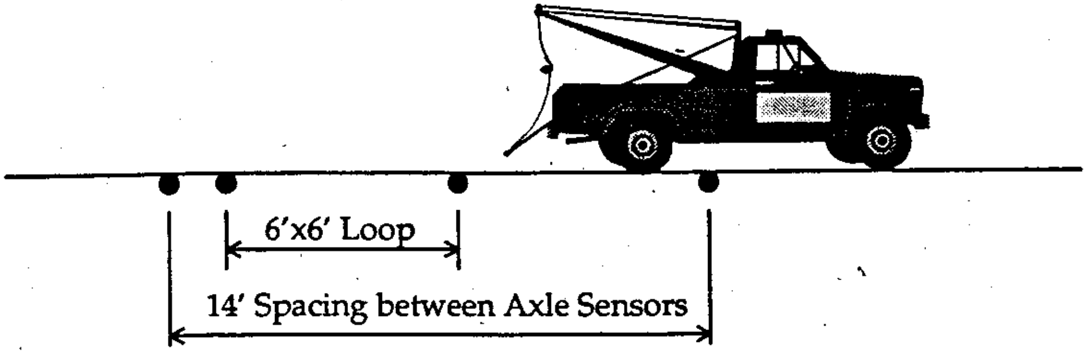

Figure 1: Axle Sensor and Loop Configuration

Similar observations are made from the classification results with the maximum axle spacing set at 45 feet (Table 6). As expected, increasing the maximum axle spacing resulted in complete elimination splitting of vehicles (error type 6). However, this was achieved at the expense of increasing the number of closely spaced vehicles that were combined into one vehicle (error type 5). On three occasions, two passengers cars were combined into one vehicle, and on one occasion three passenger cars were combined into one. In all these cases, the vehicles were subsequently classified as trucks, thus resulting in overestimation of the number of heavy vehicles. As in the previous case, introduction of the loop was able to eliminate this error, but at the expense of increased missed axle error. In fact the performance of the system with the use of the loops was significantly worse for heavy vehicles.

Table 6: Portable AVC at Maximum Axle Spacing of 45 feet

Type of Error	Without Loop				With Loop			
	All vehicles		Heavy vehicles		All vehicles		Heavy vehicles	
	No.	%-ge	No.	%-ge	No.	%-ge	No.	%-ge
1. Totally missing a vehicle					1	0.2%		
2. Discrepancy between sensors	3	0.4%			9	1.5%	2	2.4%
3. Detecting fewer axles	5	0.6%	4	3.9%	17	2.9%	17	20.2%
4. Detecting more axles								
5. Combining vehicles	9	1.1%						
6. Splitting of vehicles								
7. Wrong bin classification	23	2.8%	18	17.6%	12	2.0%	11	13.1%
Total Classification Errors	**34**	**4.1%**	**22**	**21.6%**	**29**	**4.9%**	**28**	**33.3%**
Total Vehicles	**821**		**102**		**591**		**84**	

The results presented above indicate that better system performance can be achieved if the maximum axle spacing is set between 35 and 45 feet. Table 7 presents results for a 40 feet maximum axle specification.. The proportion of combined vehicles is reduced from 1.1% of all vehicles to 0.7%. No vehicles were split.

Table 7: Portable AVC at Maximum Axle Spacing of 40 feet

Type of Error	Without Loop			
	All vehicles		Heavy vehicles	
	No.	%-ge	No.	%-ge
1. Totally missing a vehicle				
2. Discrepancy between sensors	4	0.5%	1	0.9%
3. Detecting fewer axles	5	0.6%	4	3.8%
4. Detecting more axles				
5. Combining vehicles	6	0.7%		
6. Splitting of vehicles				
7. Wrong bin classification	23	2.8%	19	17.9%
Total Classification Errors	34	4.1%	23	21.7%
Total Vehicles	832		106	

Development of a modified binning algorithm

In addition to the sensor configuration, a modified binning scheme was developed to reduce the number of type 7 errors. From the data collected for this project at the I-15 AVC site in March 1995, it was observed that most of the errors in misclassifications occurred between the following types of vehicles:

1) Passenger cars vs. 2 axle trucks (2SDs) and Recreation Vehicles (RVs)
2) 3 axle buses vs. 3 axle trucks
3) Passenger cars and RVs with trailers vs. 3 axle and 4 axle trucks.

It was further observed that RVs contributed a big proportion of all the misclassification errors. The most frequent truck on the road, the 3S2s were generally classified accurately, except in situations where the sensors miss detecting some of the axles of a truck, or when the sensors split a vehicle into two. For example, a 3S2 trucks may be classified as a single 4 axle truck because of a missed axle. Development of the modified binning algorithm consisted of the following steps:

1. Summarizing observed distributions of axle spacings for different vehicles types.
2. Identifying areas of overlap between various vehicle bin types.
3. Modifying the current binning algorithm to minimize the classification errors by selecting bin boundaries that result in "balanced" cross mis-classifications between adjacent bins (compensating errors).

Table 8 shows a summary of the distribution of axle spacings of vehicles observed in the field for this project. This data is compared to the current binning scheme used for vehicle classification. It can be observed from the data that there are big overlaps in axle spacings of different types of vehicles, especially between RVs and other types of vehicles, including passenger cars, two axle busses, and single 4-axle trucks. Also, passenger cars with trailers have overlaps with 2SDs and single 3-

axle trucks. This obviously results in cross mis-classification of vehicles in adjacent of vehicle classes. Table 9 gives the definitions of each vehicle type.

Table 10 shows the modified binning scheme. Bold italic entries in the table indicate the changes made. Since misclassifications are inevitable due to overlapping boundaries, the modified scheme is designed to result in "balanced" cross misclassification between adjacent vehicle classes, so that the errors tend to cancel each other. For example, if x_{ij} is the number of class i vehicles misclassified as class j, then the net error between the two classes i and j is $x_{ij} - x_{ji}$. If $x_{ij} = x_{ji}$, the net error would be zero. The modified binning algorithm is therefore designed to take advantage of this "compensating" effect of the errors and minimize the difference $\{x_{ij} - x_{ji}\}$ for each pair of classes i and j. The optimal decision boundary between any two classes will depend on the relative proportions of the two classes of vehicles. The performance of the algorithm will therefore be a function of the traffic mix.

A computer program was written in "C" to implement the modified binning scheme. Raw vehicle data was collected in the field and used in the lab to develop, test and evaluate the modified binning scheme. To evaluate the robustness of this binning scheme for different traffic patterns, vehicle classification data was collected from three different locations with different traffic characteristics, namely, a freeway, a 2-lane rural highway, and a 2-lane divided urban highway. The urban location would typically be characterized by effects of congestion, such as wide variations in vehicle speeds, and closely spaced vehicles. Two definitions of accuracy are used in evaluating the results obtained:

- Basic accuracy - the proportion of vehicles in each class that are correctly classified. This information is provided in the last column of the tables.
- Compensating accuracy - this is the accuracy measure that takes into account the compensating effect of vehicles cross-classified between two classes with overlapping boundaries, as described above.

Table 8: Observed Axle Spacing Distribution Vs. The Binning Scheme

Def	Bin No.	No. of Axles	Axle Spacings										Vehicles observed
			Binning Scheme Specifications					Observed Axle Spacings					
1	1	2	5.0-13.9					5.1-14.7					8172
2	2	2	19.4-29.9					20.2-25.6					13
3	4	2	14.0-19.3					10.3-23.0					330
4	1	3	5.0-13.9	7.0-17.9				7.5-13.9	8.8-22.2				67
5	3	3	21.0-29.9	3.1- 6.9				18.2-27.9	4.0 - 4.4				18
6	4	3	14.0-19.3	7.0-17.9				11.4-16.0	12.8-24.1				9
7	5	3	8.6-20.9	3.2- 6.9				9.7-20.2	4.1 - 4.7				31
8	7	3	8.0-22.0	18.0-41.9				10.0-13.9	17.7-28.8				32
9	1	4	5.0-13.9	7.0-30.0	2.0- 3.1			8.4-14.1	10.5-27.0	2.4 - 3.5			85
10	1	4	5.0-13.9	7.0-17.5	5.0-12.4			7.0-13.0	12.1-44.8	6.4-11.1			21
11	4	4	14.0-19.3	7.0-17.5	7.0-12.9			10.2-22.9	12.2-19.9	6.2-11.4			18
12	4	4	14.0-19.3	*	2.0- 3.1			10.5-17.2	12.6-34.6	2.5 - 3.5			32
13	5	4	8.6-29.7	3.2- 6.9	11.7-14.6			18.1	4.5	11.2			1
14	6	4	8.6-29.7	3.2- 6.9	3.0-11.6								0
15	6	4	3.2 - 6.9	7.0-30.0	3.2- 6.9								0
16	8	4	*	*	*			11.7-14.0	20.6-33.5	3.8 - 4.2			15
17	1	5	5.0-13.9	7.0-30.0	2.0- 3.1	2.0- 3.1		8.3-13.9	6.3-26.6	2.6 - 4.7	2.7 - 4.7		5
18	9	5	7.1-22.0	3.2- 6.9	14.7-54.7	3.2-11.4		8.8-23.3	3.4 - 4.9	19.1-42.4	3.8-10.4		344
19	10	5	7.1-22.0	3.2- 6.9	7.1-24.0	11.5-34.9		15.5-18.6	4.2 - 4.4	14.9-20.7	13.5-24.0		15
20	12	5	*	*	*	*		9.7-19.1	14.1-31.4	4.2-15.6	14.0-23.0		50
21	11	6	7.1-21.9	3.2- 6.9	*	3.2- 6.9	*	11.2-18.5	4.2- 4.7	17.4-39.1	4.0- 4.5	4.0- 4.6	7
22	11	6	7.1-21.9	3.2- 6.9	*	*	3.2- 6.9						0
23	11	6	7.1-21.9	*	2.5- 6.9	2.5- 6.9	2.5- 6.9						0
24	13	6	*	*	*		*	11.6-19.4	4.2-29.1	4.0-19.8	9.2-15.1	20.2-22.8	6
25	14	7	* * * * * *										11
26	15	8-13	* * * * * * * *										9
	16	ALL OTHER VEHICLES											

Table 9: Vehicle Types in NDOT's AVC Binning Scheme

BIN 1	PASSENGER VEHICLES
BIN 2	2 AXLE BUSSES
BIN 3	3 AXLE BUSSES
BIN 4	2SD'S and MOTORHOMES
BIN 5	O3S'S
BIN 6	O4S'S +
BIN 7	SINGLE 3 AXLE
BIN 8	SINGLE 4 AXLE
BIN 9	3S2'S
BIN 10	SINGLE 5 AXLE
BIN 11	SINGLE 6 AXLE
BIN 12	MULTIPLE 5 AXLE
BIN 13	MULTIPLE 6 AXLE
BIN 14	MULTIPLE 7 AXLE
BIN 15	MULTIPLE 8 AXLE +
BIN 16	ALL OTHER VEHICLES

Table 10: Current Vs. Modified Binning Scheme

Def	Bin No.	No of Axles	Axle Spacings									
			Current Binning Scheme					Modified Binning Scheme				
1	1	2	5.0-13.9					*5.0-13.3*				
2	2	2	19.4-29.9					*21.6-29.9*				
3	4	2	14.0-19.3					*13.4-21.5*				
4	1	3	5.0-13.9	7.0-17.9				*5.0-13.3*	*7.0-19.9*			
5	3	3	21.0-29.9	3.1- 6.9				*19.0-29.9*	3.1- 6.9			
6	4	3	14.0-19.3	7.0-17.9				*13.4-21.5*	*7.0-19.9*			
7	5	3	8.6-20.9	3.2- 6.9				*8.6-18.9*	3.2- 6.9			
8	7	3	8.0-22.0	18.0-41.9				8.0-22.0	*20.0-41.9*			
9	1	4	5.0-13.9	7.0-30.0	2.0- 3.1			*5.0-13.3*	7.0-30.0	2.0- 3.1		
10	1	4	5.0-13.9	7.0-17.5	5.0-12.4			*5.0-13.3*	7.0-17.5	5.0-12.4		
11	4	4	14.0-19.3	7.0-17.5	7.0-12.9			*13.4-21.5*	7.0-17.5	7.0-12.9		
12	4	4	14.0-19.3	*	2.0- 3.1			*13.4-21.5*	*	*2.0-13.9*		
13	5	4	8.6-29.7	3.2- 6.9	11.7-14.6			8.6-29.7	3.2- 6.9	11.7-14.6		
14	6	4	8.6-29.7	3.2- 6.9	3.0-11.6			8.6-29.7	3.2- 6.9	3.0-11.6		
15	6	4	3.2 - 6.9	7.0-30.0	3.2- 6.9			3.2 - 6.9	7.0-30.0	3.2- 6.9		
16	8	4	*	*	*			*	*	*2.0-14.6*		
17	1	5	5.0-13.9	7.0-30.0	2.0- 3.1	2.0- 3.1		*5.0-13.3*	7.0-30.0	2.0- 3.1	2.0- 3.1	
	4	5						*13.4-21.5*	*33.0-45.0*	*2.0- 3.1*	*2.0- 3.1*	
18	9	5	7.1-22.0	3.2- 6.9	14.7-54.7	3.2-11.4		7.1-22.0	3.2- 6.9	14.7-54.7	3.2-11.4	
19	10	5	7.1-22.0	3.2- 6.9	7.1-24.0	11.5-34.9		7.1-22.0	3.2- 6.9	7.1-24.0	11.5-34.9	
20	12	5	*	*	*	*		*	*	*	*	
21	11	6	7.1-21.9	3.2- 6.9	*	3.2- 6.9	*	7.1-21.9	3.2- 6.9	*	3.2- 6.9	*
22	11	6	7.1-21.9	3.2- 6.9	*	*	3.2- 6.9	7.1-21.9	3.2- 6.9	*	*	3.2- 6.9
23	11	6	7.1-21.9	*	2.5- 6.9	2.5- 6.9	2.5- 6.9	7.1-21.9	*	2.5- 6.9	2.5- 6.9	2.5- 6.9
24	13	6	*	*	*	*	*	*	*	*	*	*
25	14	7	* * * * * *					* * * * * *				
26	15	8-13	* * * * * * * *					* * * * * * * *				
	16	ALL OTHER VEHICLES						ALL OTHER VEHICLES				

Discussion of Results

INTERSTATE (I-15):

The traffic flow on this segment of the interstate was about 500 vph/lane, with the proportion of heavy vehicles (including RVs, trucks and busses) in the traffic stream varied from 15% to over 20% depending on time of day. There were generally more trucks in the early morning hours than mid- and late afternoon. A portable AVC system consisting of two tubes 10 feet apart without a loop, and a maximum axle spacing of 40 feet specified.

Table 11 below summarizes the performance of the AVC system. Taking into account the compensating effect of the errors, the system has an overall accuracy rate of 98.3%. For heavy vehicles, the corresponding accuracy rate was 91.8%. The most frequent trucks, the 3S2s, were under-estimated by about 10%, most of the errors a result of some missed axles. Vehicle type 4 consisting of 2SDs and RVs was under-estimated by about 8%. These results are much better compared to the result obtained using the current binning scheme (Table 12).

RURAL 2-LANE (US95)

This site had a lower traffic flow rate of about 220 vph/lane. The proportion of heavy vehicles was also less, at about 12%. The proportion of 2-axle trucks and RVs was higher than for interstate site. A portable system was also installed at this site. However, a slightly modified sensor/loop configuration was used. The tube spacing was reduced to 7 feet and a 6'x6' loop was placed in between the tubes, leaving only a 6" gap between either tubes and the loop. This new configuration is designed to reduce the potential errors introduced by loops, as previously discussed.

Table 13 summarizes the results obtained. The performance of the system is not as good as for interstate site, with an overall accuracy rate of only about 83.9% for heavy vehicles. While there was no problem identifying the 3S2s, the type 4 vehicles (mostly RVs at this site) were grossly under-estimated by 30%. This is essentially due to the higher proportion of these types of vehicles, relative to passenger cars, at the site. There were also several 3-axle RVs with trailers that were misclassified as 5-axle trucks (bin 12). The binning scheme could be modified to improve the compensating effect of the mis-classifications, but this would affect the performance of the system at other sites. Some of the special problem with the 2-lane site was errors introduced by overtaking vehicles (resulting in vehicles traveling the opposite direction on the sensors). Changing lanes at the site was also occasionally observed.

URBAN SITE:

Traffic flow on the urban site was about 360 vph/lane, but with shorter headways (distance headways) and reduced traffic speeds (about 45 mph). The shorter headways generally have the potential effect of increasing the number of combining closely spaced vehicles. The proportion of heavy vehicles was much less than the other two sites, only about 6.4% - 7.8%, with 2-axle trucks and RVs being major proportions of heavy vehicles. Two cases were tested, with and without a loop in order to observe the effect of shorter headways.

Case I

A portable system was used without a loop. The results for this case are given in Table 14. Because of the shorter headways between successive vehicles, there were 11 pairs of passenger car (about 0.7%) that were combined into 11 single 4-axle (bin 8) trucks, resulting in significant over-estimation of the single 4-axle trucks (15 compared to the 5 that were actually observed). Also, because of the lower proportion of 2SD trucks and RVs relative to passenger cars, there is a significant imbalance in cross-classification between passenger cars and RVs/2SDs, resulting in a 17% overestimation of the RVs/2SDs (compare this to the 30% under-estimation at the 2-lane rural highway site). There were several instances of vehicles changing lanes at the site, contributing to about 1.1% (35 of 2922 vehicles) in missed vehicles.

Case II

In this case, the portable system was used with a 6'x6' ft loop in between the tubes placed 7 feet apart. Table 15 gives the summary results. As a result of the loop, no combined vehicles were observed. However, the loop increased the number of missed vehicles from 1.1% for the non-loop case to about 2.4% (45 missed vehicles out of 1843). Some of these errors were due to vehicles in adjacent lanes activating the loop.

Summary of Results

Based on the results obtained from the field tests, the following observations were made:

- The overall accuracy for all vehicles is always greater than 90%;
- However, accuracy for trucks was generally site specific, depending of the relative proportions of the different vehicle types in the traffic stream. The performance of the system on the trucks with 5 or more axles was generally very good. The most affected vehicles include the 2-, 3-, and 4-axle trucks, RVs, and passenger cars. Buses (2 and 3-axle) are also affected, but they were generally few on the sites observed to have any significant impact. Using a different binning scheme for different sites may improve performance on individual sites. However, implementation of such a scheme may cause difficulties to field personnel.

Table 11: Performance of AVC System on the Freeway

AVC Bin => Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Accu- racy
1	1272			9	1		5	2				4				2	1295	98.2%
2		1															1	100.0%
3			8	1	1											1	11	72.7%
4	17	1		39				1				1					59	66.1%
5					8												8	100.0%
6				1													1	0.0%
7	1			2			3										6	50.0%
8				1				5									6	83.3%
9	8		1		1			1	166		1	2	4				184	90.2%
10										4					1		5	80.0%
11											1						1	100.0%
12				1								36				1	38	94.7%
13												1	3				4	75.0%
14														2			2	100.0%
15					1										4		5	80.0%
16																	0	
Total AVC	1298	2	9	54	12	0	8	9	166	4	2	44	7	2	5	4	1626	
Total Manual	1295	1	11	59	8	1	6	6	184	5	1	38	4	2	5	0	1626	
Net Error	0%	100%	-18%	-8%	50%	-100%	33%	50%	-10%	-20%	100%	16%	75%	0%	0%	#####		

All Vehicles:		
Actual Accuracy	=	95.4%
Compensating Accuracy	=	98.3%
Proportion Heavy Vehicles	=	20.4%

Heavy Vehicles:		
Actual Accuracy	=	84.6%
Compensating Accuracy	=	91.8%

Table 12: Performance of AVC System on the Freeway with the Current Binning Algorithm

AVC Bin => Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Accuracy
1	1265			8	1		13	2				4				2	1295	97.7%
2		1															1	100.0%
3			7	1	2											1	11	63.6%
4	21	4		27			2	4				1					59	45.8%
5					8												8	100.0%
6						1											1	100.0%
7	1						4	1									6	66.7%
8								6									6	100.0%
9	8				2			1	166		1	2	4				184	90.2%
10										4					1		5	80.0%
11											1						1	100.0%
12								1				36				1	38	94.7%
13												1	3				4	75.0%
14														2			2	100.0%
15					1										4		5	80.0%
16																	0	
Total AVC	1295	5	7	36	14	1	19	15	166	4	2	44	7	2	5	4	1626	
Total Manual	1295	1	11	59	8	1	6	6	184	5	1	38	4	2	5	0	1626	
Net Error	0%	400%	-36%	-39%	75%	0%	217%	150%	-10%	-20%	100%	16%	75%	0%	0%	####		

All Vehicles:

Actual Accuracy	=	94.4%
Compensating Accuracy	=	97.2%
Proportion Heavy Vehicles	=	20.4%

Heavy Vehicles:

Actual Accuracy	=	81.6%
Compensating Accuracy	=	86.1%

Table 13: Performance of AVC System on a 2-Lane Highway (US95)

AVC Bin => Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Accuracy
1	1558			11			1										1597	97.6%
2				1													1	0.0%
3			4														4	100.0%
4	31	1		60	1			3			1	8				1	107	56.1%
5			1		2												3	66.7%
6																	0	
7				3			12										15	80.0%
8								1									1	100.0%
9									66								66	100.0%
10										8							9	88.9%
11											5						5	100.0%
12												4					4	100.0%
13																	0	
14														2			2	100.0%
15															1		1	100.0%
16																	0	
Total AVC	1589	1	5	75	3		13	4	66	8	6	12		2	1	1	1786	
Total Manual	1597	1	4	107	3		15	1	66	9	5	4		2	1	0	1815	
Net Error	-1%	0%	25%	-30%	0%		-13%	300%	0%	-11%	20%	200%		0%	0%	####		

All Vehicles:

Actual Accuracy	=	94.9%
Compensating Accuracy	=	97.6%
Proportion Heavy Vehicles	=	12.0%

Heavy Vehicles:

Actual Accuracy	=	75.7%
Compensating Accuracy	=	83.9%

Table 14: Performance of AVC System on a 4-Lane Divided Urban Highway
(Case 1: No Loop)

AVC Bin => Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Accu-racy
1	2644			44				11				3	2				2738	96.6%
2		6		1													7	85.7%
3																	0	
4	26	1		82													109	75.2%
5			4		7				1								12	58.3%
6																	0	
7	1						8										9	88.9%
8				1				4									5	80.0%
9									19								19	100.0%
10										1							1	100.0%
11																	0	
12																	0	
13																	0	
14														5			5	100.0%
15															4		4	100.0%
16																	1	
Total AVC	2671	7	4	128	7		8	15	20	1		3	2	5	4	0	2875	
Total Manual	2738	7	0	109	12		9	5	19	1		0	0	5	4	1	2910	
Net Error	-2%	0%	####	17%	-42%		-11%	200%	5%	0%		####	####	0%	0%	-100%		

All Vehicles:

Actual Accuracy	=	95.5%
Compensating Accuracy	=	97.5%
Proportion Heavy Vehicles	=	5.9%

Heavy Vehicles:

Actual Accuracy	=	79.1%
Compensating Accuracy	=	95.9%

Table 15: Performance of AVC System on a 4-Lane Divided Urban Highway

(Case 2: With Loop)

AVC Bin => Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Accu- racy
1	1641	1		22			1					1					1704	96.3%
2		4		1													5	80.0%
3																	0	
4	20	4		51													78	65.4%
5			1	1	8												11	72.7%
6																	0	
7							2										2	100.0%
8								3								1	4	75.0%
9									23								25	92.0%
10																	0	
11											2						2	100.0%
12																	0	
13																	0	
14														3			3	100.0%
15															8		8	100.0%
16																	1	0.0%
Total AVC	1661	9	1	75	8		3	3	23		2	1		3	8	1	1798	
Total Manual	1704	5	0	78	11		2	4	25		2	0		3	8	1	1843	
Net Error	-3%	80%	####	-4%	-27%		50%	-25%	-8%		0%	####		0%	0%	0%		

All Vehicles:		
Actual Accuracy	-	94.7%
Compensating Accuracy	-	97.1%
Proportion Heavy Vehicles	-	7.5%

Heavy Vehicles:		
Actual Accuracy	-	74.8%
Compensating Accuracy	-	93.5%

- The other factors that affect the performance of the system include:
    - vehicle headways, the closer the vehicle spacing, the higher the likelihood of combining vehicles (although this can be eliminated by the use of loops). This is especially true for the urban environment.
    - average traffic speed. In this study the speeds were not low enough for any significant effect to be observed on the performance of the system.
    - other traffic flow characteristics, such as frequent occurrence of lane changing on urban highway, vehicles missed due to overtaking, and/or detection in the wrong direction for the 2-lane rural highway.
    - effect of the use of a loop. While the loop minimizes the potential for combining closely-spaced vehicles and/or splitting very long vehicles, it introduces other errors due to its inherent characteristics such as responding to vehicles passing in adjacent lanes, and occasionally not responding to passage of vehicles at all.
- Typically, about 1 to 4% of the vehicles are missed and therefore not classified by the system. These vehicles are either totally missed by the sensors, or have one sensor missing one or more of the axles. Passenger vehicles are generally the most affected, and proportion is typically higher when a loop is used. If these errors were eliminated, the performance of the system would improve significantly. To illustrate this point, Table 16 presents classification results for the freeway data (Table 11), but using only the vehicles that had all their axles correctly detected by the sensors. The result is an overall improvement of 4% in the accuracy of classification of the heavy vehicles. There is, therefore, also a need to improve the performance of the sensors.

Table 16: Performance of AVC System with the Modified Binning Algorithm
(only for vehicles detected with the correct number of axles)

AVC Bin -> Manual Bin	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Total	Accuracy
1	1251			8			1										1260	99.3%
2		1															1	100.0%
3			8		1												9	88.9%
4	15	1		39				1				1					57	68.4%
5					8												8	100.0%
6				1													1	0.0%
7	1			2			3										6	50.0%
8				1				5									6	83.3%
9									165			2					167	98.8%
10										4							4	100.0%
11											1						1	100.0%
12												36					36	100.0%
13												1	3				4	75.0%
14														2			2	100.0%
15															4		4	100.0%
16																	0	
Total AVC	1267	2	8	51	9	0	4	6	165	4	1	40	3	2	4		1566	
Total Manual	1260	1	9	57	8	1	6	6	167	4	1	36	4	2	4		1566	
Net Error	1%	100%	-11%	-11%	13%	-100%	-33%	0%	-1%	0%	0%	11%	-25%	0%	0%			

<u>All Vehicles:</u>

Actual Accuracy	=	97.7%
Compensating Accuracy	=	99.2%
Proportion Heavy Vehicles	=	19.5%

<u>Heavy Vehicles:</u>

Actual Accuracy	=	91.2%
Compensating Accuracy	=	95.8%

Chapter 4

Design of a Weight-based AVC Sensor System

Results from the previous chapters have shown that any further improvement in performance of the AVC system can best be achieved by introducing vehicle weight as an additional criteria for classifying vehicles. The objective of this task was therefore to design a low-cost electronic unit for axle weight detection. The weight data will be combined with axle spacing and configuration data to classify vehicles. Because this system is design only as a complement to axle spacing data for vehicle classification, the weight measurement need not have the level of accuracy that traditional weigh-in-motion system have. Hence, a cheaper system can be designed.

The design of the system involved three major tasks, namely, selection of a suitable axle sensor system, design of the electronic unit for weight detection, and design of the post processing procedure for vehicle classifications. Lab and field tests of the unit were to be conducted.

SELECTION OF SENSOR SYSTEM

Information was sought from several publications, vendors and manufacturers of AVC and weight sensor equipment. The objective of the task was to identify AVC and weight sensor systems for potential use in this project. Special attention was paid to WIM sensors such as piezoelectric, capacitive strip, and capacitive mat sensors.

A number of sensor systems were reviewed, including bridge systems (load cell or strain gauge), hydraulic load cells, bending plate weightpads, capacitive pad systems, piezoelectric cable systems (vibracoax), piezoelectric film, piezoelectric polyvinylidene fluoride (PVDF), capacitive strip system, infrared light systems, microwave systems and resistive sensor systems. Each system was reviewed based on its suitability as a portable system, costs, installation and calibration procedures, and effect of various environmental (such as pavement temperature and temperature variations) and other factors (such as vehicle dynamics) on performance of each system. The impact of temperature variations is critical for asphalt concrete pavement surfaces. This is especially important here in Southern Nevada due the temperature variations which are typically experienced throughout the year.

With NDOT's objective in mind, a review of these sensors was carried out. The piezoelectric sensor emerged as the preferred sensor, mainly because it more readily available in the market. Although it is known to have a lot of problems with regard to the consistency of the output signal with, it is the more known sensor. Other sensors considered were the capacitive strip sensors, the and resistive sensors. A summary of the evaluation of the various sensor systems is given in the appendix.

DESIGN OF THE ELECTRONIC UNIT

Based on the signals received from the sensors, this unit is designed to collect weight data, offer user controllable data collection parameters, support field supervision of the data collection process, display real time data collection activity to the user through the use of LED arrays, operate without a technician in attendance and be user friendly enough to operate with a minimum of training. This task involves merging the processor specific hardware and firmware operating system and peripheral control structure with analog pulse processing electronics to achieve the desired results. The unit was designed to perform the following functions:

1. Detect and record sensor activations by time and spacing.
2. Detect and measure the piezoelectric signal voltage from the sensors.
3. Store the data for later retrieval. This data will be downloaded for post-processing in the laboratory to produce vehicle classifications based on both axle spacing and vehicle weights.

One of the factors that make this a particularly challenging design is the instability of piezoelectric sensors. The sensitivity of the sensors tend to change with temperature, location of contact, and how long the sensor has been in use. The signal amplitude-to-weight calibration during post-processing has therefore been designed with flexibility, to allow the user to change the amplitude to weight calibrations in response to different sensor performances.

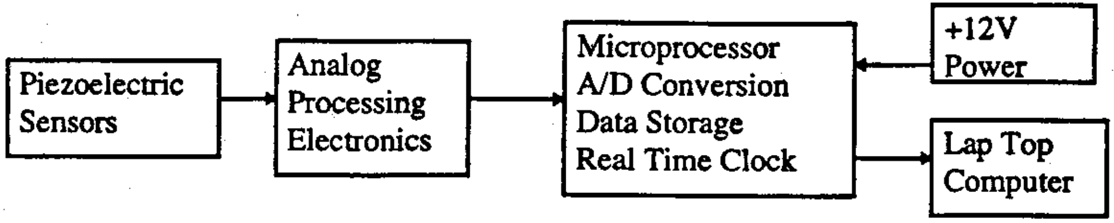

Figure 2: Block Diagram of the Basic Components of the Electronic Unit

The following steps were followed in accomplishing this design:

1. Selection of suitable micro-processor and identification of the supplier
2. Hardware and software design of the system.
3. Building the prototype unit.
4. Laboratory testing of the prototype unit, involving testing of the unit to ensure accurate circuit performance.
5. Debugging of the operating system using laboratory simulated pulse patterns, and making the necessary modifications before final programming of the microprocessor.
6. Field testing of the prototype: Testing the performance of the various aspects of the unit under field conditions, including, calibration of the axle weight measurements, interfacing with the lap-top computer, performance under different field conditions such as temperature variations, portable vs. permanent piezoelectric sensor installations, evaluating the accuracy of the unit, the sensitivity of the measurements (i.e., the minimum measurable weight difference), the consistency of the measurements (i.e., change in performance of the unit with temperature changes, etc.), and the suitability of the user interface,

7. Calibration of the axle weight-and-spacing-based binning scheme for optimal classification of vehicles, and development of a binning scheme with vehicle weight as an additional criteria for classification. Evaluation of the performance of the new binning scheme compared to the binning scheme which is based on axle spacing only.
8. Overall evaluation of the performance of the new weight-and-axle-spacing based AVC system.

The Electronic Hardware and PC Boards

The electronic circuitry is divided between two 5.5"x7" PC boards referred to by their prime functions as the "digital" and "analog" boards. The digital board contains the microprocessor with supporting logic and control chips, while the analog board contains two identical channels of analog amplifier circuits, comparators, non-resetable pulse generators and bus latches. The latches drive the five bar graph arrays displaying the amplitude/weight which has been measured by channel #2. A block diagram is shown below.

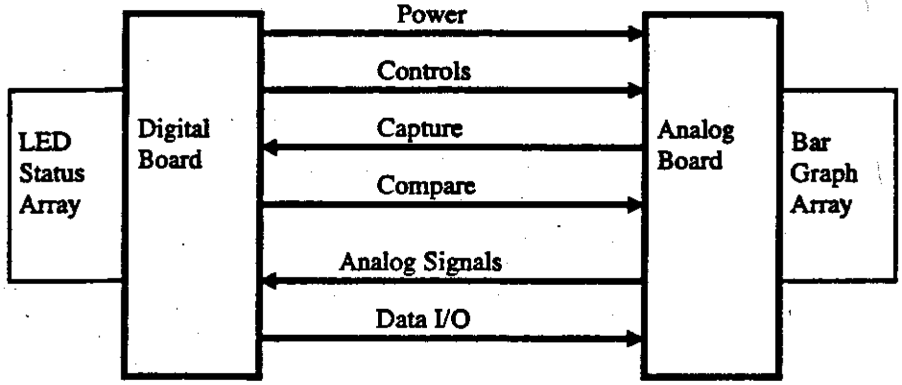

Figure 3: Block Diagram of the PC Boards

The path ways between the two boards are connected by flex cables perform the following functions:

a. 8 channel analog data: these circuits carry the analog data to be digitized by the A/D on-board the microprocessor.

b. 8 bit I/O data bus: carries the information from the processor to drive the 5 bar graph arrays.

c. 4 channel input capture: connects the output from the comparators to the processor for pulse interrupts and measurement timing.

d. 4 channel output compare: delivers output pulse patterns to the R/C shaping network and first stage of amplification used for simulation of passing vehicles and test of the operating system.

e. 4 pin power bus: delivers ground, unregulated battery power to the analog board and +5V regulated voltage to the comparators for reference.

f. 16 channels of digital switch (0-5V) control: opens and closes the bar graph latches and places "holds" and "resets" on the individual analog channels.

The reasons for dividing the system into two major segments is two-fold:

1. Compact packaging - the boards can be placed back to back and mechanically connected to fit into a small box.
2. Functional partitioning - the analog board is designed for the specific purpose of axle weight measurements, while the digital board is designed to support generalized data taking and logging tasks under microprocessor control.

Using this approach, the digital board can be re-used with alternate sensor varieties such as accelerometers, capacitive strip systems, tube/pulse generators, pressure/temperature sensors, etc., thereby reducing enormously the time, expense, and effort in developing future, improved or experimental data collection systems.

The power supply is derived from a 12 volt lead acid battery which the Diamond 2000 uses at the sensor sites. Keypad control via on-board LCD display was the desirable approach at the onset of the program, but later changed to control via laptop computer. The laptop will serve primarily as a data collection terminal until a more advanced messaging format has been developed within the AVC system.

The Digital Board and Microprocessor:

The digital board contains the following central components:

1. Microprocessor & Clock
2. Non-Volatile Data Storage Memory
3. Real Time Clock with Power Down Update Capability
4. I/O Data Bus
5. Multiplexer/Control Logic
6. Timer Chip
7. Low Voltage Reset and Visual Warning (LED) Driver
8. COP (Computer Operating Properly) LED Driver
9. RS 232 Port
10. LED (System) Status Display
11. Dipswitch (Initial Conditions/System Mode After Reset)

Detailed description of components and their attributes:

1. The microprocessor used on this board is an 8 data bit Motorola MC68HC711E9. Selected specifications of the processor are as follows:
   a. RAM - 512 bytes
   b. Program Space (EPROM) - 12k bytes (~4.3K bytes are used for this operating system)
   c. EEPROM - 512 bytes, electrically erasable & programmable by the processor.
   d. 8 dedicated A/D channels
   e. Synchronous and Asynchronous Serial Port Communications

   The external clock speed is 1.8427 Mhz, while the maximum speed for this processor is 8 Mhz. Thus, the operating system runs at less then quarter speed providing tremendous potential for enhanced capabilities in the future. The analog to digital converter as part of the 68HC11 microprocessor divides a 0 to +5V analog signal into 256 intervals (8 data bits). If, for example, the range of axle weights to be measured is between 500 lb and 6,500 lb, then the output unit will be accurate to within 6000lb./256 bits = 23.4 lb./bit. The digital voltage displayed during test of the pulse amplitude measurement software has been demonstrated to measure the "peak" pulse voltage to within an absolute range of +/- 50 millivolts.

2. The storage memory shipped with the prototype board is a single Dallas Semiconductor device with 1/2 Megabyte of non-volatile memory with an internal lithium battery that will maintain the data record for approximately 10 years after power down. Storing 24 bytes per axle, the 1/2 MB memory can store data on over 20,000 axles. The PC board however, is designed to hold two random access memories containing as much as 4 megabytes each without alteration to the PC board - simply "plug in" and use. This level of storage will hold data from over 300,000 axles.

3. The real time clock also contains an internal lithium battery which continually updates the internal clock after power-down. This clock maintains and updates the year, month, day of the week, hour, minute and second for up to 10 years after initial use. Time stamps of the individual axles contain only hour, minute and second to increase data storage capabilities, but the entire "calendar" is placed at the beginning of each recording session and uploaded to the laptop with the data.

4. The eight bit I/O bus is controlled by Port C and is used to read the dipswitch, read and write to the storage memories, real time clock, set the LED status display, and drive the bar-graphs on the analog board.

5. The multiplexer/control logic is under the control of Port B. The four "dual 2 to 4 decoder" chips in this functional group control the storage memories, real time

clock, COP logic on the digital board, along with the analog voltage and bar graph array control on the analog board.

6. The timer chip produces periodic "wake-ups" of the microprocessor in the absence of axle pulses. This allows the processor to strobe the COP LED, check the RS 232 port and other miscellaneous functions while remaining in the "wait" or "stop" mode most of the time. The periodic wake-up reduces power drain on the battery between passing vehicles. The timer output can be electrically connected to either the IRQ or the XIRQ interrupt pins on the processor without altering the PC board.

7. The "low voltage reset" chip places the processor in the "reset" (no activity) mode when the 5 volt regulated supply drops below ~4.75 volts. This prevents uncontrolled or "run away" operation of the processor during periods of power supply malfuction. The red (warning) LED on the box exterior is set whenever the external battery falls below ~11.5 volts. The manual reset switch on the outside of the box also functions through this chip.

8. The green COP (computer operating properly) LED remains lit when strobed by the processor on the average of 100 milliseconds or less. Strobing requires the synchronized use of ports B & C in order to drive the COP logic. "Run away" or uncontrolled operation of the processor cannot perform this function on a period basis and under those conditions, the COP light will go out.

9. The RS-232 communications is an industry standard. Sophisticated message transmissions can be developed using a PC interface and "message execute" software in the microprocessor. Two thirds of the potential program space remain open in the chip for further communications software development.

10. The 8 LED status display can be programmed to indicate system functions taking place such as successful axle weight measurements, RS-232 communications, etc.

11. The dip switch is presently used to communicate a nominal sensor spacing of 7.5 feet to the processor for vehicle classification purposes. Sensor spacing between

6 and 10 feet can be programmed into the dipswitch at the start or "power up" of each data taking session. The switch can also be used in combination with the manual reset switch to denote other communication modes and variables to the operating system.

The Analog Board - Pulse Measuring Circuits

There are two identical "channels" of pulse handling capability on the analog board, each "channel" being electrically connected to one of two piezo-electric sensors with two levels of output amplification, 4X and 18.5X and associated comparator logic as shown below.

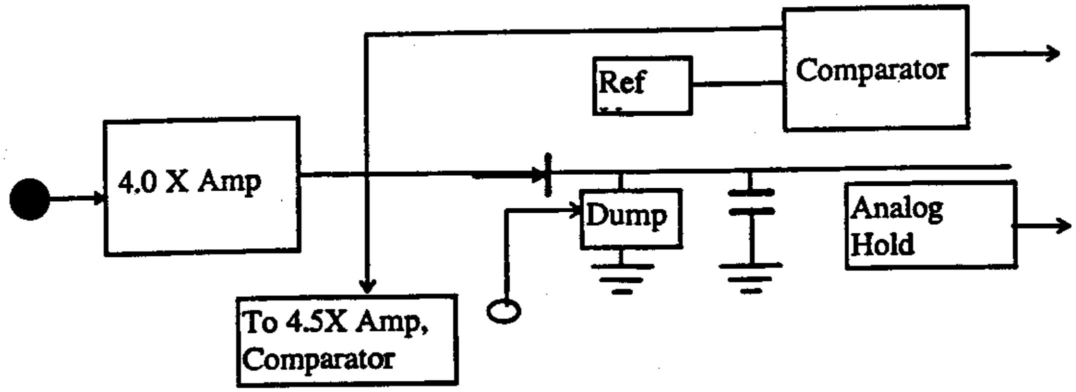

Figure 4 - Single Level of Amplification with Comparator, One Channel

These levels were chosen as a result of sensor signal data taken from three independent piezo electric sensors located on Interstate 15 over a three hour period and documented with photographs.

A very high amplitude pulse will saturate the 18.5X output but produce an amplitude between 0-5 volts on the 4X output. On the other hand, low amplitude pulses will only register on the 18.5X output. Thus, with two levels per channel, a wide range of piezo electric responses can be measured. Potentiometers are used to set the 4X and 18.5X amplifications and can be easily readjusted.

Each of the two amplification levels presents a comparator output which is used to initiate interrupts in the processor. Any of these outputs can be programmed to act as interrupts to begin measurement of the pulse from a passing axle. They are also used as markers for pulse width and time duration of the axle between two sensors.

Supporting Circuitry on the Analog Board

The 8 bit bus along the bottom of the board carries information to the five latches that control the bar graph arrays. Controls for the latches runs along the top of the board and is driven by one of the dual 2 to 4 multiplexors on the digital board.

Power for the analog and bar graph systems enters through the four pin power/ground bus which is also located at the top of the board. The main power is supplied directly from the +12V battery through a protection diode. Regulators on the analog board produce +/- 5.2 volts which power the amplifiers, comparators and bar graph arrays.

This permits large swings in analog current demand (which can exceed 500mA when all bars are lit), while minimizing the regulation requirements of the digital board (which draws only ~45mA for the crystal clock and microprocessor).

Retrieved Data

The data retrieved through the RS232 port from the non-volatile storage memory will contain the following parameters:

a. axle number bytes (axle #1 to #65,536)

b. measurement status byte - denotes whether the high or low level of amplification was used and whether "pulse" timing or "time between axle" errors were encountered.

c. pulse amplitude for the axle measured from sensors #1 and #2, in bits (2 bytes)

d. pulse widths for the axle from sensors #1 and #2, in microseconds (2 bytes)

e. speed, feet/second, in ft. decimal ft (2 bytes)

f. trap time (time of flight) between sensor #1 and #2, microseconds (2 bytes)

g. time stamp: hour, minute and second (3 bytes)

h. time between axles, sensor #2 (2 bytes)

i. vehicle number (veh#1 to #65,536)

It may appear that much effort has been expended by collecting pulse widths and vehicle speed information that could otherwise be extracted during post processing. The actual situation is that the "input capture clock" which is hard-wired circuitry inside the microprocessor, stops at the beginning and ending of the pulse and is retrieved and stored using only four lines of code. Thus the pulse width can be extracted from the difference of these times and stored in the axle information with little effort.

Trap time, a required output, is used to calculate vehicle speed necessary for the processor to determine when to return to the "wait" mode for low power operation. This is an inherent requirement of the operating system for extended battery operation and the knowledge of vehicle speed is the easiest parameter to use in determining maximum "wait" or "end of vehicle" time and thus vehicle number. Vehicle speed (as calculated) is also used in conjunction with "time between axles" to compute axle spacing.

Laboratory Testing and Simulation of the code

Testing of the code in simulation is a vitally important but laborious process. This is essentially an activity of debugging the computer code and testing the circuit design. A series of tests were conducted to test each element of the circuit as well as program subroutine. The final lab testing involved simulating a train of typical axle weight pulse from a vehicle and observing the performance of the entire system.

STATUS OF THE DESIGN

The basic design of the electronic unit is complete. This task involved the software and hardware design of the unit to enable the micro-chip to process piezoelectric sensor signals, translate them into axle data and store them for later retrieval and post-processing in the laboratory. Simulation tests of the unit in laboratory were successfully completed. However, time and funds ran out before field tests and calibration of the system could be completed. Therefore, to complete this effort, the following future activities are recommended.

Recommended Future Efforts:

To complete this effort, it is recommended that the following tasks have to be performed:

1. Field testing of the prototype: Testing the performance of the various aspects of the unit under field conditions, including, calibration of the axle weight measurements, interfacing with the lap-top computer, performance under different field conditions such as temperature variations, portable vs. permanent piezoelectric sensor installations, evaluating the accuracy of the unit, the sensitivity of the measurements (i.e., the minimum measurable weight difference), the consistency of the measurements (i.e., change in performance of the unit with temperature changes, etc.), and the suitability of the user interface,
2. Calibration of the axle weight-and-spacing-based binning scheme for optimal classification of vehicles, and development of a binning scheme with vehicle weight as an additional criteria for classification. Evaluation of the performance of the new binning scheme compared to the binning scheme which is based on axle spacing only.
3. Overall evaluation of the performance of the new weight-and-axle-spacing based AVC system.

POST PROCESSING OF AXLE DATA

Two major steps are involved in post-processing of the data received from the electronic unit. First, the raw axle data has to be translated into vehicle data. This is accomplished by a computer program written in "C" to read the downloaded raw axle data and translate it into vehicle data with vehicle speed, axle weights and spacing. Maximum axle spacing is the criteria used to distinguish successive axles into separate vehicles. It is currently recommended to use 40 feet as the maximum axle spacing in vehicles. However, the program is designed to accommodate vehicles with wider axle spacing followed by tandem axles. For axle weights, the program will be calibrated to translate detected pulse height and width into axle weight, and ultimately, vehicle weight. The next step is to classify the vehicles based on a modified weight-based binning scheme, as described below.

THE MODIFIED WEIGHT-BASED BINNING SCHEME

A program that implements a modified binning algorithm that utilizes axle weights as well as the number and spacing of axles has been written in C++ on a PC. The modified binning scheme focuses on providing better distinction between vehicle classes that are not easily distinguishable by using axle spacing data alone. The program is therefore designed to post-process the vehicle weight and axle spacing data obtained from the new unit. The program then classifies vehicles by the number and spacing of axles, as well as the gross weight of the vehicles. The binning scheme is easily user modifiable.

The weight threshold values for distinction between various vehicle classes were to be determined after collecting vehicle weight data using the unit during field testing. However, from preliminary analysis of available vehicle classification data, not all vehicle classes need the weight information to be distinguished from other classes. The analysis indicates that vehicle class distinctions that are likely to significantly improve by using the gross vehicle weight are bin 8 (single 4-axle truck) vs. bin 4 (Motor homes and 2SDs with 2 axle trailers), bin 4 (2-axle motorhomes and 2SDs) vs. bin 1 (passenger cars). The distinction between 2SDs vs. motorhomes, light 2SDs vs. heavy 2SDs, may also be possible if gross vehicle weight is used. Data collected during field testing will be used to evaluate this and other possible classification improvements that can be achieved by using gross vehicle weight.

Since only a few vehicle classes would benefit from the use of gross vehicle weight as one of the classification criteria, the new binning scheme, therefore, maintains axle spacing as the primary criteria for classification of vehicles. For vehicle classes with significant overlaps in axle spacing configuration, the new program would allow the user to include gross vehicle weight as an additional criteria for vehicle classifications. The user can be able add or remove a vehicle class, modify any desired axle spacing configuration and gross vehicle weight criterion.

Table 17 shows a sample modified binning table with gross vehicle weight as an added criteria to distinguish between bins 4 and 8 for 4-axle vehicles, and bins 1 and 4 for 2-axle vehicles. For example, this table implies that there is significant overlap in axle spacing configuration for 2-axle vehicles with axle spacing between 10.1 feet to 15 feet. Therefore, any such vehicle will be classified based on its gross vehicle weight, i.e., if gross vehicle weight is 2 tons or less, the vehicle is a bin 1 class (passenger automobile), else, if gross vehicle weight is between 2.1 tons and 40.5 tons, the vehicle is a bin 4 class. However, the full development of the binning scheme with gross vehicle weight criteria can only be completed after collecting field data on gross vehicle weights for all critical vehicle types.

Table 17: Binning Scheme Using Gross Vehicle Weight Criteria for Some Vehicle Types

Seq. No.	Bin No.	No. of Axles	Axle Spacings (feet)									Range of Gross Weight ('1000 lb)
1	1	2	5.0 - 10.0									
2	1	2	10.1 - 15.0									0.0 - 2.0
3	4	2	10.1 - 15.0									2.1 - 40.5
4	4	2	15.1 - 21.9									
5	2	2	22.0 - 29.9									
6	1	3	5.0 - 13.3	7.0 - 19.9								
7	4	3	13.4 - 21.5	7.0 - 24.9								
8	3	3	19.9 - 29.9	3.1 - 6.9								
9	5	3	8.6 - 19.8	3.2 - 6.9								
10	7	3	8.0 - 22.0	20.0 - 41.9								
11	1	4	5.0 - 13.3	7.0 - 30.0	2.0 - 3.1							
12	1	4	5.0 - 13.3	7.0 - 17.5	5.0 - 12.4							
13	4	4	13.4 - 21.5	7.0 - 31.1	*							0.0 - 40.5
14	5	4	8.6 - 29.7	3.2 - 6.9	11.7 - 14.6							
15	6	4	8.6 - 29.7	3.3 - 6.9	3.0 - 11.6							
16	8	4	*	3.2 - 6.9	15.0 - 40.0							
17	8	4	*	30.0 - 50.0	*							
18	8	4	*	*	*							40.6 - 100.0
19	1	5	5.0 - 13.3	7.0 - 30.0	2.0 - 3.1	2.0 - 3.1						
20	4	5	13.4 - 21.5	33.0 - 45.0	2.0 - 3.1	2.0 - 3.1						
21	9	5	7.1 - 24.0	3.2 - 6.9	14.7 - 54.7	3.1 - 11.4						
22	10	5	7.1 - 22.0	3.2 - 6.9	7.1 - 24.0	11.5 - 34.9						
23	12	5	*	*	*	*						
24	11	6	7.1 - 21.9	3.2 - 6.9	*	3.2 - 6.9	*					
25	11	6	7.1 - 21.9	3.2 - 6.9	*	*	3.2 - 6.9					
26	11	6	7.1 - 21.9	*	2.5 - 6.9	2.5 - 6.9	2.5 - 6.9					
27	13	6	*	*	*	*	*					
28	14	7	*	*	*	*	*	*				
29	15	8	*	*	*	*	*	*	*			
30	15	9	*	*	*	*	*	*	*	*		
31	15	10	*	*	*	*	*	*	*	*	*	
32	16	ALL OTHER VEHICLES										

SPECIFICATIONS
AUTOMATIC VEHICLE CLASSIFICATION EQUIPMENT

1. General Requirements

These specifications cover the supply of piezo-electric automatic vehicle classification (AVC) systems. The terms "AVC," "equipment," and "systems" mean piezo-electric cable or piezo-electric film AVC systems, including all sensors, electronic, interconnections and software.

The operation of systems supplied under this specification shall be compatible with the requirements of the Strategic Highway Research Program (SHRP).

One (1) set of operator's manuals for each AVC unit shall be submitted with the equipment.

One (1) maintenance manual shall accompany each unit when delivered. Maintenance manuals shall include schematics, circuit diagrams, parts list, parts price list, parts lists with cross-reference of all components by manufacturers, and instructions suitable for state technicians to perform services and repairs.

Software will be compatible with IBM XT,AT and PS/2 and other 100% compatible computers. The software will be used on several computers and it must not be copy protected to avoid problems in installing on any computer used and to allow for routine backup of the software.

All software used with the AVC system shall be clearly documented and provided at no additional cost. The software shall be capable of telemetry programming and down loading of data. A software manual, including documentation, shall be provided for each AVC system.

Acceptance testing of the equipment, including piezo sensors will be for a minimum of thirty (30) days of continuous operation.

If the equipment does not operate according to the specifications during the acceptance testing period, the state will have the option of returning the equipment at vendor's cost.

The vendor shall provide training for State personnel in operation, maintenance, trouble-shooting, and repairs for the equipment. The vendor shall also supervise state forces with the site installation of the AVC including piezo axle sensors in 4 lanes on one site. Installation shall take place within 20 days of delievery of equipment. Training shall began after site is operational. Site is in RENO, NEVADA.

2. Operating Environment

The system shall operate in through traffic lanes of interstate and principal highways covering the full range of traffic volumes and truck percentages.

The piezo sensors shall operate within specification when installed in asphalt concrete, segmented portland cement concrete,and continuously reinforced portland cement concrete pavements.

The electronic shall meet specifications from a temperature of 0 to +160 degrees Fahrenheit, and up to 95% relative humidity. The system shall be capable of wihtstanding temperatures in the range -40 to +160 without permanent damage or deterioration.

3. Durability

The piezo sensors shall have an operating life of at least one (1) year. Failure during that period will require replacement at the vendor's expense. The electronics sub-system shall have an operating life of at least two (2) years. Failure during that period will require replacement at the vendor's expense.

4. In-Pavement Sensors

Piezo sensors shall be mounted in accordance with the guide lines in FHWA demonstration project FHWA-DP-88-76-006. Other mounting may be considered, where the vendor can provide independent evidence of satisfactory operation. Piezo cable mountings shall be permanently installed, flush with the pavement surface, using epoxy adhesive (Hermetite or similar) along the entire length of each sensor.

5. Data Input and Processing

The AVC shall be capable of monitoring signals from two piezo per lane, two road tube's per lane, two loops and one piezo per lane. The vehicle classifier algorithm shall be user programable and have the capalitity of 36 vehicle definations to sort into 18 bins. Additionally the alogrithm shall be programmable to provide out put in accordance with FHWA Scheme F.

Provision shall be made for on-site input of all system operating parameters including data processing and system software. Diagnostic checks of system operation and performance shall include, as a minimum, checks for low battery power, axle sensor failure, telemetry errors, and condition of data. The unit shall be capable of recording in intervals of 1 minute to 24 hours in one minute increments.

6. Data Storage and Output
All data output shall be ASC11 and RS232 compatible. External data transmission rates shall include 300 to 9600 baud. protocols, and handshaking shall be provided for communication to external printers, terminal and IBM microcomputers. Output shall have "xon/xoff" type protocol. An RS232 port shall provided for data output at the AVC site. Individual vehicle data shall include time of passage to seconds, speed in mph, number of axles, spacing between axles to 1/10 foot. Data storage capacity shall be provided for at least 320k.

7. Data Retrieval System
Provision shall be made for portable data retrieval for the site. Take away memory, portable memory modules, downloading to a dedicated retrieval unit, downloading to a portable microcomputer, or a similar system shall be clearly defined and demonstrated by the manufacturer.

8. Power and Telemetry
The system shall be designed for low power consumption and continuous operation. It shall be capable of operating on batteries and a solar panel. System shall include a telemetry sub-system able to receive and transmit data via an auto-answer modem. Provision shall be made for error trapping and re-transmission of data. All of the system input parameters shall be capable of being monitored and re-set via the telemetry sub-system.

9. Design Requirements
All electric components shall be of solid state design with high noise immunity utilizing low power, CMOS technology. Logic and data storage components shall be mounted on replaceable plug in circuit boards. all components shall be firmly mounted and housed so that they will not be damaged by jolts and vibrations encountered in transportation and use. Electronic components shall be fully protected against overloads, power surges and transients. Service and delivery of spare parts shall be assured.

10. Performance
The system shall be capable of a classification accuracy of 90 percent or greater, to allow for compensation or canceling between vehicle categories. This level of accuracy shall be achieved for all vehicle categories contained with the Nevada WIM system, considered either individually or in any combination, provided that the total number of vehicle surveyed in the group exceed 100 during the period of the accuracy survey.

11. Delivery
Delivery of equipment shall be within 60 days from date of award for the counter/classifier.

12. The right is reserved to reject any and all bids and to waive technical errors as may be deemed best for the interests of the State of Nevada.

With Respect to the aforementioned requirements and conditions, we are ordering 10 Automatic Vehicle Classifiers and 8 Piezzos (2 per lane).

If there are any questions concerning this specification, call Mr. Andrew Mathiesen (702) 687-3443 or, Mr. Cecil Crandall (702) 687-5575.

Literature Review of AVC and WIM Weight Sensor Systems

by

Robert A. Schill, Jr.

I would like to acknowledge Mr. Murali Ande for his efforts in identifying potential journal aritcles pertinent to this study and for performing much of the leg work required to obtain the documents needed to write this report.

A literature review is being conducted on the state of the art in AVC and WIM sensors and the commercial availability of the sensors. Accuracy, reliability and cost are the components which are crucial in the choice of sensors. Below lists a variety of state of the art sensors or sensor systems. Not all of these sensors are commercially available or viable at this time.

- Bridge Systems (load cell or strain gauge)
- Hydraulic Load Cells
- Bending Plate Weightpads
- Capacitive Pad System
- Piezoelectric Cable System (Vibracoax)
- Piezoelectric Film
- Piezoelectric Polyvinylidene Fluoride (PVDF)
- Capacitive Strip System
- Infrared Light Systems
- Microwave System
- Resistive Sensor System

With NDOT's objectives in mind, a brief review of these systems or sensors are provided below.

Bridge Systems (load cell or strain gauge)

- Temporary Application
    - not available

- Permanent Application
    - typical cost 25K pounds for a single lane
    - installation time 3 days
    - axle weight accuracy 10%
    - major disruption to highway during installation
    - heavy lifting equipment required
    - generally installed on a single lane only

Bending Plate Weightpads

- Temporary Application
    - not available

- Permanent Application
    - typical cost 20K pounds for a single lane using 2 weigh pads
    - installation time 3 days
    - gross weight accuracy 6%
    - moderate disruption to highway during installation
    - lifting equipment required at site
    - single and multi lane application

- strain gauges mounted on steel plates monitored; requires pavement excavation—expensive

Capacitive Pad (Capacitive Weighmats) System

- Temporary System
    - typical cost 9K pounds for single lane
    - installation time 1 hour
    - gross weight accuracy 10%
    - axle weight accuracy 18%
    - care needed to ensure sensor durability, application and handling
    - single lane only

- Permanent Application
    - not available

- Contact area of tire on one side of axial is practical
- Both tire tracks could be covered with individual sensors in the lane, cost increases significantly due to complex electronics and power consumption and multiple capacitor sensors
- Current state of the art (10% variation with 95% confidence is obtainable)

Piezo Cable System (Vibracoax Piezoelectric Cable)

- Temporary Application
    - not available

- Permanent Application
    - typical cost 7K pounds for single lane
    - installation time 1 day
    - cross weight accuracy 12%
    - axle weight accuracy 18%
    - risk of sensor drift and performance variation with temperature change
    - single lane or multi lane application

- Performs well under pure direct loading with a fairly linear load/output relationship
- Sensor consistency, probably due to difficulty with manufacture quality control, and sensor mounting are problems
- Sensor picks up all kinds of stress including surface layers under load whose signals are superimposed on the direct axial load measurements
- The mechanical properties of soft pavement are temperature dependent which affect the sensitivity of sensors like the piezo-electric. This has proven impossible to set reliable calibration levels because of apparent seasonal variation in pavement stiffness.

Capacitive Strip System

- Permanent Application
    - typical cost 8K pounds for single lane
    - installation time 1 day

  - gross weight accuracy 8%
  - axle weight accuracy 10%
  - no systematic temperature or drift
  - digital signal to max feeder length
  - can measure static weights
  - single or multi lane application

- Temporary Application
  - typical cost 5K pounds for single lane
  - installation time 1 hour
  - gross weight accuracy 17%
  - check installation frequently up to 3 weeks with inspection
  - single or multi lane application

- Wheel loads determined by integrating sensor signal as the wheel passed over a linear sensor
- Design different from capacitive mat since the mechanism of deflection could not be directly reproduced with a linear device; strip does not contain rigid separators to needed to linearly change the mode of deflection of the device
- Possible to obtain uniformity of output
- Possible to obtain a linear response to load at any one position

Piezoelectric Sensors (General)

- Capable of monitoring transient loads involving relatively short period changes in stress
- Charge generated by the application of a load decays over a few seconds to several minutes depending on the nature of the piezoelectric material and the characteristics of the measuring circuit
- Not useful for static weighing or possibly very low speeds
- The mechanical properties of soft pavement are temperature dependent which affect the sensitivity of sensors like the piezo-electric. This has proven impossible to set reliable calibration levels because of apparent seasonal variation in pavement stiffness.

Piezoelectric Polyvinylidene Fluoride (PVDF)

- May be used to support entire wheel load avoiding the use of integration algorithms in a mat or strip sensor
- More sensitive than piezoelectric cable
- Very thin, useful as a low profile sensor
- Sensitive to surface layer loading as in the cable
- Sensor mounting is crucial in the sensor design
- Reverse piezoelectric effect may be used
- Sensor must be shielded from drastic temperature changes since charges can be developed by the pyroelectric effect
- It is not clear if this sensor has the same problem regarding the mechanical properties of soft pavement and its temperature dependency as does the piezoelectric cable.
- Others claim that it may be possible to design a sensor in which the effect of bending in the composite is reduces and practically eliminate temperature drifts. Current state of the art is unknown at this time.

Resistive Sensors

- Electrical resistive strain gauges used or conductive rubber which changes resistance when loaded
- Low cost
- Simple circuitry required to interface the sensor to the monitoring circuitry
- Little research beyond preliminary studies conducted
- Conductive rubber - problem: contact resistances and repeatability

Infrared Light Systems

- Single reflex-type infrared sensor mounted just off the shoulder and working off a retro-reflective raised pavement marker in the center of the outside traffic lane can be used to count the tires on one end of each axle of a moving vehicle with accuracy comparable to human observers or to a flush-mounted piezo-strip sensor.
- Tests not conducted in snow or heavy rain.
- Arrays of sensors can be used to detect vehicle-body presence, vehicle speed, axle spacing, and tire-contact patch dimensions, single or dual tires, detect direction of vehicle movement, sense over height vehicles.
- Off shoulder reflex-type infrared sensors with retro-reflective raised pavement markers operated for up to three months without cleaning.
- Correlations between infrared light-beam sensor measurements and weight were not sufficient to make adequate weight estimates from such measurements practicable.
- Occasional cleaning of the lenses and retroreflectors may be necessary.
- If the sensors are placed too close together false signals can occur due to specular reflections from highly polished cars.
- Environmental effects such as temperature, road film, rain, shock and vibration from vehicles affect the operation of the sensors with retro-reflective markers.
- Sensors were not tested for life expectancy and long-term reliability.

Microwave System

- Classifies vehicles into at least 5 groups with about a 75% accuracy
- May be useful in urban areas
- System provides a look-a-like profile of vehicle and then classifies vehicle
- Unless continuously monitored, will require a significant amount of memory if vehicle profiles are to be maintained
- Reflections off of different parts of vehicle will yield different speeds.
- Does not appear to measure weight
- In the research stage

Based on this review, the capacitive strip sensors seem to be the most promising devices on the market at this time. Both the piezoelectric and the resistive sensors are also likely candidates depending on the state of the art today. The dates of the references reviewed range between 1988 to 1993 inclusive. We are in the process of contacting vendors and evaluating their products and costs.

Sensor calibration is not a simple task and in most cases for single or two sensor systems it is an impossible task when measuring dynamic weights. There is no guarantee that the weights being measured on strip sensors are accurate nor can a direct correlation be made to appropriate static weights. Recent reports indicate that calibrating a system with single or two sensor systems are virtually impossible because:

- Vehicles have a natural 2 to 4 Hz oscillation frequency when in motion
- Each vehicle has is own unique suspension system and dynamic weight distribution which affects vehicle oscillation in transit
- Roughness of pavement and sensor profile results in multiple bouncing on the sensor and a dynamic shift of axle weight.
- Nonlinear loading effects may result at initial impact
- The mechanical properties of soft pavement are temperature dependent which affect the sensitivity of sensors like the piezo-electric. This has proven impossible to set reliable calibration levels because of apparent seasonal variation in pavement stiffness.
- Dynamic calibration requires a large number of representative vehicle passes over a range of speeds. Calibrating the device for a single vehicle class does not guarantee that the sensor will operate satisfactory for other classes of vehicles.
- Simple aging of sensor and electronics when subject to the elements causes a calibration drift. In Nevada, sensor systems will be subjected to over 110^0 F temperature range. The recording unit contained in a closed metal box is constantly subjected to the suns rays. The heat build-up in the metal box (oven) may effect the electronics thereby decreasing the life time of the unit.
- Calibration drift is also a result of the normal wear which depends on the number and weight of the axles passing over the sensor.
- Site selection is crucial
    - The approach to the site should be smooth and level, at least 300 meters prior to the site and 150 meters after the site.
    - Roads with pronounced camber should be avoided.
    - Traffic should be free flowing with good lane discipline.
    - Absolute vehicle speeds are generally not critical be sectors of significant acceleration and deceleration and gear changing should be avoided.

It is recommended at this time that an array of 3 to 9 sensors be used if vehicle weight a required parameter. By averaging the responses obtained by the sensor array, errors resulting from road roughness, vehicle differences and natural oscillations can be minimized. Further, if one sensor fails because of wear, the system will still provide adequate responses needed to determine the dynamic weights. It is also suggested that the temperature characteristics of the pavement be monitored near the sensors. Such information can be used for sensor calibration especially during large temperature differences in a 24 hour period as well as a 12 month period. It is also important to note that individual piezoelectric sensors contribute differently to the system performance. Some of this can be averaged out by using multiple sensors if quality control is not good.

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