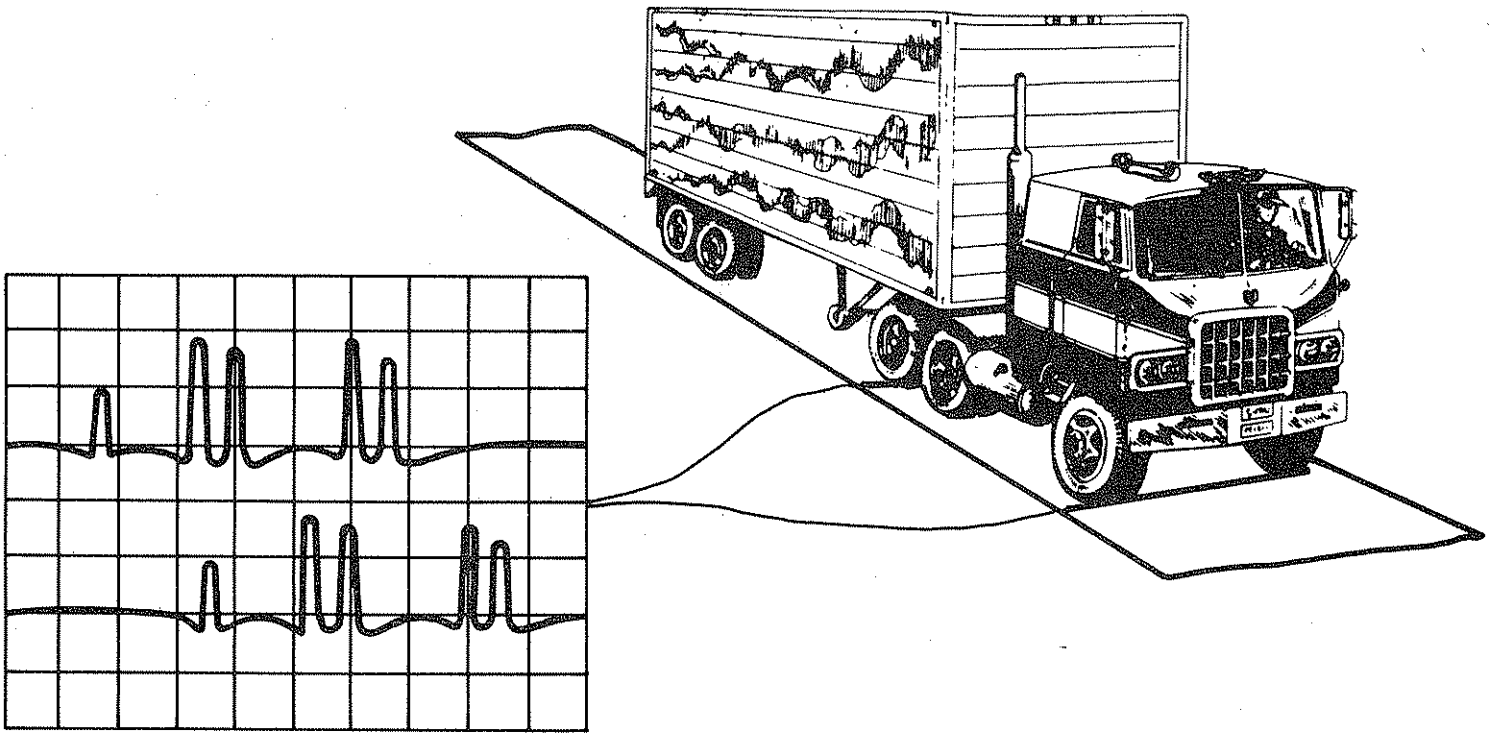
U.S. Department
of Transportation

**Federal Highway
Administration**

Demonstration Projects
Division

Automated Traffic/Truck Weight Monitoring Equipment (Weigh-In-Motion)



FHWA-DP-88-76-006

May 1988

FEDERAL HIGHWAY ADMINISTRATION

Automated Traffic/Truck Weight Monitoring Equipment (Weigh-in-Motion)

DEMONSTRATION PROJECT NO. 76

IOWA HIGHWAY RESEARCH BOARD
PROJECT 282

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Federal Highway Administration, Minnesota Department of Transportation,
Iowa Department of Transportation and the
Iowa Highway Research Board

May 1988

Technical Report Documentation Page

1. Report No. FHWA-DP-88-76-006	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Automated Traffic/Truck Weight Monitoring Equipment (Weigh-in-Motion)		5. Report Date: May 1988
		6. Performing Organization Code
7. Author(s): Castle Rock Consultants		8. Performing Organization Report No.
9. Performing Organization Name and Address: Iowa Dept. of Trans. Office of Trans. Research 800 Lincoln Way Ames, IA 50010	Minn. Dept. of Trans. Office of Trans. Data, Research and Analysis Transportation Bldg. St. Paul, MN 55155	10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTFH71-85-966-IA-16
12. Sponsoring Agency Name and Address: Federal Highway Administration Demonstration Projects Division 400 7th St., S.W. Washington, D.C. 20590		13. Type of Report and Period Covered: Executive Summary and Final Report & Specifications May 1986 - November 1987
		14. Sponsoring Agency Code: HHO-43

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

This report documents work undertaken in the demonstration of a low-cost Automatic Weight and Classification System (AWACS). An AWACS procurement specification and details of the results of the project are also included. The intent of the project is to support and encourage transferring research knowledge to state and local agencies and manufacturers through field demonstrations.

Presently available, Weigh-in-Motion and Classification Systems are typically too expensive to permit the wide deployment necessary to obtain representative vehicle data. Piezo electric technology has been used in the United Kingdom and Europe and is believed to be the basic element in a low-cost AWACS.

Low-cost systems have been installed at two sites, one in Portland Cement Concrete (PCC) pavement in Iowa and the other in Asphaltic Cement Concrete (ACC) pavement in Minnesota to provide experience with both types of pavement. The systems provide axle weights, gross vehicle weight, axle spacing, vehicle classification, vehicle speed, vehicle count, and time of arrival. In addition, system self-calibration and a method to predict contact tire pressure is included in the system design.

The study has shown that in the PCC pavement, the AWACS is capable of meeting the needs of state and federal highway agencies, producing accuracies comparable to many current commercial WIM devices. This is being achieved at a procurement cost of substantially less than currently available equipment. In the ACC pavement the accuracies were less than those observed in the PCC pavement which is concluded to result from a low pavement rigidity at this site. Further work is needed to assess the AWACS performance at a range of sites in ACC pavements.

17. Key Words: Weigh-in-Motion, Classification, Piezo Cable		18. Distribution Statement	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

NOTICE

ACKNOWLEDGMENTS

This report is supported by the Iowa Highway Research Board, the Iowa Department of Transportation and the Minnesota Department of Transportation in cooperation with the Demonstration Projects Division of the Federal Highway Administration (FHWA). Thanks are due to Ed Finn of the FHWA Iowa Division Office for his support of the project and to Bill McCall and Samil Sermet of the Office of Transportation Research of the Iowa DOT and to Richard Stehr, Gary Graves and Don Kieffer of the Office of Transportation Data, Research and Analysis of the Minnesota DOT for their assistance and cooperation in all phases of the study. Without their close involvement the project would not have been possible.

Thanks are also due to the many personnel in the Offices of Maintenance, Transportation Inventory and Transportation Research of the Iowa DOT and in the Offices of Maintenance, Electrical Service Unit, District Five and Transportation Data, Research and Analysis of the Minnesota DOT for making the project a reality.

Finally, thanks are due to GK Instruments Limited for providing equipment which more than met the technical requirements of the program within the overall timescale.

Development of a Low-Cost Automatic Weight and Classification System (AWACS)

Executive Summary

developed and tested within the project. Comprehensive results of all tests and their outcome are outlined in this summary and detailed in the final report.

Previous Work

'Vibracoax' piezo-electric cable was patented by Philips in 1971. This cable forms the basis of current low-cost WIM developments. More than ten years of research and development have been carried out in Europe to define preferred techniques for cable installation and signal processing. This project builds directly upon that basis of solid, scientific research.

Vibracoax comprises a copper-sheathed coaxial cable containing a highly-compressed, piezo-electric ceramic dielectric. During manufacture, the cable is poled using a radial electric field at an elevated temperature. The cables generate charge in proportion to changes in radial and longitudinal stress. Problems have arisen in the past with variations in response along cable lengths, which can only be addressed through rigorous testing before and after mounting.

The importance of the mounting design used with the piezo-electric cables cannot be overstated. More than thirty mountings were tested before the current design utilized in this project was selected. This design can be manufactured under license to the UK Transport and Road Research Laboratory (TRRL).

Signal processing requires real-time digital integration of output voltages from charge amplifiers, at a sampling rate of between 1 and 2 kHz. Provision must be made for tracking background drift, elimination of pavement bending effects and compensation for vehicle speed. Appropriate algorithms had been derived for these purposes before the start of this demonstration.

Test Program

A testing and analysis program was agreed to establish preproduction system performance and reliability in PCC and asphalt pavements during the various seasons of one year. The program comprised laboratory tests, random vehicle evaluations, test vehicle appraisals and a long-term assessment. Random vehicle evaluations were the major type of field tests, serving to calibrate the system, assess its weigh-in-motion performance, evaluate its axle spacing measurement accuracy and determine its ability to measure tire widths and lengths. The other appraisals provided supporting evidence to assess system performance under more extreme conditions.

Site Selection

A quantitative scheme was developed to help states select AWACS sites consistently. Engineering factors considered to be of prime importance include pavement rigidity, profile, surface condition and maintenance schedules. Other factors to be considered for economic and administrative reasons include availability of services, equipment housing, and proximity to a static weighscale. The site selection scheme should be further developed in the light of experience with future AWACS sites.

FIRST GENERATION SYSTEMS

The first generation AWACS systems were procured from GK Instruments in accordance with a specification prepared within the demonstration project. The system was capable of monitoring up to six piezo-electric cables and one inductive loop located in a single traffic lane. It used established sensor designs and signal processing techniques, and operated from mains power or battery backup over a temperature range of -40 degrees F to 160 degrees F, in a relative humidity of up to 95%.

Three modes of operation were provided in the first generation system. In continuous mode, data were output in real time as each vehicle traversed the sensor array. In selection mode, only selected vehicles were logged using a push-button trigger. Finally, in remote mode, summary data were stored for subsequent retrieval. All data are ASCII and RS232-C compatible.

Laboratory Testing

Laboratory tests examined the uniformity of the cable before and after mounting. Standards are recommended within this project for cable uniformity prior to installation, assessed by a standardized test procedure. Not all cables tested during the program met required standards; one batch was rejected and returned to the manufacturer.

Environmental tests also examined the performance of sensors and electronics under extremes of temperature and humidity. The tests indicated that the first generation AWACS equipment met the provisional specification. Additional tests were performed on the response of the system at low temperatures following the winter's field observations. These tests were used to form the basis for a temperature compensation feature incorporated into the second generation system.

Installation (AWACS1)

The first generation system was initially installed in August/September 1986, though subsequent feature upgrades continued throughout the project. Two different site configurations were utilized initially, one in Iowa and one in Minnesota. Piezo sensor installation requires four persons for one day to cover one to two highway lanes. Rigorous control and experienced supervision of the sensor installation are essential if satisfactory results are to be achieved. Electronics installations can follow normal practices for roadside equipment.

Weigh-in-Motion Accuracy (AWACS1)

Random and test vehicle data collected during September and December 1986 in Iowa and Minnesota were analyzed, identifying systematic and random differences between static and dynamic weights. Systematic differences are given by the mean of the weight difference distribution, and random differences by its standard deviation. The conclusions of the analyses were as follows:

1. During September 1986, in Iowa, random differences between static and dynamic weight with two full-length piezo sensors were 8.9% for axle weights and 6.3% for gross weights. In December 1986, the random difference was 10.5% for axle weights and 8.1% for gross weights.

2. Expressed in terms of the HELP 'funnel' concept, September 1986 random differences for two full length sensors were 758 lbs below 10,000 lbs, and 7.8%, above this value. In December 1986 the equivalent results were 1018 lbs and 9.4%. Systematic differences were less than 1% above 10,000 lbs.

3. The Minnesota data were less satisfactory, with large percentage errors in weight measurement for certain combinations of axle sensors. Modifications were made at the Minnesota test site, but the sensors continued to perform less well than those in Iowa. During the December tests, random differences were found to be 15.5% on axle weight and 13.1% on gross weight. In terms of the 'funnel' concept, these axle weight differences equate to 1312 lbs below 10,000 lbs, and 14.8% above 10,000 lbs. Systematic differences were less than 1%.

4. The tradeoff between system cost and system performance utilizing one, two or three weight sensors was examined. A system with two weight sensors appeared to represent an optimum, meeting user needs while minimizing costs.

5. Differences in weighing accuracy between weight ranges were found in the Iowa data. These differences indicate that the AWACS equipment showed least random variation, in percentage terms, for weighing heavy axles.

Vehicle Classification Accuracy (AWACS1)

1. The accuracy of FHWA Scheme F classification using previously-existing flow-charts did not satisfy draft HELP guidelines. Enhanced classification routines were developed which aimed to substantially improve classification accuracies.

2. Classification accuracies achieved using an inductive loop as well as piezo cables were significantly worse than accuracies achieved without an inductive loop. The loop was excluded from the second generation system design.

Tire Length and Width (AWACS1)

1. The first generation AWACS was capable of measuring tire contact lengths with a random error of less than one inch. Tire width measurements had a random error of less than two inches. This is easily sufficient to distinguish single from double tires.

2. Several refinements to signal processing algorithms were implemented in the second generation system, which aimed to increase the reliability of tire contact measurement, avoiding tires being missed.

SECOND GENERATION SYSTEMS

The second generation AWACS systems were developed to include additional features such as automated tire length and width measurement, diagnostic checks and self-calibration. They also implemented several system modifications which were determined during the first generation system tests.

The principle of self-calibration is that loads on the steering axles of 3S2s show relatively little variation, regardless of the loading on the truck. Once a sufficient number of 3S2 steering axles have been weighed, the calibration factor is automatically adjusted so that the measured axles fit the expected mean.

Installation (AWACS2)

The Minnesota piezo sensors were removed and reinstalled in such a way as to profile the sensors more closely to the pavement surface. Two of these three sensors subsequently failed, within three months of being moved. No other sensor failures were recorded at any

time in the project. The failures resulted from damage to the PVC sheaths of the coaxial feeders during their removal from the pavement. The three sensors were replaced by new equipment which functioned without problems.

The second generation sensor arrays in both states standardized on a modified subset of the original Iowa installation. Two parallel, 12 ft sensors spaced 16 ft apart provide both weight and classification data. An additional short sensor allows for off-scale vehicle detection, and a diagonal sensor for tire width measurement.

The short sensor, located in the right wheeltrack, determines whether vehicles wholly or partially avoid the main axle load sensors. Off-scale vehicles are weighed less reliably because the complete tire contact area does not pass over the active length of the load transducers.

Weigh-in-Motion Accuracy (AWACS2)

The analysis of random and test vehicle data collected in the second generation system appraisal led to the following main conclusions.

1. Based on the Iowa test results, the second generation AWACS system gave overall random differences between static and dynamic weight of 12.3% for axles and axle groups of all weight ranges combined. Second generation random differences between static and dynamic weight were calculated to be 1126 lbs below 10,000 lbs and 11.8% above this value.

2. The second generation AWACS should be capable of satisfying user needs for gross weight accuracies. Iowa test data indicate that these have a random static/dynamic difference of 9.4%.

3. The Minnesota data are less satisfactory, with larger percentage differences in weight measurement. With charge amplification of 15 nC/volt, random differences between static and dynamic weight were found to be 1418 lbs below 10,000 lbs and 16.7% above this value. Overall random differences for all axles and axle groups were 16.5%. These differences may result from characteristics of the approach profile, or could be related to the low pavement rigidity at this site. Further work is needed to assess the AWACS performance at a range of sites on asphalt cement concrete (ACC) pavements.

4. Systematic differences for random samples of vehicles were generally less than 2%, due to the calibration procedure utilized in the tests associated with the need to recalibrate after each equipment upgrade. Longer-term appraisal of calibration factor stability is now required, including an assessment of self-calibration performance.

5. Axle spacing measurement accuracy is very high in all tests (± 1.5") and should satisfy all user needs.

6. Test vehicle results indicate that individual test vehicles are generally not representative of the vehicle population. For this reason, calibration of the AWACS using test vehicles is considered inappropriate.

7. Unusually large static/dynamic weight differences associated with certain vehicles appear to be a function of the design particular to that type of vehicle. This has important implications for WIM performance specifications, vehicle design and pavement loadings.

8. Analyses indicate that over the temperature range in which the second generation tests were conducted (70 degrees F to 100 degrees F), there is no appreciable change in calibration or axle weight accuracy corresponding to changes in temperature. Further tests are required over the coming winter to fully determine system performance at low temperatures.

9. Random differences for offscale vehicles are higher than for those which are onscale. From a sample of 435 trucks in Iowa, 26 were identified as offscale. Analysis indicated that they were approximately 2 feet right or left of the wheel track. From a sample of 527 vehicles in Minnesota, 71 were classed as offscale, using a shorter offscale sensor. The shorter sensor did not create any increase in weighing accuracy over that achieved in Iowa.

Vehicle Classification Accuracy (AWACS2)

The analysis of vehicle classification data collected throughout this project led to the following major conclusions on absolute and compensated accuracies, where absolute accuracies relate to individual vehicles and compensated accuracies to periodic totals.

1. In Iowa, the second generation AWACS achieved absolute and compensated accuracies of 95.2% and 98.9% respectively for all vehicles. The classifier also gave excellent results for trucks and buses, with absolute and compensated accuracies of 94.8% and 97.6% respectively.

2. The second generation system in Minnesota gave absolute and compensated accuracies of classification for all vehicle types combined of 89.4% and 98.9% respectively. Trucks and buses have absolute and compensated accuracies of 90.3% and 94.0% respectively.

3. The overall count accuracy is very high with less than 0.1% of vehicles being missed or double counted in Iowa and less than 0.4% of vehicles being missed or double counted in Minnesota.

4. Results indicate that enhanced classification routines implemented following the tests in September and December 1986 significantly improved compensated accuracies between particular categories of vehicle, particularly between cars and pickups.

5. The enhanced classification logic for trucks and buses gives a statistically significant increase in accuracy for these categories of vehicle.

Tire Length and Width (AWACS2)

The analysis of tire length and width data collected in Iowa in May 1987 and in Minnesota in September 1987 led to the following main conclusions.

1. The second generation AWACS equipment is capable of measuring tire contact lengths and widths with a random error of between one and two inches. Systematic differences in static and dynamic tire measurements can be reduced to less than half an inch by the use of a simple additive correction.

2. The results suggest that accuracy of tire contact widths on lead axles is greater than that on other axles. This may be due to the incidence of single and double tires on lead and other axles respectively.

Final Recommendations

Three final recommendations emerge from the analysis of the second generation AWACS weigh-in-motion results, which have considerable significance for WIM performance specifications. These are as follows:

1. Calibration (or checking the self-calibration) should be carried out using random samples of trucks, weighed statically, making comparisons between static and dynamic weights in such a way as to minimize systematic differences for the actual truck population observed at the site.

2. Verification of WIM performance should use standard test vehicles on repeated runs, to examine the capability of the WIM to give consistent results representative of each truck's unique interaction between the pavement and its suspension system.

3. Assessment of the site characteristics and vehicle population characteristics requires comparisons between test vehicle data and random vehicle data. The difference between the scatter of results achieved with test vehicles and the scatter

of results observed with random vehicles will indicate the characteristics of the site in terms of pavement approach profile and vehicle population.

CONCLUSIONS

The overall conclusion of the project is that for PCC pavements, low-cost weigh-in-motion giving accuracies comparable to those of conventional WIM equipment is now a proven reality. Procurement specifications are presented in the final report for complete systems including electronics hardware, software, sensors and all other components. They provide sufficient detail for manufacturers to follow necessary approaches and reach required standards of performance without restricting the peripheral areas of technical design.

Within this project, preproduction systems have been demonstrated under actual traffic volumes, pavement types and climatic conditions experienced in two states. Two generations of low-cost WIM equipment have been developed and tested. Comprehensive results of all tests are presented in the final report.

This project does not answer all the questions on low-cost weigh-in-motion; further work is required and will continue as the systems spread more widely and as operational experience broadens. What has been accomplished is technology transfer of piezo cable WIM from research to manufacturing, and initial implementation through the states. Considerable progress has been made, and much has been learned. The states must now take up the challenge of using the new techniques in their vital continuing truck traffic monitoring and appraisal activities.

Development of a Low-Cost Automatic Weight and Classification System (AWACS)

Final Report and Specifications

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ABSTRACT

This report covers work undertaken between May 1986 and November 1987 in the development and demonstration of a low-cost Automatic Weight and Classification System (AWACS). The work was carried out by Castle Rock Consultants (CRC) for the States of Iowa and Minnesota, in association with the Federal Highway Administration. An AWACS procurement specification and details of the results of the project are included.

The low-cost AWACS developed and tested in this project utilizes piezo-electric cable sensors installed across the full width of a single traffic lane, connected to a roadside microprocessor unit. The units can produce reliable truck weight and classification data in real time, for vehicles operating at normal highway speeds. The data can be stored, summarized and/or transmitted to a central point by telemetry.

The procurement specifications developed in this demonstration project will form the basis for the low-cost weigh-in-motion (WIM) element of the Heavy Vehicle Electronic License Plate (HELP) program. The equipment may also be utilized within the Strategic Highway Research Program (SHRP) and other state or federally-mandated truck weight monitoring programs.

Work began on the 19-month demonstration on May 1, 1986. The agreed work program was completed at the end of November, 1987, on time and within budget. The study has shown that on Portland Cement Concrete (PCC) pavements, the AWACS is capable of meeting the needs of state and federal highway agencies, producing accuracies comparable to many current commercial WIM devices. This is being achieved at a procurement cost of around $6,000 for a single-lane, basic system.

1. Introduction

1.1 STUDY OVERVIEW

Recent developments in microprocessor and traffic sensor technology have for the first time made low cost weighing and classification of trucks a practicable proposition. Specific advances have been made in both permanent and portable sensors for low-cost weigh-in-motion (WIM), while robust microprocessor equipment has been proven for signal processing, data storage and transmission of information.

Piezo-electric cable technology provides a means of developing a low cost sensing device that can unobtrusively collect representative truck weight data. The overall aim of this study was to translate international research and development efforts carried out over several years into operational systems for low-cost truck classification and weighing, designed to meet the needs of state and federal highway agencies.

This report covers work undertaken between May 1986 and November 1987 in the development and demonstration of a low-cost Automatic Weight and Classification System (AWACS). The work was carried out by Castle Rock Consultants (CRC) for the States of Iowa and Minnesota, in association with the Federal Highway Administration. The report also includes specifications developed during the project, suitable for the immediate procurement of production AWACS equipment from manufacturers. The results of the project serve to provide proven hardware and software designs in the public domain that can be manufactured by competing companies.

1.2 PROBLEM STATEMENT

Truck data are used for many purposes. Some of the prime needs are identified below.

* Federal Highway Administration (FHWA) mandated programs require truck weight, bridge formula compliance and equivalent single axle load data.

* The Strategic Highway Research Program (SHRP) includes a Long Term Pavement Performance study (LTPP) collecting truck class/weight, environmental and pavement condition data at 2000 sites over 20 years.

* The Heavy Vehicle Electronic License Plate (HELP) program aims to provide much broader information on truck operations, combining automatic vehicle identification (AVI), automatic vehicle classification (AVC) and weigh-in-motion (WIM), at up to 6000 sites across the nation.

* State government requirements include truck data for use in the highway programming process, pavement and bridge design, monitoring compliance with weight limits, assessing the cost responsibilities of different truck types and as an input to pavement management systems.

These diverse programs share a common need for affordable and representative truck weight and classification data.

Present techniques for truck weight data collection are very costly to all concerned. Currently, in Iowa, the biennial truck weight study collects data every second year, on weekdays during summer months at nineteen locations. In 1985, a total of 18,500 truck weight records were obtained within the study. While valuable, the present method has several disadvantages.

1. Only a limited amount of data can be collected at specific sites;

2. data may be biased due to weighscale avoidance;

3. the trucking industry suffers delay costs;

4. dollar costs to the State are high;

5. crews are exposed to actual hazard on the highway.

A similar situation existed in Minnesota. Now, with three permanent WIM sites in the State, more vehicles are weighed every six weeks than were weighed in the previous forty-eight years of static weighing. This has produced a vast improvement in the quantity and quality of data available for pavement design and maintenance. The high cost of Minnesota's present WIM system, however, limits its application to a small number of sites, probably unrepresentative of the State as a whole.

Other states have similar needs for affordable, representative low-cost WIM. Washington State Department of Transportation has undertaken a study similar to that of Iowa/Minnesota, taking existing piezo equipment and monitoring its performance in the field. The piezo system tested in Washington was manufactured by the French Laboratoire Central des Ponts et Chausees (LCPC) - the central laboratory of roads and bridges. It did not meet state requirements for weigh-in-motion performance (Hallenbeck et al, 1987).

The heavy vehicle electronic license plate (HELP) program envisions a network of low-cost weigh-in-motion and vehicle classification sites across the continental United States. The

HELP program is ambitious, complex and controversial. However, studies predict that its benefits to government and industry could outweigh the significant costs of implementing the system.

Like HELP, the Strategic Highway Research Program (SHRP) anticipates a requirement for a low-cost truck weighing and classification system. SHRP is a $150 million, five year investigation of current practice and opportunities in the field of highway pavements and bridges. One aspect of the SHRP program is the twenty-year Long Term Pavement Performance study (LTPP) which aims to correlate pavement life with traffic loadings and environment. SHRP will need networks of permanent WIM and AVC sites, whose cost must be low enough to give much wider coverage than has been achieved to date.

Piezo-electric axle load transducers offer a solution, having been developed in Europe and refined over the past seven years. Research programs in England, France, West Germany, the Netherlands and Scandinavia have established the feasibility of low-cost WIM and classification systems based on piezo-electric technology. Work is now in progress in several countries which aims to demonstrate commercial systems using this new approach.

1.3 OBJECTIVES

Unlike presently available WIM systems, which are too expensive to permit the widespread deployment necessary to obtain representative data, piezo-based WIM promises to be affordable. This demonstration project was conceived therefore to bring this promising concept to proven reality.

This required coupling state-of-the-art piezo-electric transducer and microprocessor technology with the latest techniques of automatic vehicle classification. These new techniques should result in better information on truck classification and weights becoming available at low cost, providing a database that can be used for improved planning, design and management.

Within the overall framework of the project, the following detailed objectives were identified:

1. To provide a thorough review of state-of-the-art piezo-electric axle load sensing systems.

2. To use the review findings to evaluate the feasibility of meeting the contract requirements, wholly or in part.

3. To procure and install preproduction low-cost permanent automatic weight and classification systems.

4. To supplement existing tests and evaluate preproduction system accuracies for both weighing and classification using laboratory and field tests.

5. To further establish the effects of environmental conditions such as temperature, humidity and power supply fluctuations on overall system performance, using laboratory and field tests.

6. To determine the preproduction systems' reliability and durability under representative climatic conditions, traffic volumes and pavement constructions, through field evaluations in Iowa and Minnesota at one site on Portland Cement concrete (PCC) and one site on asphaltic concrete.

7. To evaluate the effect of using multiple transducer arrays on system weighing accuracy.

8. To determine the impact on vehicle classification accuracy of using an inductance loop in conjunction with piezo-electric transducers.

9. To assess the feasibility of using a diagonally mounted sensor to measure dynamic tire width and predict the resulting tire contact pressure on the pavement.

10. To develop hardware and software techniques for tire width and contact pressure estimation and to evaluate their performance through the field test program.

11. To establish the ability of the piezo-based vehicle classification system to meet the requirements of the FHWA vehicle categories defined in the traffic monitoring guide.

12. To examine the feasibility of developing a self-calibration feature based on lead axle weights of 3S2 tractor/semi-trailer trucks, and carry out field trials where appropriate.

13. To develop and begin to apply the system to meet the needs of the Strategic Highway Research Program (SHRP), state weight monitoring programs, the Heavy Vehicle Electronic License Plate (HELP) program, and FHWA-mandated programs of truck weight data collection.

14. To use the findings of the evaluation to prepare procurement specifications for low-cost weigh-in-motion and automatic weight and classification systems including optional features such as tire width measurement, with a minimum system price of under $5,000.

1.4 STUDY APPROACH

In order to achieve the various objectives of the project, a series of research and development tasks were undertaken. These tasks are summarized in this section, and expanded later, each task forming a chapter of this report. A bar chart illustrating the inter-relationship and scheduling of the major study tasks is presented in Figure 1.1.

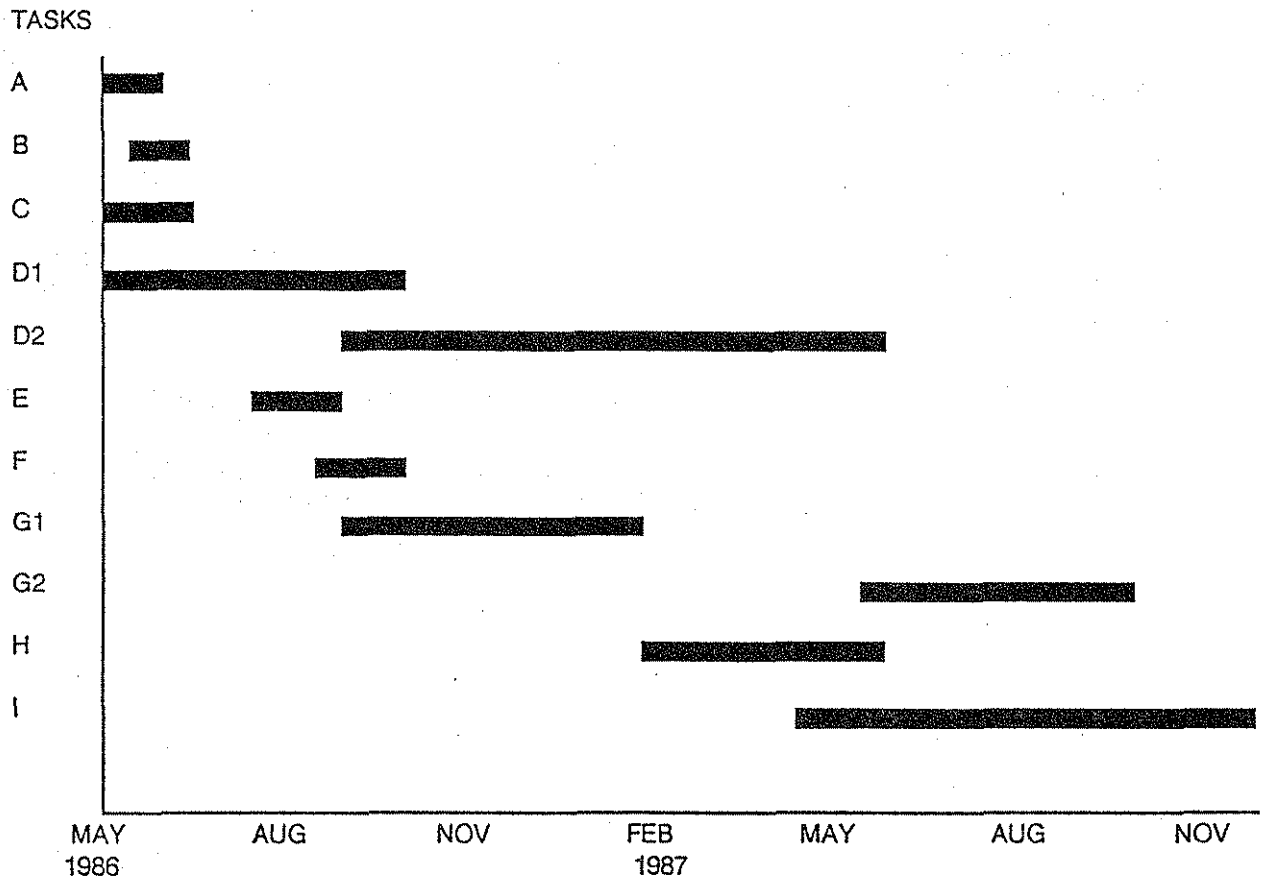


Figure 1.1 Schedule of major study tasks

Task A - Review of Previous Work

Task A, described in Chapter 2, involved a comprehensive review of state-of-the-art piezo-electric axle load sensing systems. This was international in scope, covering the major development efforts undertaken in the UK and France, together with smaller-scale efforts notably in Holland, Denmark, North America and Australia. The primary aims of the review were to ensure that future developments of piezo-electric systems were soundly-based, and to increase the states' knowledge base for this type of technology.

This review task included the state-of-the-art in the following subjects:

(1) fundamental properties of piezo-electric load transducers;
(2) effectiveness of alternative transducer mounting techniques;
(3) interpretation and processing of signals from piezo-electric systems;
(4) transducer assembly performance.

The state-of-the-art in each of these key areas was measured against the requirements of this project. The feasibility of meeting the requirements based on piezo-electric technology was assessed taking account of technical constraints, economic constraints, and the needs of potential system users.

Task B - Development of Testing and Analysis Program

A testing and analysis program was developed to establish preproduction system performance and reliability in PCC and asphalt pavements during the various seasons over one year. The program was designed to fully assess the performance of the axle load transducer assemblies, signal processing electronics and all other aspects and components of the preproduction systems. The test program is detailed in Chapter 3.

The study team assessed the validity and accuracy of existing system performance data, and defined what specific additional data were required from the test program. The following test and analysis categories were included:

* sensor response tests
* environmental and power supply tests
* WIM accuracy evaluation
* classification accuracy evaluation
* axle spacing and speed measurement accuracy evaluation
* system reliability assessment
* system durability assessment
* transducer configuration evaluation, including
  - dynamic tire width and length measurement
  - effect of multiple transducers on WIM accuracy

- effect of inductance loop on classification accuracy.

This task also specified the statistical parameters and procedures to be used in evaluating the preproduction systems' performance in each of the test and analysis categories outlined.

Task C - Site Selection

The study team assisted the states in assessing the suitability of alternative locations for the piezo-electric systems in each state. Site installation details were prepared and passed to each state prior to installation of the preproduction systems.

As part of this task, a quantitative scheme was devised to evaluate sites for low-cost AWACS systems, based on the conditions at specific locations, and on their relative importance. This aims to give the states a consistent basis on which to assess the suitability of sites for installation of production AWACS systems. The site selection scheme is described in Chapter 4.

Task D - Preproduction Systems

Preproduction systems were supplied by an established vendor of traffic monitoring systems for installation at the test sites in Iowa and Minnesota. Two generations of systems, detailed in Chapters 5 and 10, were supplied at different stages of the program, allowing comprehensive testing and analysis of all the operational factors included in the project.

D1 First Generation Systems

Two first generation systems were supplied at the beginning of the test program for installation at the field test sites. These each covered one lane and consisted of five piezo-electric sensors, each fixed in a specially developed mounting; one inductance loop; computer hardware and software for signal processing; computer hardware and software for data storage and transmission; and all interconnections.

D2 Second Generation Systems

The second generation systems initially utilized the same sensors installed at the beginning of the program, but incorporated desirable modifications identified during the first phase. The second generation equipment included a number of features additional to those of the first generation systems, including prototype software and hardware to measure dynamic tire width and length. They also contained additional diagnostic checks and a prototype self-calibration feature. The software and hardware for the additional features were developed during the first phase of the test program, utilizing the data collected and analyzed at the field test sites.

Task E - Laboratory Testing

Laboratory and environmental tests were conducted on preproduction systems and components prior to installation, as specified in Task B. Results of the laboratory tests are presented in Chapter 6.

Uniformity tests were carried out on the mounted sensors using an electronic servo-controlled hydraulic testing machine. These established the extent of variation in sensor output with position along the sensors' lengths. Linearity of response to load at a given position was also checked for each sensor at this stage. This was done using the same apparatus, generating controlled pulsed loading to simulate different wheel passages at representative positions on each sensor.

Environmental testing of the preproduction systems encompassed all system components and subsystems, including sensors and all electronics. These tests aimed to ensure that the system was capable of operating in the extreme climatic conditions experienced periodically in the two states.

Tests on the susceptibility of the preproduction systems to power supply fluctuations were also carried out in the laboratory.

Task F - Installation and Calibration of Equipment

Detailed instructions were provided to the states for the field installation and calibration of the preproduction systems in Iowa and Minnesota. The project team supervised transducer assembly and installation of all electronic equipment and interconnections by the states. The team also supervised state calibration of the systems, and tested all subsystem and system outputs before and after calibration.

Installation of sensor hardware involved slot-cutting and fixing of the piezo-electric sensors and inductance loops in the slots. Installation of system electronics was conducted in parallel and upgraded at intervals throughout the project. Installation procedures are detailed in Chapter 7.

Task G - Evaluation of System Performance

G1 First Generation Systems

Once the equipment had been installed and initially calibrated, evaluation of the first generation system performance took place over a five month period in accordance with the test program developed in Task B. This involved two principal efforts, data collection and data analysis, described in Chapter 8.

The major effort in data collection came from the states, who collected field data from the sites in accordance with the agreed test plan. This effort was coordinated by the project team working with Iowa and Minnesota DOT staff.

Data analysis undertaken for the first generation system concentrated on accuracy and reliability. An assessment was made of the system's operation after five months, so that any necessary modifications could be determined at that stage for incorporation in the second generation equipment.

G2 Second Generation System

Following the evaluation of the first generation system, a second generation system was installed and calibrated at the two sites. Additional features and system modifications were tested in order to determine their impact on overall system performance. The results of the second generation system appraisal are presented in Chapter 11.

Task H - System Modifications

System modifications recommended following the evaluation of first generation system performance were implemented in stages, and are described in Chapter 9.

The precise nature of modifications to the systems was determined from interim results and analyses of the field and laboratory data collection efforts. It also depended on the preliminary results of the life cycle cost analysis. Modifications involved alterations to sensor configurations, electronics hardware and software.

Comparisons were made between data obtained before and after the modifications to determine whether there were any significant changes in performance.

Task I - Final Report and Procurement Specifications

The end products of the study are performance specifications suitable for the procurement of equipment from manufacturers. These are for complete systems including sensors, electronics hardware, software and all other components. Procurement specifications correspond to different levels of system ranging from a simple, low cost, basic system to a fully automated weight and classification system incorporating optional extra features such as tire width and length determination or enhanced memory capabilities.

1.5 SUMMARY

This chapter has summarized the aims of the demonstration project and has outlined the tasks to be accomplished. Subsequent chapters of the report contain detailed descriptions of the work undertaken under each of the tasks presented above. Summaries and conclusions are given at the end of each chapter, and are drawn together finally in Chapter 13. The executive summary, under separate cover, outlines the main points and recommendations from the study as a whole.

2. Review of previous work

2.1 INTRODUCTION

This chapter describes the project's review of state-of-the-art piezo-electric axle load sensing systems, covering the major development efforts undertaken in the UK and France, together with the smaller-scale efforts undertaken in Holland, Denmark and North America. Much of the review had been carried out prior to the start of the project, as was indicated in the proposal. The primary aims of the review were to ensure that future developments of piezo-electric systems are soundly-based and to increase the states' knowledge base for this type of technology. To achieve this end, the following key areas were considered as part of the review.

1 fundamental properties of piezo-electric load transducers

- piezo-electric materials:

  causes of the piezo-electric effect
  theory of piezo-electric cable operation

- cable response to different stress conditions:

  effects of internal geometry on sensor operation
  effects of loading frequency on sensor response
  effects of loading width on sensor response

- mechanical properties and cable durability

2 effectiveness of alternative transducer mounting techniques

- requirements for a successful mounting design:

  minimal sensitivity variations in the mounted sensor
  minimal sensitivity to bending of the pavement
  output independent of loaded width
  low cost of construction
  high durability
  simple construction and installation

- alternative mounting techniques:

  filled metal channels
  rubber mats
  epoxy blocks
  oil-filled tubes
  air-filled tubes
  steel 'sandwich' mountings
  surface mountings
  dual element sensors

3 interpretation and processing of signals from piezo-electric systems

- vehicle weighing in motion:

  peak signal approach
  signal integration approach

- vehicle classification:

  2 piezo-electric sensors alone
  2 piezo-electric sensors + 1 inductance loop
  1 piezo-electric sensor + 2 inductance loops

- dynamic tire width and contact pressure measurement

- diagnostic checks

- self-calibration

4 transducer assembly performance

- laboratory tests in the UK and France

- track tests in the UK

- field tests in the UK, France, Holland, Denmark and North America.

The state-of-the-art in each of these key areas was measured against the requirements of the demonstration project, and the feasibility of a low-cost AWACS system based on piezo-electric technology was assessed taking account of technical constraints, economic constraints and the needs of potential system users.

2.2 PREVIOUS WORK

The review of state-of-the-art piezo-electric axle load sensing systems included previous work on the fundamental properties of piezo-electric axle load sensors, on alternative sensor mountings, the state-of-the-art in signal processing, and on sensor performance under laboratory, track and field conditions.

In 1971 the Philips Corporation patented a piezo-electric cable known as Vibracoax (Philips, 1971). It is a 3 mm diameter cable (approximately 1/8" diameter) consisting of an inner central copper conductor and outer copper sheath, separated by a densely packed piezo-electric powder. Field trials undertaken in the early 1970s in Paris and Nancy (Siffert, 1974, Gloagan et al, undated) used unmounted cables buried in the pavement surface. Vehicles of known weight were driven over the installation and the piezo-electric sensor output recorded. Tests on the effect of speed and contact length of the tire indicated that integrated signals rather than peak values showed reasonable correlation with static weights but that delicate calibration of the sensor was necessary.

A conventional dynamic axle weighing system was initially developed in France by the Laboratoire Central des Ponts et Chaussees (LCPC) (Siffert, 1972). Up to 1978, more than 50 scales had been installed in France and another 10 were in use elsewhere. The unit consisted of upper and lower steel platforms set in the pavement and separated by six piezo-electric quartz crystal transducers.

Currently, 150 piezo cable weigh-in-motion systems are being installed in France and two pieces of equipment have been developed to collect and process the data (Siffert, 1986). The two data collection devices are the SAFT (Station D'Analyse Fine du Trafic) scale system and the AP-16 scale. Hallenbeck et al (1987) conducted tests on these systems for the Washington State DOT. They concluded that even the more expensive system (SAFT) at $37,000 did not meet the HELP WIM specifications, producing standard deviations of static/dynamic weight differences of around 20%.

A Norwegian piezo-cable WIM system is described by Johansen (1986). This is designed to survive arctic winters when vehicles use studded tires and snow chains. The piezo-electric cable is placed four inches below the pavement surface for protection. The vertical load is transferred to the piezo-electric cable by a 'piston' of a relatively solid compound called Rebafill.

In Australia a system called P-WEIGH is being developed under contract to the Australian Road Research Board (ARRB) by La Trobe University (Stewart, 1986). This system uses the peak sensor current and tire contact time to estimate axle weight.

In Denmark, similarly, the National Road Laboratory has been working on low-cost weighing sensors since 1980 (Banke, 1986). No commercial systems have been developed to date, but a prototype was demonstrated during an OECD meeting held in

1986 at the UK Transport and Road Research Laboratory (TRRL) test track at Crowthorne, England.

In Britain, a four-phase investigation is described by Davies et al (1981, 1982, 1984, 1985). The work was carried out under contract to the UK Transport and Road Research Laboratory. Phase One of the research project investigated the fundamental properties of piezo-electric axle load sensors. The composition and theory of operation of the sensors, and causes of variations in sensor sensitivity were examined. Sensor mountings were identified as the major cause of inconsistencies in the output from these sensors, though lesser problems may be associated with manufacturer's quality control, particularly when cable was supplied from the manufacturers coiled.

During the second phase of the research project, several possible causes of variations in unmounted sensor sensitivity were eliminated by laboratory tests, leaving internal geometry and bending of the cable showing significant relationships with output variations along the length. The variation of output with tire width was greatly reduced by the use of rubber-faced platens between the load and the cable, which has important implications for the mounted sensor design.

Phase Three of the project involved the further development of prototype sensor mountings and the evaluation of the designs through laboratory testing. The assessment of each composite sensor design was on the basis of laboratory tests both in a servo-controlled hydraulic loading machine and in a moving wheel test facility. The uniformity of response of the sensors was assessed, together with additional trials to determine the likely effects of temperature and loading width on sensor response. Tests on new piezo-electric cables obtained from the manufacturer without bending were also conducted using both pressure jacket testing equipment developed by the manufacturer and the hydraulic load testing rig used in Phases One and Two.

The assessment of the performance of the many sensor designs tested enabled a preferred sensor to be selected on the basis of uniformity of response, likely construction cost, and durability. A specification and design drawings for the preferred sensor were produced. Phase Four of the research involved a prototype study and evaluation of piezo sensors constructed according to the preferred designs of Phase Three.

Sensors constructed to the same preferred design were subsequently installed at test sites and their performance is currently being investigated through a series of field trials. Results suggest that reasonable accuracies can be expected from field appraisals of the preferred sensor design.

Building on this brief review of recent and current work on piezo-electric cable, the following sections summarize the state-of-the-art relating to key issues associated with piezo-electric axle load measurement systems.

2.3 FUNDAMENTAL PROPERTIES

Understanding of the fundamental nature and properties of piezo-electric cables was one of the most important areas of background information that has contributed to the success of this project. The principles of operation of the piezo-electric sensor had to be well understood in order to produce a good sensor design, and to make any modifications necessary during the course of the project.

Piezo-electricity is 'pressure electricity'. When a force or pressure is applied to certain parallel faces of a piezo-electric crystalline material, electrical charges of opposite polarity appear at the parallel faces. The size of the piezo effect depends upon the direction of the force in relation to the axes of the crystal. Another characteristic is that the piezo effect is dynamic, in that charge is generated only when the forces are changing. Should a constant force be applied, the initial charge will decay.

The sole source of supply of piezo-electric cables of the type so far utilized in the Iowa/Minnesota project is a company called Thermacoax, which is a French subsidiary of the Philips group. The 'Vibracoax' cable produced by Thermacoax utilizes a piezo-electric material in the form of a compressed powder which acts as the dielectric of the copper-sheathed coaxial cable. During manufacture, the powder is poled by a radial electric field applied between the inner and outer conductors, producing a piezo-electric response to radial stress.

The behavior of piezo-electric cables under bending conditions is of primary importance in understanding mounted sensor performance. Unmounted and mounted cable sensors tested during the early stages of the UK development effort produced very different results when loaded under similar conditions. The output signals from a simply-mounted sensor were shown to be dependent on the radial compressive stress, longitudinal compressive stress and tensile stress induced within the cable itself under various loading conditions. These in turn depend upon the position of the cable within the mounting, relative to the neutral axis. In highway installations, the bending of the pavement under traffic loading can produce sufficient longitudinal stresses in the cable to completely override the signal produced due to the radial compressive stress imposed on the cable by a wheel passage. This highly undesirable effect can only be reduced by careful design of the sensor mounting.

2.4 ALTERNATIVE TRANSDUCER MOUNTINGS

The importance of the mounting design used with piezo-electric cables cannot be overstated. Depending on the mounting used, the performance of piezo cable sensors can range from being virtually useless to being very suitable for use as an axle load sensor. As well as aiming to reduce or eliminate stresses produced by bending of the pavement,

mountings should also aim to eliminate the variations in output with loaded width which are inherent in unmounted cable. Mountings should also be durable and resistant to permanent deformation under traffic loading. A number of mountings have been developed and tested in the UK, France and Holland, some of which are briefly described below.

The current mounting utilized in the French research and development effort was developed by the Laboratoire Central des Ponts et Chaussees, following tests on several alternative mounting designs (Peltier, 1984). The cable is mounted in an epoxy resin with foam rubber strips at each side. These are intended to reduce stresses produced by bending of the pavement. The mounted sensor is set into a slot cut into the pavement and bedded on a sand-filled epoxy resin compound. The mounting is surrounded with more resin compound and the pavement surface is slightly domed.

This latest French design is relatively new and is thought to improve on earlier designs. However, problems have been reported with its performance, due to its failure to eliminate the effects of pavement deformations. The French Ministry of Transport is believed to be working on an improved design which may reduce these problems.

The mountings developed by the Dutch have been designed and tested by the Rijkswaterstaat - the Dutch government department responsible for highways and canals (Maessen and van Zwieten, 1983). Their latest work involved field testing of three tentative mounting designs. The first of these consisted of an epoxy bitumen block with the cable positioned approximately one inch below the highway surface. The second utilized a rubber-filled U-shaped steel channel, again with the cable set about one inch below pavement level. The third design tested utilized a different approach, with the cable set into a shallow rubber mat. Field test results indicated that reasonable performance could be obtained from the U-channel design, while the other two gave less favorable responses.

The UK research and development team has tested more than thirty different mounting designs over the past six years, each with the following design considerations in mind:

1 minimizing sensitivity variations in the unmounted sensor;
2 minimizing sensitivity to bending of the pavement;
3 obtaining an output independent of the loaded width;
4 achieving a low cost of construction;
5 achieving high durability; and
6 ease of construction and installation.

Initial mounting designs included several utilizing oil-filled and air-filled PVC tubes, and some with a mild steel 'sandwich' design. Later developments included surface mounting techniques and filled channels. Since the initial tests, the UK team has undertaken considerable further research and development on mounting design. The preferred design was refined in a test program which included consideration of the effects of depth of cover, material hardness and cable diameter. Testing of cables mounted in the refined design has produced what are thought to be the best results obtained in any of the

international research and development efforts. This design, which can be produced by any manufacturer under license to the UK Transport and Road Research Laboratory, formed the basis of the preproduction systems supplied for this project.

2.5 SIGNAL PROCESSING AND INTERPRETATION

Signal processing for weigh-in-motion is currently performed in one of two ways. The first of these is currently utilized by the French research and development team, and uses analog voltage measurements to determine the peak output from high impedance amplifiers connected to the sensors. However, although this approach is valid for systems in which the whole axle load is located on the weight sensor at one time, such as the capacitive weighmat, for piezo-electric sensors and other similar 'strip' sensors it can lead to considerable errors in the axle weights produced. This is because the output of narrow cable or strip sensors is related to the tire contact area, as well as the contact pressure.

The second approach takes account of the relationship between output and tire contact area by digitally integrating the output from the piezo-electric sensors after charge amplification. This approach to signal processing has a much sounder theoretical basis, as is borne out by the improved results it has produced.

The classification function of the AWACS system can be performed utilizing two piezo-electric sensors alone, or alternatively two piezo-electric sensors with an inductance loop. Use of two piezo cables with an inductance loop is a well-established configuration, initially developed at the UK Transport and Road Research Laboratory (Moore et al, 1982). The piezo cables simply act as axle detectors, with the inductance loop serving as a vehicle presence detector. The signals from the inductance loop can be used to distinguish individual vehicles. Classification is carried out principally on axle spacings, with additional parameters to distinguish between certain classes of vehicles.

Classification software using two piezo-electric sensors alone is a more recent development. This software uses a minimum of sensor hardware in or on the highway pavement.

An alternative approach to minimizing costs is to use one piezo sensor per lane with two inductive loops. This produces a longer array with less accurate speed and weight measurements; however, it would serve to minimize investment in piezo cables.

Determination of dynamic tire width and contact pressure through interpretation and processing of the signal output from a piezo-electric system had yet to be achieved when this project began. However, preliminary ideas had been developed involving the use of a diagonal sensor, and measurement of both parameters appeared to be practical.

Software algorithms specifically designed for diagnostic checks in piezo-electric cable systems had also yet to be fully developed at the start of this project. However, diagnostic checks were included in a number of weight or classification systems available at that time. The study team therefore aimed to adapt suitable routines for use with piezo-electric systems during the early stages of this project, so that a number of diagnostic checks could be implemented and tested for the AWACS system.

The system which probably includes the highest level of diagnostic checks at present is the automatic vehicle classification system developed by the UK Transport and Road Research Laboratory (Moore and Willis, 1984). Most of its software checks are aimed at diagnosing sensor failures, which are the most likely form of failure of any AWACS system. Checks to diagnose impending faults in the sensors could also be included in the AWACS system. These would anticipate sensor failure before it reached a critical stage, and allow repairs to be made.

Other diagnostic features are included in several commercial WIM or AVC systems. These include software which looks for speeds, axle weights or axle configurations which are highly improbable. Monitoring of battery voltages and data stored in memory are two other diagnostic options which have been included in many systems, and which may be desirable in the AWACS production system.

2.6 TRANSDUCER ASSEMBLY PERFORMANCE

Field testing of transducer assemblies has been international in scope, with test programs having been conducted in the UK, France and Holland. Track testing of piezo-electric systems has been less extensive to date, with most published material concentrating on laboratory or field trials. Early field trials were reported in France in the 1970s, as already described. Small-scale trials have continued on various prototype systems up to the present time.

Dutch field trials of piezo-electric cables involved three different sensor assemblies installed on the A29 near Numansdorp, which is a major Dutch freeway. Comparisons were made between sensor output and weight measurements taken from a nearby weighscale installation, to obtain accuracy figures for the prototype systems.

Field trials with piezo-electric cable sensors have also been conducted in the UK (Moore et al, 1982). The UK Transport and Road Research Laboratory has installed transducer assemblies at various sites throughout the UK for evaluation purposes. These include heavily and lightly trafficked sites, so that sensor performance can be assessed for a variety of operating conditions. A mixture of highway categories has been chosen for evaluation purposes, including:

two-lane, two-directional highways;

four-lane highways with median;
six-lane freeways.

A number of performance aspects are being evaluated including those concerned with sensor reliability and durability, as well as accuracy.

Prior to the Iowa/Minnesota project, CRC installed and assessed an array of piezo-electric sensors at a test site near to the company's UK offices and close to a static scale. The sensor array was similar to that proposed for the AWACS system. Research was undertaken to assess the feasibility of using piezo-electric axle load sensors for automatic weighing and vehicle classification. The operational life of the sensors was also examined. Similar research has been undertaken at a second test installation in the UK at Milton Keynes, adjacent to the major freeway running north from London, funded by GK instruments.

More recently, the UK Transport and Road Research Laboratory has funded an experimental piezo WIM sorter at Wylye, near Stonehenge, Wiltshire. Two further installations are currently going ahead in others parts of England. The results of these trials will complement those of the Iowa/Minnesota project.

To summarize, provided that good quality piezo-electric cable is obtained from the manufacturers, cable mounting need not introduce any further errors into the system and satisfactory axle weights can be achieved. Lower grades of cable would be satisfactory for basic vehicle classification, or tire width measurement. Durability of the mounted cable appears to be satisfactory, though further experience is needed before firm conclusions can be drawn.

2.7 RECOMMENDATIONS

Four key issues were addressed in Task A, in assessing whether the state-of-the-art provided a basis from which to proceed with this project. These were:

1. Is it feasible to expect to advance the technology base to the point where a system can be procured that will:

   * weigh vehicles
   * classify vehicles
   * count vehicles
   * measure speed
   * measure axle spacing
   * measure dynamic tire width

* estimate tire contact pressure

within the duration and budget limitations of this project?

2. Is it economically feasible to expect to procure these systems at the target costs at the end of this project?

3. Is the developed system likely to meet the requirements of the potential users for:

* State data collection programs?
* FHWA-mandated truck weight programs?
* the Strategic Highway Research Program (SHRP)?
* the Heavy Vehicle Electronic License Plate (HELP) system?

4. Would the developed system represent a significant advance on existing systems?

This first question was broken down by function to identify probabilities of success in each area. Past work indicates

* a reasonably high probability of successfully weighing vehicles

* a very high probability of successfully counting and classifying vehicles

* that no problems will be met in measuring speed and axle spacings.

However, the two final functions of tire width and contact pressure measurement had yet to be examined in practice. As such, their chances of success could not easily be assessed when the project started.

The second question on economic feasibility is closely linked to progress with state-of-the-art technology. Recent advances have been made in both permanent and portable sensors for low-cost weigh-in-motion (WIM), while robust microprocessor equipment has been proven for traffic monitoring. International research and development efforts carried out over the past five years can now therefore be translated into operational systems for low cost classification and weighing, designed to meet the needs of state and federal highway agencies.

Assuming that sufficient quality control can be achieved when the cable is produced, piezo-electric axle load transducers promise to be sufficiently accurate, and affordable. First-shot estimates suggest that a single lane AWACS system would cost approximately $5000. This would consist of $2000 for sensors, $2000 for electronic processing of signals

and $1000 for support features. A two-lane system would probably cost in the region of $8000. The actual cost of any system would however depend heavily on total deployment and market forces, as well as on the strength of the dollar in relation to imported system components.

The third question concerns user needs. Current techniques for truck weight data collection are costly. Additionally, data obtained using current methods may be biased and unrepresentative of the traffic stream as a whole. A new approach is needed to acquire better information on truck classification and weights, providing a database that can be used for improved highway planning, design and management.

State and federal truck weight data collection programs have to date been severely limited by the high cost of existing approaches. Static scales are very expensive to install and operate. Weigh-in-motion systems have also been costly, though more attractive than the previous static equipment. States would benefit substantially from affordable weigh-in-motion. SHRP and HELP have also identified very central needs for low-cost weigh-in-motion systems. Both programs have separately determined that low-cost piezo cable WIM offers the best chance of meeting program requirements over the next few years.

The final question compares the proposed system with existing equipment. At present, the lowest cost weigh-in-motion is based on the capacitive weighmat, with monitoring electronics marketed by the Golden River Corporation, Streeter-Richardson and Truvelo. The capacitive weighmat represents a major advance over earlier equipment, but its significant cost and obvious lack of permanence limit its application.

A lower-cost, portable capacitive strip was also developed under contract to the Federal Highway Administration, which if in commercial production could overcome cost barriers associated with the weighmat. However, like the weighmat itself, capacitive strips cannot be used in the snow belt for substantial periods of the year, and are suitable only for portable applications.

The study team's conclusion from its review of previous work was that it should be feasible to meet the requirements of this contract utilizing piezo-electric technology. The team recommended that the demonstration project should therefore proceed, with the aim of bringing this promising concept to immediate reality.

3. Development of test program

3.1 INTRODUCTION

This chapter details the test program prepared for the states to appraise the performance of AWACS sites within their jurisdictions. The test programs were later executed by the states in cooperation with study team members.

The testing and analysis program aimed to establish preproduction system performance and reliability in PCC and asphalt pavements during the various seasons over one year. The original program was amended to achieve compatibility with the Heavy Vehicle Electronic License Plate (HELP) WIM Performance Specification contract being executed by Texas Transportation Institute (TTI). The program assessed the performance of the axle load transducer assemblies, signal processing electronics and other components of the preproduction systems.

The following testing and analysis categories were included:

(a) Laboratory Tests

* sensor response tests
* environmental tests
* power supply tests

(b) Field Tests

* WIM random vehicle evaluation
* WIM test vehicle evaluation
* classification accuracy evaluation

(c) Long-Term Tests

* system reliability assessment
* system durability assessment
* life cycle cost analysis

Statistical parameters and procedures were also developed for use in evaluating the preproduction systems' performance in each of the testing and analysis categories outlined above.

3.2 TRANSDUCER CONFIGURATIONS

Before any tests could begin it was necessary to consider alternative transducer configurations for use in Iowa and Minnesota. In accordance with the project objectives, evaluation of the effect of using different transducer configurations on the performance of the preproduction systems was included in the test program. This included evaluation of the effect of using multiple transducers on weighing accuracy, and determination of the effect on vehicle classification accuracy of using an inductance loop in conjunction with piezo-electric cables. It also included assessment of the ability of a diagonally-mounted cable sensor to measure dynamic tire width, and to predict the resulting tire contact pressure on the pavement.

There were several possible piezo transducer configurations which could be tested in order to attain the optimum layout. Three promising configurations are shown in Figures 3.1 to 3.3.

The first configuration option is based on the 'Z' array, which had been successfully implemented at several sites by the project team. The core of the configuration utilizes two piezo cables mounted at 90 degrees to traffic flow across almost the full width of each traffic lane, with a third piezo cable fixed at a relatively shallow angle of approximately 30 degrees to the first two. If necessary, further piezo cables can be fixed parallel to the two transverse cables to improve weighing accuracy through repeated reading and averaging of truck weights. Use of this configuration on a two-lane highway would involve duplication of the transducer configuration in the second lane, adjacent to the first.

A second configuration option again utilizes two transverse piezo cables with a diagonal cable placed between them. However, in this option the diagonal cable is fixed at approximately 45 degrees across half the lane width, extending onto the shoulder. Two variations on this theme are possible where the system is to be used in the second lane, depending on whether the highway has a paved median. If a paved median exists, the diagonal cable can extend on to the median to form a mirror image of the right lane configuration. If there is no paved median, a short cable can be used to cover half the second lane width. As with option one, further piezo cables could be utilized on either side of the core configuration.

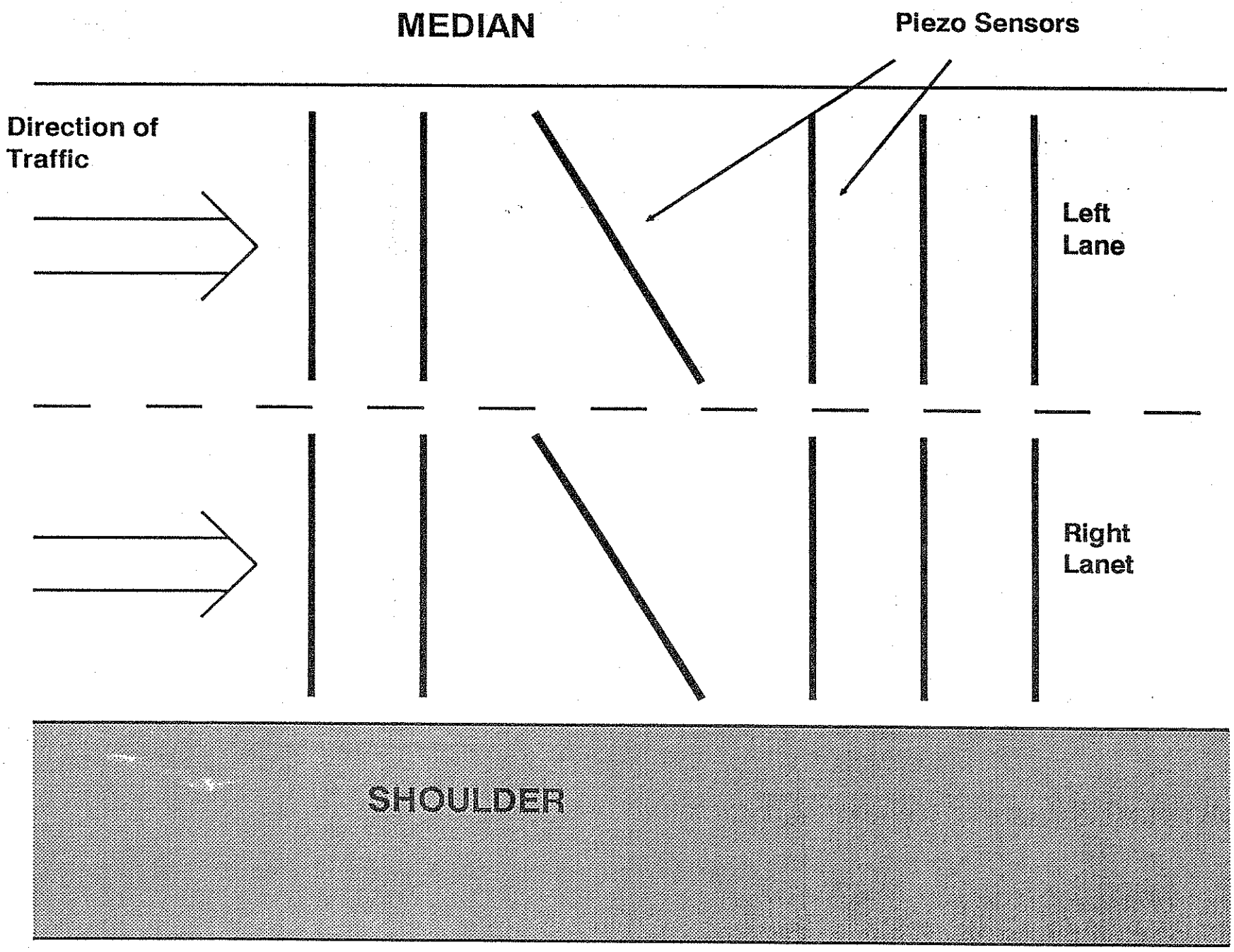


Figure 3.1 Thirty degree sensor configuration

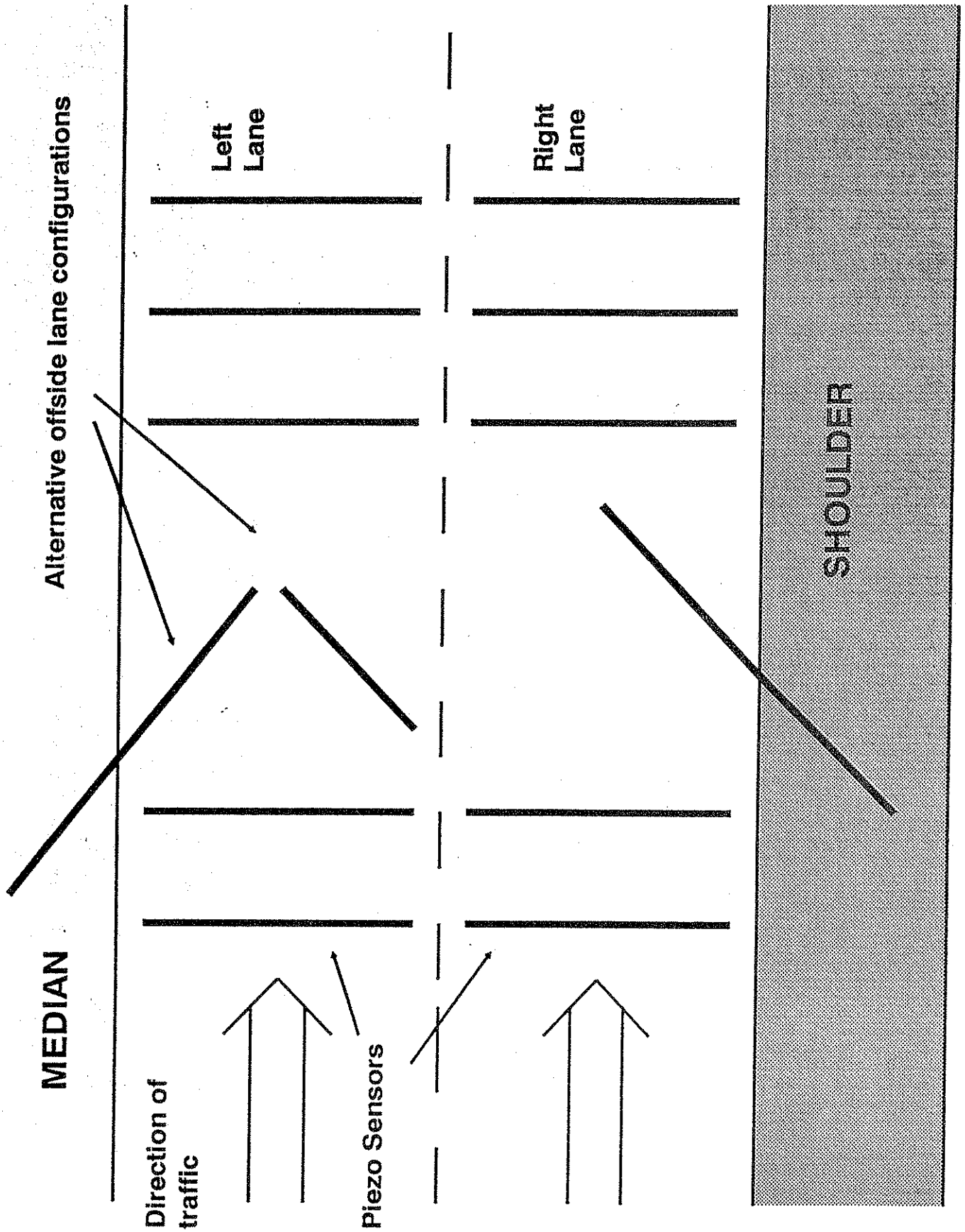


Figure 3.2 Forty-five degree sensor configuration

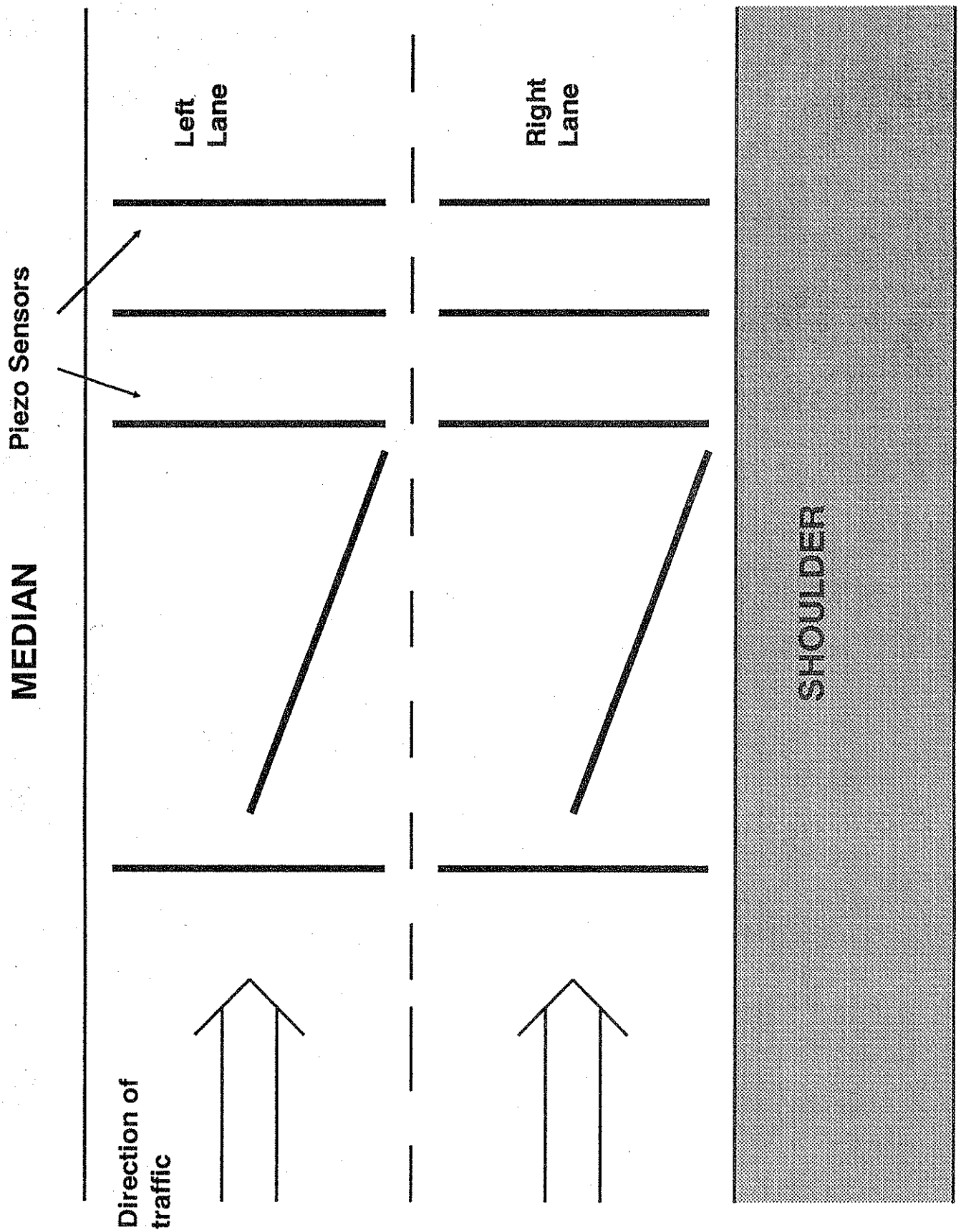


Figure 3.3 Sixty degree sensor configuration

The third configuration option is similar to the other two options outlined. However, in this option the diagonal piezo cable is fixed at a larger angle than either of the two previous options, at approximately 60 degrees to the transverse cables. As with Option Two it covers only half of the traffic lane, but does not extend on to the shoulder. Again, further cables could be utilized on either side of the core array.

For the purposes of the test program, it was agreed that different arrangements would be tested in each state. Final recommendations on site layouts and installation procedures for the initial AWACS systems in both Iowa and Minnesota are presented in Chapter 4.

3.3 TESTING AND ANALYSIS PROGRAM

The study team evaluated priorities for the piezo-cable testing and analysis program. The first priority was for field testing and evaluation of the axle load sensors. The twelve-month test period was principally designed to ensure that the load sensors could be effectively tested over a wide range of traffic and environmental conditions. Sensors were therefore installed at the field test sites at the beginning of the test program, with first generation electronics based on existing technology. Data on sensor performance were then collected throughout the twelve month period. Accuracy, reliability and durability of the sensors were major performance aspects tested. Feedback on design for winter conditions was also obtained by having the sensors operate throughout one complete winter in Iowa and Minnesota.

The second priority for the program was the development and testing of second generation equipment which enabled some of the additional desirable system features, such as dynamic tire width measurement, to be included. Based on past experience it was considered that the testing of the software, hardware and interconnections would require less time than that required for sensor appraisal. The initial period of the test program was therefore devoted to development of the second generation electronics system, which was tested on simulated signals prior to installation in the field.

Once the second generation electronics had undergone preliminary testing, the third priority was the appraisal of the final system at the field test sites. This appraisal covered all aspects of accuracy, reliability and durability for all components of the system, including sensors, signal processing, data transmission electronics and all interconnections.

The statistical parameters and procedures used in evaluating the preproduction systems' accuracy and overall performance over the 12 month test period were also considered. It was vital to the success of the project that the test program was designed on a sound statistical basis in order that the results could be compared with those of other programs and used in developing the procurement specifications. Statistical issues are discussed in Appendix A.

In the design of the statistical procedures, consideration was given to the basic principles of repeatability and sample size. Repeatability, or repetition of the experiment, was important because it provided a basis for determining the significance of observed differences.

The testing program is outlined in the following paragraphs. Field testing procedures and methods of data collection are detailed in later chapters.

3.4 LABORATORY TESTS

Sensor Response Tests

The first test category concerned the response of the sensors to dynamic loading. Two important properties were tested for each sensor: uniformity of response to load along the sensor length, and linearity of the relationship between load and response as loading levels are changed.

The first tests that were undertaken were tests on sensor uniformity. Non-uniformity reduces the performance of the affected sensors for both weighing and classification purposes. Laboratory tests were specified to check that the unmounted cable and mounted sensors were sufficiently uniform for their intended purpose. A typical sensor considered suitable for use in the pavement has a standard deviation of the recorded sensor outputs around 10% of the mean value.

Identical load tests were conducted on the mounted or composite sensor. The force level applied through the test platens approximated to the maximum contact pressure anticipated on the pavement surface. A typical sensor considered acceptable for use in the highway would have a standard deviation around 15% of the mean output value.

Linearity of response was also tested by applying a succession of increasing dynamic pulsed loads at representative points on each sensor. The fundamental theory of operation for piezo cables indicates that the response should increase linearly with load. The typical response of a sensor considered suitable for use in the road has a correlation coefficient of the load/output data greater than 0.95.

Environmental Tests

Environmental tests were to be performed at an early stage of the test program, prior to installation of the system components at the field test sites. These required specialized environmental test chambers, within which conditions could be closely controlled. Both

sensors and electronics were to be tested to ensure that the system and components met the approved specifications. Further details of the high and low temperature tests, and humidity tests, are presented in Chapter 6.

Power Supply Tests

The final category of laboratory tests was concerned with power supply fluctuations. Susceptibility of the system to different levels of variation in the power supply was assessed utilizing standard laboratory equipment in conjunction with specially adapted testing rigs. It was considered that changes of 5% or more in the expected output levels were unacceptable, whether caused by external power supply or internal battery voltage.

3.5 FIELD TESTS

Random Vehicle Evaluation

The WIM random vehicle evaluations were the major type of field test proposed for AWACS appraisals. They served to calibrate the system; to measure its ongoing systematic and random static/dynamic weight difference components, including the effects of temperature trends; to evaluate its axle spacing measurement accuracy; and to determine its ability to measure tire width and tire contact length. These data items were collected simultaneously at the static weigh station and AWACS site during each random vehicle appraisal.

The accuracy of the WIM function of the AWACS was assessed by direct comparison of static vehicle weights, measured at a weighscale, with WIM measurements produced by the prototype system. This accuracy was determined both for single axles or axle groups, and gross vehicle weights. Before these accuracies could be assessed, it was necessary to calibrate the AWACS measured weight against static weight so that systematic bias in the equipment could be initially minimized.

This calibration of the WIM function of the AWACS was achieved by plotting the WIM output against static load for a sample of individual axle loads. The calibration was found by fitting the best straight line through these points and the origin. In the subsequent analysis and testing of the WIM function, this calibration was applied to scale the system output in the prototype equipment. It was expected that the calibration achieved for individual axle or axle group loads would apply equally to gross vehicle weights.

The sample of axles used for this calibration needed consideration. Two options were available: firstly, to band the axle loads into a few groups and collect data in each band;

or secondly, to take a random selection from the population of trucks at the site. The first approach would lead to the points on the calibration being well spread, while the second recognizes the fact that light axles may be less important. It also recognizes the need to achieve a calibration that produces the lowest errors for the vehicle population of greatest interest, namely that of those trucks that most commonly cross the site. Accordingly, it was agreed that a random sample of trucks would be used for the calibration, with a sample size determined by the required accuracy of calibration and the inherent variabilities of the data. An additional advantage of collecting a randomly selected sample was that the same data could be used for the accuracy evaluation.

Because differences in errors between various weight ranges could be significant, it was agreed to incorporate different weight ranges into the analysis. Each of the calibration data sets was sub-divided into axle readings in each weight range. Significant changes in the variance of the static/dynamic weight differences were tested for between the ranges.

The accuracy of axle spacing measurement for the AWACS system was also evaluated during the random vehicle test program. Axle spacing measurement accuracy was determined by comparison of outputs from the system with manual measurements. These comparisons were carried out at the same time as the random vehicle weight accuracy data collection effort. Manual measurements were obtained while the trucks sampled from the traffic stream were being weighed on the static weighscale. Overall accuracy measurements were calculated in terms of systematic and random differences between AWACS and manual measurements.

As assessment was also made of the ability of the AWACS to measure both tire width and tire footprint length. Algorithms were developed in this project to compute these measurements from a comparison between the signals produced by a parallel and the diagonal sensor. The tire footprint length and tire widths measured in this manner were compared with those obtained by direct measurement of static vehicles. A proportion of the randomly-selected vehicles used in the initial system calibration were measured for this purpose. This led to a sample from which figures for the mean accuracy of the dynamic tire width and footprint length were estimated to known levels of confidence.

WIM Test Vehicle Evaluation

The WIM test vehicle evaluation investigated the effect of speed on WIM accuracy; the accuracy of speed measurement with the AWACS system; and the possibility of estimating tire contact pressures. Detailed planning of the test program took account of all these requirements.

The first of these variables, namely speed, was examined to establish its effect on AWACS WIM accuracy. While randomly-selected vehicles were preferred for assessment purposes, test vehicles were utilized in the assessment of speed trends. Effects of speeds

on WIM results are difficult to identify from random vehicles because the observed speed ranges are too small.

To test for any speed trend, three speed bands were examined using three different truck types as test vehicles. A low speed band was utilized around 20 mph, a medium speed band around 40 mph, and a high speed band around 55 mph. Each vehicle was tested for bias relative to the high speed band, since the mean and the variance of the sample of results in the high speed band was not significantly different from that of the initial random sample. This was because the mean speed of the vehicles in the random sample was expected to lie in this high speed band. Once the tests had been carried out for each vehicle and for each band, significant differences between the means and variances were looked for to assess whether there was any speed trend variation.

AWACS speed measurement accuracy was determined by comparison of AWACS system outputs with speeds measured using a radar speed meter. These comparisons were carried out at the same time as the test vehicle weight accuracy data collection effort. The accuracy of the system was computed in terms of the absolute and percentage differences.

An analysis was made of the possibility of estimating tire contact pressures, and whether this measurement was a useful feature to be incorporated into the production system. Since the AWACS measures axle load together with both tire width and length, tire contact pressure can in theory be calculated. If this contact pressure can be related to tire pressure, then contact pressure measurement might prove a useful parameter to incorporate into the system. It was proposed to use test vehicles, whose tire pressures could be varied easily, to look for this relationship.

Classification Accuracy

Ideally, the approach to estimating classification accuracy would have been to compare AWACS with another classification system which was 100% accurate over several hundred hours. No such system exists in practice. Even manual techniques for classifying vehicles have serious problems as vehicles can be missed, double-counted, wrongly identified or entered wrongly on the recording sheet. Comparisons carried out by the UK Department of Transport between a dedicated full-time team and teams locally recruited for routine survey work at three sites indicated no consistent biases but considerable variations in both absolute totals and percentage discrepancies. These variations were as high as $\pm$ 37% for certain categories of vehicle at 95% confidence limits.

Because of these difficulties it was necessary to adopt a highly disaggregated approach and perform pairwise comparisons between AWACS and manual readings on individual vehicles in a sample. In carrying out observations, it was important to employ adequate numbers of manual survey staff, according to traffic levels, in order to avoid fatigue and to minimize the chances of confusion.

In defining classification accuracies, the following options arose.

* Firstly, we could use an overall measure of accuracy for all categories combined, or calculate separate statistics for each vehicle type.

* Secondly, we could calculate absolute classification accuracies, or allow compensating errors to cancel.

* Thirdly, we could simply measure accuracy over the total vehicle sample, or subdivide the sample into separate periods to see how accuracies fluctuated.

For the purposes of evaluating the prototype system, both overall accuracy figures and results by vehicle type were determined. In addition, these results were presented in terms of absolute accuracy and accuracy allowing for compensating errors. The analysis also examined how the classification accuracies fluctuated with sample size by subdividing the data collected into several smaller samples.

The sample size required for AVC assessment was not easily defined. Previous studies have evaluated classification systems with samples of around 500 vehicles, but this number is too low to state with any confidence the true accuracy of the system for classification. Errors in certain categories are considerably higher than in others, so differences in the "mix" of the 500 vehicle sample can lead to erroneous conclusions on AVC system accuracy. Accuracy evaluations performed by members of the study team in association with the UK Transport and Road Research Laboratory have used samples of about 10,000 vehicles, where the number of classification categories was 25.

For AWACS evaluations, it was agreed that around 3000 to 5000 vehicles represented a realistic sample size for thirteen category FHWA Scheme F classification accuracy appraisals. These numbers represent a compromise between an 'ideal' situation and previous Scheme F appraisals. Meaningful figures were obtained for overall system accuracies and for accuracies of the more common vehicle types. Insufficient data were obtained to make definitive statements about classification accuracies of uncommon vehicle types.

A total sample of about 5000 vehicles collected from one of the sites was subdivided into sets of around 100 vehicles, representing the results of individual period counts at a typical rural site. Separate accuracy matrices were derived for each subset of the data, and separate statistics calculated for each period. The standard deviation of these statistics gave a measure of random fluctuations in individual period count accuracies, as opposed to long-term systematic biases.

Assessment was made of the effect of using an inductance loop in addition to the cable transducers to improve classification accuracy. Comparisons were made with

classification accuracy using cable sensors only. For this purpose, a sample of 3000 vehicles was taken without using the inductive loop, and a further 3000 vehicles with the loop in operation. Statistical tests were then carried out to look for significant differences in the classification accuracy between these two samples.

3.6 LONG TERM TESTS

System Reliability and Durability

The reliability of the preproduction systems was an important operational aspect which was assessed within the testing and analysis program. Reliability is the ability of a system to perform a required function under stated conditions for a stated period of time. Reliability for both transducers and electronics can be measured in terms of:

1. mean time between failures,
2. mean time between maintenance actions,
3. mean time between corrective actions,
4. mean time to repair,
5. mean cost to repair,
6. the average weight transducer life (hours and total equivalent axle loading), and
7. average electronics system life.

Items 6 and 7 are also a measure of system durability.

Production of meaningful data on reliability over the twelve month test period required careful logging of all incidents related to each of the parameters outlined above. Reliability data on the electronics sub-systems were of limited value due to frequent changes and upgrades as the project progressed.

The durability of the preproduction systems was another operational aspect which was assessed through the testing and analysis program. The two principal measures of durability were the mean electronics subsystem life and the mean piezo-electric sensor life. Neither of these measures could be fully assessed during the twelve month evaluation period. As with system reliability, this was due to the long-term nature of the durability characteristic. The approach utilized in producing a reliability and durability standard for

the procurement specification therefore used the results of field and laboratory trials on similar systems elsewhere, in conjunction with data produced by this project.

Life Cycle Costs

Likely life cycle costs for the production systems, to be manufactured to the procurement specification produced at the end of this project, were estimated from data collection efforts during the twelve month testing and analysis program and the results of other related studies such as the HELP concept development study.

3.7 SUMMARY

This chapter, which details the work undertaken in Task B, describes the test program developed for the appraisal of the AWACS equipment. Within Task B, alternative transducer configurations were defined, and a multi-aspect program was detailed for laboratory, field and long-term system testing. The program was evaluated in terms of statistical parameters and procedures to be adopted in the assessment of the AWACS sites. It represented a significant advance on customary procedures, practices and sample sizes used in earlier WIM and AVC appraisals.

4. Site selection

4.1 INTRODUCTION

This chapter addresses the issue of site selection for the installation of low-cost AWACS equipment, considered in Task C of the project. The aim of the chapter is to present guidelines and criteria to enable states locating AWACS sites within their jurisdictions to achieve maximum utility in the post-demonstration stage. These guidelines were applied to the sites utilized in Iowa and Minnesota. Site configuration and installation details are also outlined in this chapter, for the two configurations initially utilized in the demonstration project.

4.2 SITE SELECTION

There are a number of factors which could influence the choice of specific highway sites for the installation of low-cost axle weighing systems. These were initially considered for the two proposed sites in Iowa and Minnesota, and have been subsequently revised in the light of experience. Potentially relevant factors include:

pavement rigidity;
pavement profile;
surface condition;
lane width;
availability of services;
equipment housing;
maintenance schedules;
highway safety; and
location of static weigh scales.

As part of the site selection task, a quantitative scheme was devised to evaluate potential sites. This involves awarding points on pre-determined scales for each of a number of assessment factors selected from those listed above. The number of points awarded depends on the merits of the location being evaluated. Weightings are applied to these scores to reflect the relative importance of the factors, allowing quantitative comparison to be made between alternative locations during the project and in subsequent applications of low-cost AWACS systems.

Not all of the above factors will be relevant to all site selections. They should however all be considered in order to provide a consistent basis on which to compare the merits of competing sites, increasing the prospects of satisfactory selection of AWACS sites in the future.

The following method of site appraisal has evolved from that originally used at the outset of the demonstration project. The major difference between the original site selection method and the method below is that consideration has now been given to pavement rigidity, in accordance with later findings.

The following paragraphs outline the significance of each of the factors which are recommended for use in choosing site locations.

Pavement rigidity

Pavement rigidity has been found to have a major effect on the performance of the AWACS. Large pavement deflections associated with heavy loading cause the piezo-electric sensors to give substantial output voltages before and after wheel passages. These can be reduced but not entirely eliminated within the signal processing algorithms. The amount of deflection due to a given load is a function of the rigidity of the pavement. This parameter may be assessed using a Falling Weight Deflectometer (FWD).

Pavement profile

The profile of a site, both across the pavement and along its length, could affect the performance of WIM systems. Significant cross slopes or grades will affect the vehicle dynamics and redistribute the vehicle weight onto different axles or wheels. This, in turn, may lead to significant errors in the estimation of static axle loads and gross vehicle weights from dynamic measurements. A suitable location for an AWACS system will therefore be as flat as possible, free from sudden changes in grade or cross-slope.

Surface condition

The pavement surface condition at a site may substantially affect the performance of a WIM system. Older pavements with worn surfaces tend to be rougher. This produces more pronounced 'bouncing' of a vehicle on the pavement surface. The increased dynamic effect this has on the weight transducers will result in a decrease in accuracy of the inferred static weights of vehicles. Pronounced cracking of the pavement or severe rutting may also lead to mechanical distress where piezo sensors cross these undesirable features. Therefore old, worn surfaces are less suitable for AWACS systems than relatively new pavements.

Lane width

Traffic lane width at a particular location can affect its suitability as a potential site. Unusually wide lanes will make it necessary to extend the length of the piezo-electric

cables, increasing the overall cost of the installation and exacerbating any problems of uniformity along the piezo cable length. Very wide lanes have to be sub-divided and accurate classification becomes impossible.

Service availability

The availability of services may also be an important factor in choosing between alternative AWACS sites. Provision of power and telephone services can form a significant part of the total cost of installing low-cost WIM systems, particularly in isolated areas where the cost of connection to these services can be very high. Sites where services already exist will therefore hold distinct cost advantages over those where services are not easily accessible.

Equipment housing

The housing of equipment at a site is the sixth factor which may be significant in choosing between alternative sites. In some instances, roadside cabinets will already be installed at a particular location, associated with other equipment. Any spare capacity within these cabinets that could be used for housing electronics and maintenance equipment should be taken into account in making the choice of site.

Maintenance schedules

Maintenance schedules should be carefully considered in selecting specific system locations. The main issue here is maintenance of the pavement, including scheduled reconstruction, overlays and other routine operations. It is clearly undesirable to install a system in a location which is scheduled to have maintenance work disruptive to sensors carried out within a short time of installation. Maintenance schedules should therefore be checked in making the location decision.

Highway safety

Highway safety is a particularly important factor to be considered in locating sites. Sites should be located so that installation operations do not cause a hazard to traffic through obstruction of lines of vision, for example, or to staff who are installing the apparatus. A further related consideration concerns traffic control. Sites should preferably be positioned so that equipment may be installed during off-peak hours without undue interference to the normal traffic flow.

Static weighscale location

Static weighscale location relative to the alternative sites under consideration is the final major choice factor. In order that full use is made of the equipment, it may be possible to combine the data collection system function with that of enforcement weighing. In some instances, therefore, AWACS sites could be located adjacent to static weighscales and used as a screening device for enforcement purposes. Location of the AWACS sites near

to static weighscales assumed particular importance in the Iowa/Minnesota test program because of the need for comparisons between dynamic and static loads.

When considering the desirability of potential sites, all the above factors should be considered and points awarded depending on the merits of the location being evaluated. However, before these scores can be used in a quantitative scheme of site selection, it is necessary to apply weights to each factor. These reflect the relative importance of factors and are applied to scores obtained under each heading before calculating a total score for the site under consideration. A site which scores reasonably well on the most important factors may therefore be preferred to another site which scores highly on less important criteria.

In devising the site selection scheme, the factors were considered in turn and evaluated in terms of their relative importance in ensuring that low-cost AWACS systems can be installed safely which should be capable of operating within specified performance criteria.

Factors were first divided into two categories - engineering factors of prime importance, and other factors of secondary importance. Engineering factors are considered to be pavement rigidity, pavement profile, surface condition, lane width and maintenance schedules. These are of such importance that if an individual site does not reach the minimum acceptable standard under any one of these headings, i.e. a numerical score above zero, then the site should be rejected.

The other factors of service availability, equipment housing, highway safety and proximity to a static weighscale will be of secondary importance to the efficient performance of the AWACS system and need only be considered for economic and administrative reasons. Highway safety, although included as a secondary factor, is only classed as such because sites likely to be unmanageable for safety reasons would be ruled out during consideration of pavement profile among the primary engineering factors. Proximity to a static weighscale, while being of importance during the experimental phase of the project, may not be of primary concern when installing a production system. As such, no score is awarded under these headings and they do not therefore contribute to the quantitative ranking of sites. They are however qualitative factors which could distinguish between sites with similar scores.

Having defined the primary and secondary factors, the study team proceeded to consider the relative importance of individual primary engineering factors. A possible quantitative assessment procedure is described in the following paragraphs.

For each factor, a physical characteristic is measured and assessed against a range of values which relate to 'ideal' conditions through 'conditions best to be avoided'. If under any particular heading, conditions are thought to be 'ideal' then a score of 5 points is awarded for that particular site. 'Acceptable' conditions score 3 points and 'best to be avoided' score only 1. The numerical scores of 4 and 2 are to be used when it is difficult to decide which of two main categories applies in this particular instance. If conditions are

wholly unacceptable in any respect then 'veto' is registered and the site is rejected without consideration of any other factors.

Taking each factor in turn, the physical characteristics against which 'ideal' through 'unacceptable' situations can be measured are shown in Table 4.1.

It is impracticable at this stage to fully quantify some of the physical measurement that might be made after the more widespread utilization of AWACS systems, so subjective assessments have been shown instead. This is for two reasons. Firstly, actual highway conditions in each state would determine the extreme range of certain physical characteristics, so that it may be impossible to achieve preferred physical conditions if the limits are set too narrow. Secondly, it is desirable to further explore the possibility of utilizing criteria already formulated as part of existing highway assessment procedures for maintenance purposes. Both aspects should be the subject of further liaison between state personnel to ensure that generally acceptable assessment criteria are formulated.

Having assigned a score under each heading, a weighting factor must then be applied which reflects the relative importance of each. Suggested weighting factors are:

1	*Pavement Rigidity*	Weighting factor
	FWD	5
2	*Pavement Profile*	
	(a) cross slope	0.5
	(b) grades	0.5
	(c) bumps	3
3	*Surface Condition*	
	(a) rut depth	1
	(b) joints	1
	(c) cracks	1
	(d) potholes	3
4	*Traffic Lanes*	
	(a) lane width	1
	(b) lane discipline	1
5	*Maintenance Schedule*	
	Time to next resurfacing	3

Conditions: Score:	Ideal 5	Acceptable 3	Better Avoided 1	Reject (Veto)
1 Pavement Rigidity FWD results	high	medium	low	very low
2 Pavement Profile (a) cross slope (b) grades (c) bumps	0-2% < 1% Flat	2-3% 1-3% Minor bumps > 50' from the sensor array.	3-4% 3-6% Significant bumps > 50' from the sensor array. Minor bumps 20-50' from sensor array	> 4% > 6% Bumps adjacent to the sensor
3 Surface Condition (a) rut depth (b) joints (c) cracks (d) potholes	< 0.2" None None None	0.2-0.4" One or more > 30' from the sensor array. Some minor, shallow cracks Minor potholes > 50' from sensor array	0.4-0.6" One or more within 30' of the sensor array. Significant number of shallow cracks. Minor potholes 20-50' from sensor array	> 0.6" Failure of joints Deep cracks Major potholes
4 Traffic Lanes (a) lane width (b) lane discipline	12' Good	11'-13' Moderate	13'-15' < 11' Poor	> 15' No lane markings
5 Maintenance Schedule (a) time to next resurfacing	5-10 yrs	2 - 5 yrs	1 - 2 yrs	< 1 yr

Table 4.1 Revised Site Selection Scheme

As previously stated, if a potential site is given a veto under any one heading then the site should be rejected. Otherwise the minimum possible score would be 20 and the maximum possible score would be 100. In the early stages of AWACS system development, sites should preferably be limited to those with good, very good or excellent characteristics, according to the following ranking:

Excellent	90 - 100
Very Good	80 - 90
Good	70 - 80
Fair	60 - 70
Poor	50 - 60
Unacceptable	< 50

Once greater experience has been obtained with AWACS system operation, lower grades might be tested or the grading system revised.

4.3 SITE APPRAISAL

In the Iowa/Minnesota project, the site selection methodology was utilized in assessing the suitability of specific locations for the piezo-electric systems in each state. The Iowa site was in Portland Cement Concrete (PCC) and the Minnesota site in Asphalt Cement Concrete (ACC). State personnel identified specific site locations based on their detailed local knowledge. The suggested Iowa site was on I35 northbound, about 10 miles south of Ames, and the Minnesota site was on US10 eastbound, 40 miles northwest of the Twin Cities. The proposed AWACS test sites were evaluated in cooperation with State DOT staff by applying tentative site selection criteria which preceded those developed above.

The Iowa site was in the right lane of a two-lane reinforced PCC pavement with a paved shoulder. The depth of the reinforcement was not known. The pavement rigidity was high. The pavement profile was relatively even, both along and across the site. The surface condition was reasonably good, for a 22 year old pavement, without severe cracking, ruts or potholes. Joints were widely spaced and in good repair. Cross slope and grade were slight, and the lane width was close to the standard 12 feet. Automated profilometer readings were taken in both lanes to assist with the final choice of location.

Telephone and power cables were available close to the highway boundary. Space was available for a portable temporary building located well away from the pavement, within

the highway right-of-way. No unusual highway safety problems were anticipated at the site and no major maintenance activities were planned. A static weighscale was located about two miles north of the site.

The Minnesota site was in the right lane of a two-lane ACC pavement with shoulder. Prominent reflection cracking at lateral and longitudinal construction joints suggested that the asphalt overlayed a PCC pavement, though records indicated that this was not so. Aligator cracks and crazing of the wearing course were also evident in typical sections of each lane. A downgrade was obvious on the approach to the site, which eased close to the selected location. Cross slope and lane width were standard. It became clear during the project that unlike the Iowa site, the pavement rigidity in Minnesota was low.

As in Iowa, telephone and power cables were available close to the highway, and space was available for a temporary building within the highway right-of-way. No unusual highway safety problems were envisioned at the site. A static weighscale was located about one mile east of the proposed location. No major maintenance activities were currently proposed covering the whole of the highway section in question.

Because of the pavement surface condition, with pronounced reflection cracking as well as cracks or crazing of panels between joints, Minnesota DOT overlayed the test section over a distance of some 650 feet. About 2" of asphalt was applied in two layers, beginning 500 feet in front of the piezo location.

Application of the revised site selection criteria to the two test sites yields the results shown in Table 4.2. These results satisfy the proposed "pass mark" of 70 for early AWACS sites.

4.4 SITE CONFIGURATION

A number of different sensor arrays were initially identified as potentially suitable for this project. Two promising sensor configurations were selected for the test program. The variations between the chosen arrays were designed to assess the merits of alternative configurations, extending the experience gained in earlier pre-demonstration project testing.

Chapter 3 discussed possible alternative configurations for the experimental installations in Iowa and Minnesota. The main variables were piezo sensor spacing; location of the inductive loop; and angle of the diagonal sensor. Two different configurations were therefore tested at the Iowa and Minnesota sites, as shown in Figures 4.1 and 4.2, so that certain effects of these variables could be explored.

	Iowa site		Minnesota (original)		Minnesota (with overlay)	
	Basic	Scaled	Basic	Scaled	Basic	Scaled
1 Pavement Rigidity	5	25	0	0	1	5
2 Pavement Profile						
(a) cross slope	4	2	4	2	4	2
(b) grades	4	2	3	1.5	3	1.5
(c) bumps	3	9	1	3	4	12
3 Surface Condition						
(a) rutting	4	4	2	2	3	3
(b) joints	2	2	2	2	5	5
(c) cracks	4	4	1	1	5	5
(d) potholes	3	9	4	12	5	15
4 Lane Width						
(a) lane width	5	5	5	5	5	5
(b) lane markings	4	4	4	4	4	4
5 Maintenance Schedule						
(a) time to next resurfacing	5	15	3	9	5	15
Totals	-	81	-	41.5	-	72.5

Table 4.2 Revised Site Selection Assessment

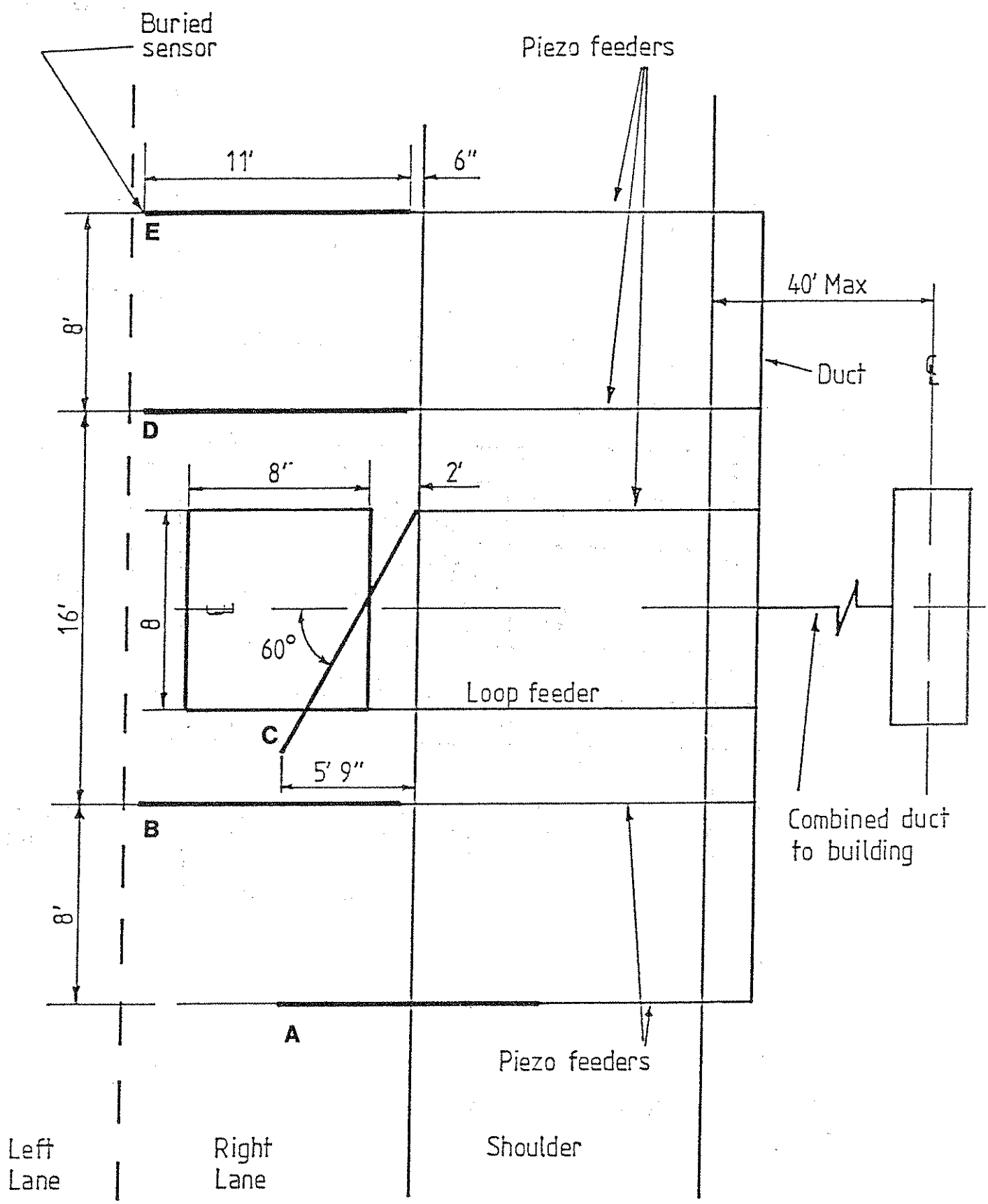


Figure 4.1 Recommended Iowa Site Configuration

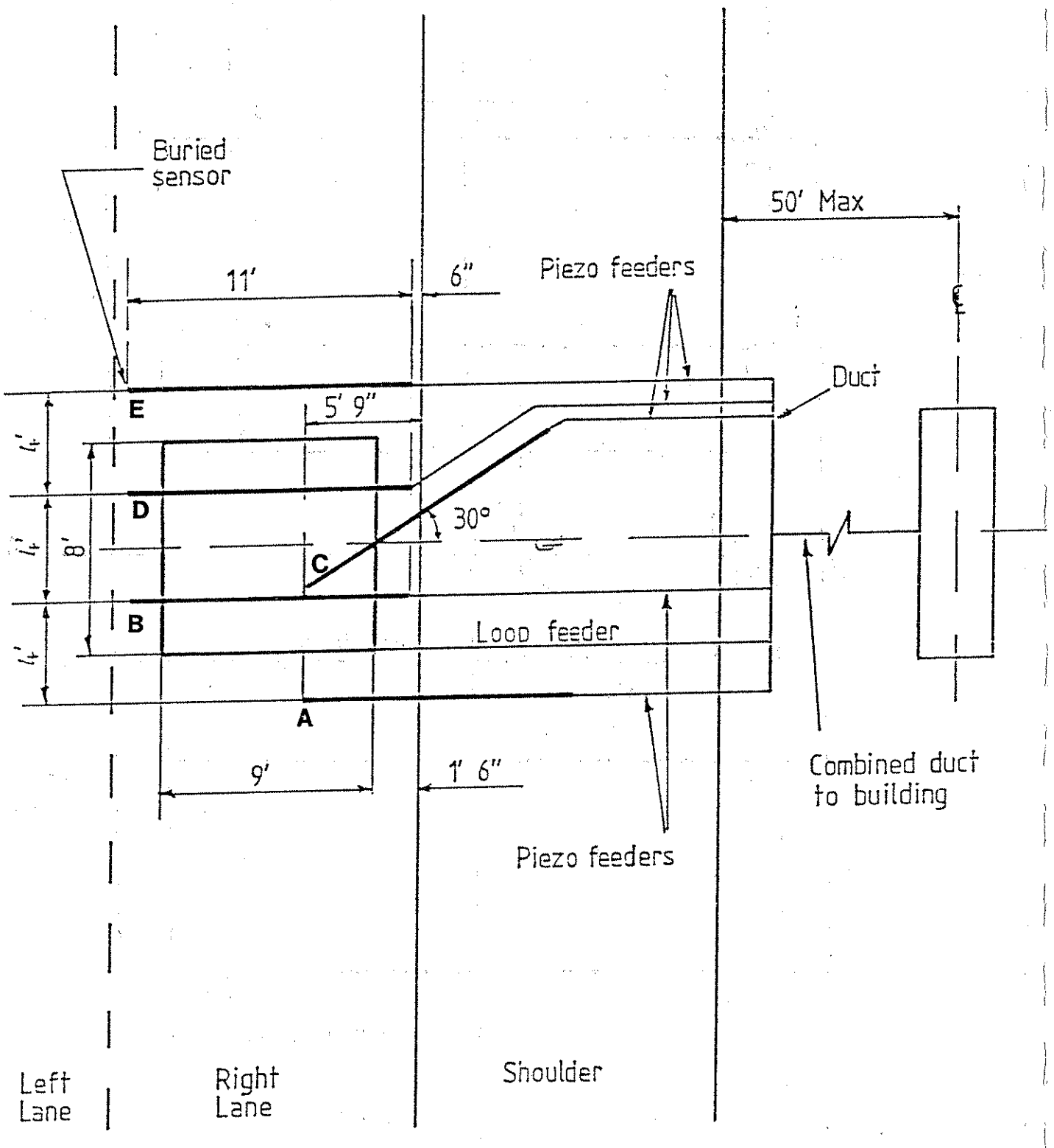


Figure 4.2 Recommended Minnesota Site Configuration

A significant difference between the two initial test configurations was the spacing of the piezo sensors. The Iowa site incorporated relatively widely spaced sensors, generally 16 eet apart, while the Minnesota site was more compact. The widely-spaced sensors allowed an inductive loop to be positioned between the piezo sensors rather than having the main sensors positioned over the loop.

Both sites included an inductive loop in addition to the piezo cable transducers, to permit an examination of the effect on vehicle classification. The dimensions of the inductive loops were fairly standard for vehicle classification purposes and were proportionate to the width of lane.

A further difference between the two initial configurations was the angle of the diagonal sensor. Examination of the duration of the loading pulse produced when a vehicle axle passes over the diagonal sensor was to be used experimentally, in conjunction with the speed of the vehicle, to determine the width of the tire in contact with the pavement. In practice the maximum angle for the diagonal sensor relative to the parallel sensors is determined by the spacing of the sensors within the array. With a compact array, the angle must be relatively small. As the distance between sensors increases, the angle of the diagonal sensor can also increase. A 45 degree angle had been previously used at UK test sites and consequently, angles of 30 degrees and 60 degrees were adopted in the demonstration to determine the best configuration for tire width measurement.

To evaluate these various factors, at the Iowa site, a long array was tested with piezo sensors widely spaced on either side of the inductive loop. A 60 degree angle for the diagonal piezo sensor was selected for high resolution tire width measurement (Figure 4.1).

At the Minnesota site, a compact layout was tested with three piezo sensors located over the inductive loop. A 30 degree angle of diagonal piezo sensor was tried for tire width measurement, permitting some off-scale detection on the shoulder. A wider inductive loop was also used at this site producing a slightly different electromagnetic field pattern (Figure 4.2).

At both the Iowa and Minnesota test sites, the leading sensor in the array was positioned half in the highway lane and half in the shoulder. This was intended to provide off-scale detection of vehicles which partially avoid the load transducer cables, and to simplify the algorithms required to calculate dynamic tire width. The final sensor in both arrays was buried to a depth of approximately 3/4", in order to significantly reduce or eliminate the possibility of damage from snowplows.

4.5 SUMMARY

This chapter has reviewed the factors relating to site selection for AWACS systems. A site selection scheme is advocated which will help to achieve consistency in locating AWACS equipment. This scheme, revised in the light of experience gained in the project, has been applied to the demonstration project sites in Iowa and Minnesota. The chapter concludes with recommended site configurations for the Iowa and Minnesota demonstrations. With this work completed, the scene was set for commissioning of the first generation AWACS equipment.

5. First generation system procurement

5.1 INTRODUCTION

This chapter concerns the hardware and software components and system characteristics of the first generation preproduction automatic weight and classification (AWACS) systems. The report covers the specification supplied to GK Instruments for the procurement of first generation systems, and the development plan used to ensure that the systems could be delivered on schedule.

The first part of the chapter is in the form of a specification for the procurement of first generation preproduction systems. This documents the characteristics of the systems for evaluation in the test program, including software and hardware components.

The second part of the chapter describes the plan used by GK Instruments to ensure that the first generation AWACS systems were developed in a manner compatible with the requirements of Iowa and Minnesota. Tasks which were to be performed to complete the first generation systems on schedule are detailed, together with their relative timings.

5.2 FIRST GENERATION SYSTEM SPECIFICATION

The first generation preproduction systems were purchased from GK Instruments, an internationally established manufacturer in the field of automatic traffic data collection equipment. The study team worked closely with the manufacturer to detail the outline specification given in the proposal document. The principal features specified for the first generation system were as follows.

Sensors

1. The first generation preproduction AWACS will utilize piezo-electric cable sensors mounted in a filled aluminum channel, previously designed by CRC staff working in conjunction with the UK Transport and Road Research Laboratory.

2. The system shall be capable of simultaneously monitoring a minimum of six piezo-electric cable sensors and one inductive loop positioned in a single traffic lane.

Signal processing

1. For each of the piezo-electric sensors, the first generation AWACS will obtain values for the peak, duration and integrated area of every signal due to an axle passage over that sensor.

2. The scanning algorithms utilized will be based on a flowchart supplied by CRC, which aims to eliminate unwanted signals due to road bending, interference and temperature effects.

3. Each piezo-electric sensor will be scanned at a rate of 1 kHz or faster.

4. It shall be possible to monitor the raw data collected by each piezo-electric sensor for selected vehicles. This data will comprise the raw signal data points, peak, duration and area.

Input

1. The first generation preproduction AWACS will operate on commercial power input of 110-120 VAC, 60 Hz, and will be protected against mains power fluctuations or overloads due to lightning.

2. The AWACS will have a battery backup capable of supporting the system for a minimum of 30 minutes. This backup will take over automatically following commercial power input failure.

Environmental

1. The AWACS electronics will be capable of operating over a temperature range -40 degrees F to +160 degrees F, and in a relative humidity up to 95%.

Modes of operation

Three distinct modes of operation will be provided in the first generation preproduction system:

1. *Continuous Mode.* In this mode, data are output in real time as each vehicle traverses the sensor array. No data will be stored for summaries, and data not captured by the output recording terminal (eg. printer or microcomputer) may be lost.

2. *Selection Mode.* In this mode, data on selected vehicles only will be logged. Selection will be made by some manually operated means, such as a push button on the hardware itself, or by priming the system via the user terminal. Again, no summary data will be stored and data not captured by the recorder may be lost. This mode will be used for collecting data on site during field testing operations.

3. *Remote Mode*. This mode is intended for use during remote monitoring of the equipment via the telemetry link. In this case, summary data will be stored, either on an hourly or daily basis. It should be possible to store a minimum of 48 hours of data.

Data Output

1. All data output will be ASCII and RS232-C compatible.

2. The main data output, outlined below by mode, will be available via a single RS232-C port, or via the telemetry sub-system. Additional ports will be supplied as necessary for the output of raw sensor data in selection mode.

3. It is desirable, though not essential, that the data output is subject to an XON/XOFF type protocol.

4. Data transmission rates will be at 300/300 baud and/or 1200/1200 baud.

(i) Continuous mode:

1. In this mode the first generation preproduction systems shall output the following data for each passing vehicle:

   a) a vehicle number to aid in the subsequent analysis of the data;
   b) the time of arrival;
   c) the vehicle speed in mph, and direction of travel;
   d) at least one axle spacing measurement, eg. between the first and second axles;
   e) the vehicle classification according to FHWA Scheme F;
   f) an estimate of the gross vehicle weight and individual axle weights (with tandem and triple axles summed and quoted as a total value).

(ii) Selection mode:

1. In this mode the first generation preproduction system shall output the following data for each passing vehicle:

   a) a vehicle number to aid in the subsequent analysis of the data;
   b) the time of arrival;
   c) the vehicle speed in mph, and direction of travel;
   d) at least one axle spacing measurement, eg between the first and second axles;
   e) the vehicle classification according to FHWA Scheme F;
   f) for each piezo sensor and for each axle of the vehicle, the signal peak, duration and speed-adjusted signal area;

g) an estimate of the gross vehicle weight and individual axle weights (with tandem and triple axles summed and quoted as a total value).

(iii) Remote mode:

1. Output will be made via the telemetry sub-system (auto-answer modem).

2. In this mode, hourly or daily summary data will be produced containing the following information:

   a) the period the summary covers, with an indication if the summary has been interrupted for manual data collection;
   b) for each vehicle class, a count of the number of vehicles in that class that have been logged;
   c) an indication of the system status so that sensor failures, power or data loss, or operational errors can be detected.

Parameter input

1. Provision shall be made for entering various parameters via a user terminal, and by the telephone modem. These will include:

   a) site identification;
   b) time and date;
   c) sensor data: which piezos to log, sensor separation, identification of the diagonal sensor, and sensor initial calibration;
   d) mode of operation: continuous, selection or remote;
   e) any other parameters necessary for setting up the system.

5.3 FIRST GENERATION SYSTEM DEVELOPMENT PLAN

The study team worked closely with GK Instruments to ensure that the first generation systems were produced according to the specification supplied. Requirements for the system under the terms of the AWACS contract were agreed with the manufacturer, with specific reference being made to data collection procedures during the test and analysis program. The first generation systems were based on the following electronic components, with piezo-electric sensors mounted as described in the system specification:

GK 6002 Federal Highways Classifier;
3 dual piezo-electric interface boards;
64k memory module; and
telemetry subsystem.

A number of modification and development tasks were identified at the start of the project to complete production of a prototype AWACS system within the contract timescale. In particular, the basic GK 6002 classifier unit needed to be specially adapted so that it could process signals from the piezo-electric sensors to produce vehicle axle weights, as well as classification to FHWA Scheme F.

An outline schedule of tasks was produced in conjunction with GK Instruments, which is shown in Figure 5.1. Although under the terms of the Iowa/Minnesota contract, development of the system needed to be complete by July 1986, an earlier deadline of June 1986 was set, in order that the sensors and electronics could be tested further prior to field installation. The development tasks shown in Figure 5.1 are as follows:

1. Design and manufacture charge amplifiers. Test and adjust amplifiers, both in the laboratory and in the field.

2. Design and manufacture 8-bit fast analog-to-digital convertors. Carry out functional testing on the charge amplifiers. Test at a field site to check on signal levels and adjust if necessary.

3. Write the interrupt- driven signal processing software for the piezo sensors with a scan interval of 1 ms or less. Ensure that output data format (sensor number, arrival time, signal area, peak and duration) is in a form that can be incorporated into existing classification software.

4. Make existing classification software work with the data output from Task 3.

5. Develop software to give both individual and gross axle loads from the piezo signal data logged by the interrupt in Task 3.

6. Combine classification and weighing software into one system.

7. Final hardware design. Make up various units on a single printed circuit card per lane.

8. Final assembly and testing prior to laboratory and field tests.

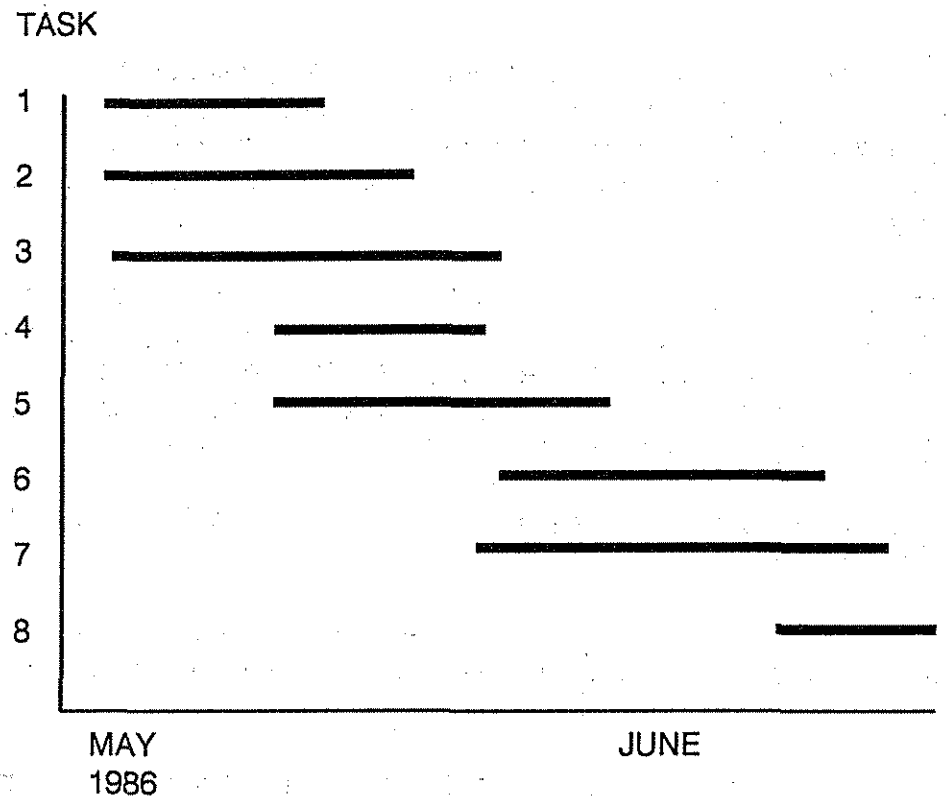


Figure 5.1 System development timeplan

5.4 OUTCOME

Delivery of the first generation system did not meet the June 1986 deadline, and significantly overran the subsequent July date on which laboratory testing was scheduled to begin. It was late August/early September before equipment was available from the manufacturer to meet the needs of the field and laboratory test programs. These delays were accommodated, however, by rescheduling the tests in parallel and accelerating certain test elements. CRC also made its pre-contract prototype hardware and software available to the states to allow the test program to proceed without delay. The outcome of these tests is detailed in the chapters which follow.

6. Laboratory testing

6.1 INTRODUCTION

This chapter describes the laboratory and environmental testing performed during the initial development of the AWACS system. Testing of the preproduction systems and components was undertaken to ensure the prototype equipment supplied by GK Instruments satisfied the first generation AWACS system specification. The test plan used for this task was based on the test and analysis program previously described in Chapter 3 of the report.

Following this introduction, the chapter is divided into three sections. The first section contains a description of the final test procedures, including details of apparatus and equipment used. The second section of the report gives an analysis of the main test results, presented in graphical form where appropriate. The final section describes conclusions drawn from the laboratory testing of the preproduction system and components.

6.2 TEST PROCEDURES

The tests were performed using the extensive facilities available from past work on piezo-electric cables at the University of Nottingham. These had been developed and adapted specifically for piezo-electric testing over the previous six years. All the testing was undertaken by highly experienced personnel, familiar with piezo-electric cable sensors and their associated electronics.

Three different categories of laboratory tests were undertaken during this task:

1. Sensor response tests;
2. Environmental tests; and
3. Power supply tests.

Sensor response tests were carried out on both the unmounted piezo-electric cable and mounted sensors using an electronic servo-controlled hydraulic testing machine. The variation in sensor output with position along the sensors' lengths was established. Linearity of response to load at given positions was also checked for each sensor during

these tests. This was achieved using controlled pulsed loading from the same apparatus to simulate representative wheel loads at specific positions on each of the sensors.

Environmental testing of the preproduction systems encompassed all the relevant system components and sub-systems, including the piezo-electric sensors. The vehicle classification unit was not included in the laboratory tests, due to the problems of simulating different types of vehicles. It was agreed that the classification sub-system would only be tested in the field, using the sensor array and real vehicles.

For the environmental laboratory tests, an environmental chamber was utilized. The equipment was tested over a wide temperature range, and up to a relative humidity level in excess of 95%, to ensure that the system was capable of operating in the extreme climatic conditions periodically experienced in Iowa and Minnesota.

Tests on the susceptibility of the preproduction systems to power supply fluctuations were also carried out in the laboratory. While the mounted sensor was repeatedly loaded, the power supplied to the AWACS system was varied and any levels at which the system started to malfunction determined.

Details of the procedures adopted for each of the three areas of testing are described below.

Sensor Response Tests

The first test category concerns the response of the sensors to dynamic loading. To undertake these tests, each unmounted cable was first marked out into test sections 6 inches long. After fixing the cable in the testing machine, shown in Figure 6.1, a dynamic compressive load was applied along the central 4 inch length of each test section through rigid platens. The dynamic load was applied in the form of a half sine wave pulse, with magnitude and duration of 360 lbf and 40 ms respectively. Each cable was tested at all sections along its length and repeat tests were performed at several sections. Identical load tests were conducted on the mounted or composite sensor. Again several sections were repeat tested for consistency of results.

Linearity of response was also tested for the mounted sensor. Eight equal increments of load up to maximum of 360 lbf were applied to each sensor at a representative position. This maximum load is representative of maxima likely to be encountered when the sensor is mounted in actual highway pavements.

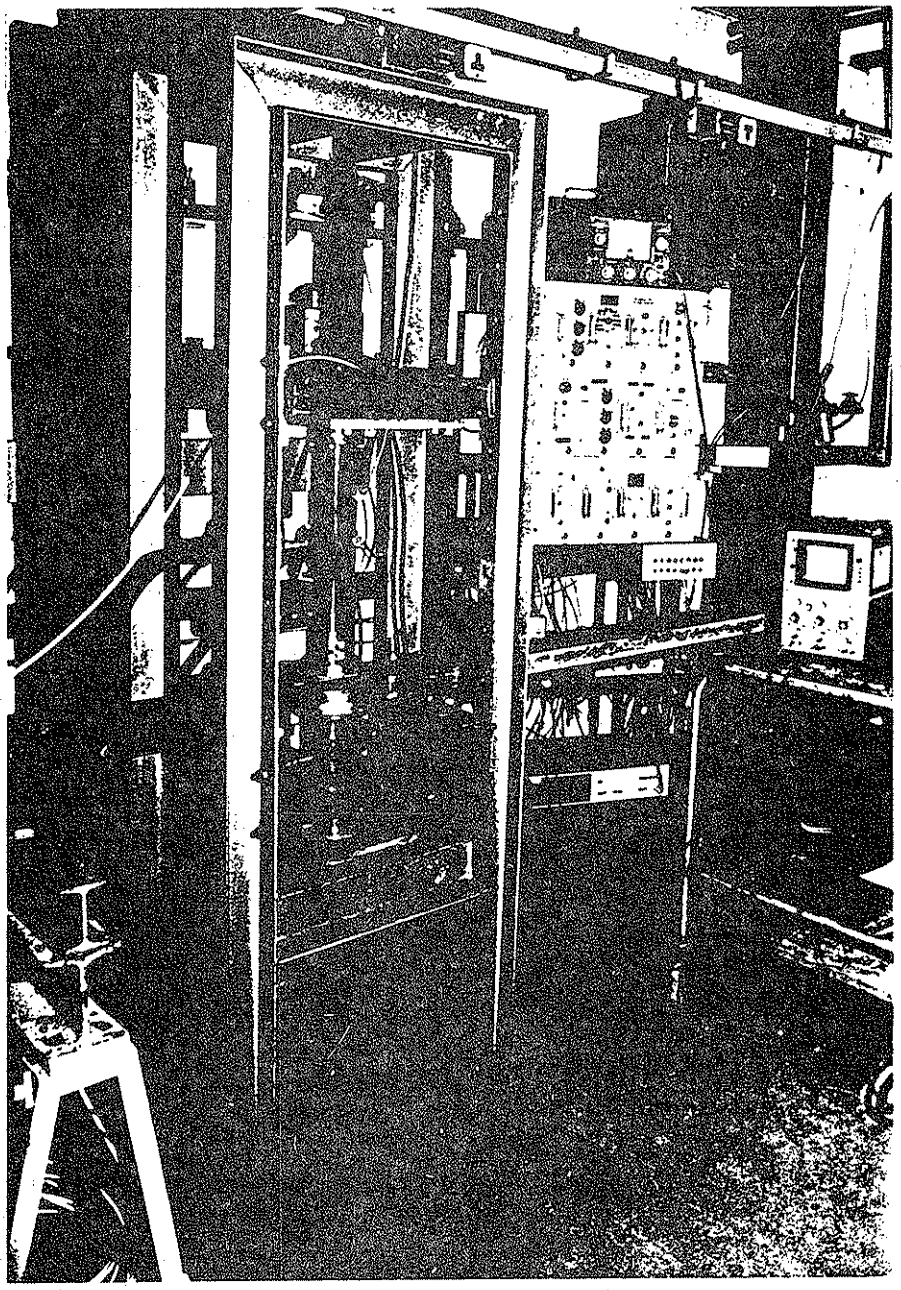


Figure 6.1 General View of Test Rig

Environmental Tests

Environmental tests constituted the second category of test performed as part of the AWACS test and analysis program. Specialized environmental chambers were used, within which conditions can be closely controlled, to ensure that the system satisfied the approved specifications. Other specially constructed apparatus, including a portable test rig, was used to facilitate the testing of individual components of the complete system.

The first stage of the environmental tests involved temperature testing of the cable sensor to establish its operating performance over the specified temperature range. A test rig was brought into the environmental chamber for this purpose and the sensor was dynamically loaded. The temperature in the chamber was progressively altered and the effect on the sensor's operation assessed.

The performance of the electronic components in isolation was also assessed, by maintaining the sensor at a constant temperature and varying the temperature of the system electronics while observing the output under simulated wheel loads.

Further testing of the system electronics involved connecting the electronics to a sensor, whose operation at the temperature extremes had already been investigated, and verifying the operation of the entire system under controlled temperature and loading conditions. Again, a number of temperature increments was used while other environmental conditions were held constant. In all tests the ambient and surface temperatures were measured locally using copper/constantan thermocouples.

Testing of the electronic components' susceptibility to humidity also utilized a purpose-built environmental chamber. Here, the temperature was set at a suitable level to reflect likely operating conditions in Iowa and Minnesota, while the entire system was operated at various controlled humidity levels, up to a relative humidity of 100%.

Power Supply Tests

Power supply tests were the final category of laboratory tests. A variac was used to incrementally reduce the voltage supplied to the electronic system, and the reduced voltage level at which an unsatisfactory output first occurred was determined. Other tests involved rapid manual adjustment and switching of the variac to determine whether malfunctions occurred. The effect of reduced voltage from the system battery on the output levels was also investigated.

6.3 TEST RESULTS

The following sections summarize the results from each of the types of test, following the data analysis that was undertaken to determine the performance of the preproduction systems and components under laboratory test conditions.

Sensor Response

Figures 6.2 and 6.3 show typical results from the uniformity tests and varying dynamic load tests carried out on an unmounted sensor. Figures 6.4 and 6.5 show the corresponding results for the mounted sensor.

The uniformity of the sensor can be estimated by measuring output from the sensor with the same dynamic load applied at various positions along its length. Uniformity can then be measured as a coefficient of variation, which is the standard deviation of the various sensor outputs expressed as a percentage of their mean. For the unmounted sensor as shown in Figure 6.2, the mean output was 3.08 volts. The standard deviation of the individual results about the mean was 0.28 volts, giving a coefficient of variation of 9.1%. For the mounted sensor the mean output and standard deviation were 0.31 volts and 0.034 volts respectively. This gives a coefficient of variation of 11%.

On analyzing the results it can be seen that the output from the mounted sensor is significantly lower than that from the unmounted cable. There is also a slight reduction in uniformity when the cable is mounted, which is a typical result.

The output from the sensor shows the greatest variation along its length at the end positions. In the unmounted sensor this end effect is probably due to the sealing of the cable where it has been cut from a longer length by the manufacturer, and the joining of the piezo to the coaxial feeder cable. For the mounted sensor the same effect can be caused by the mechanical fixing of the cable in the mounted sensor assembly.

When the sensor is used in the field, the end effect previously described becomes less significant as the likelihood of the vehicles' wheels crossing the sensor at any one position decreases significantly toward either end of the sensor. It should also be noted that when the sensors are subjected to actual wheel loads, the loading width will increase significantly from that used in the test rig. This will tend to increase the uniformity of response.

The linearity of response under load was estimated by plotting the output from the sensor for various dynamic loads. These tests confirm that when the sensor is loaded at representative points, the output produced for varying loads shows a straight line relationship. Correlation coefficients for the load/output data were typically in excess of 0.95.

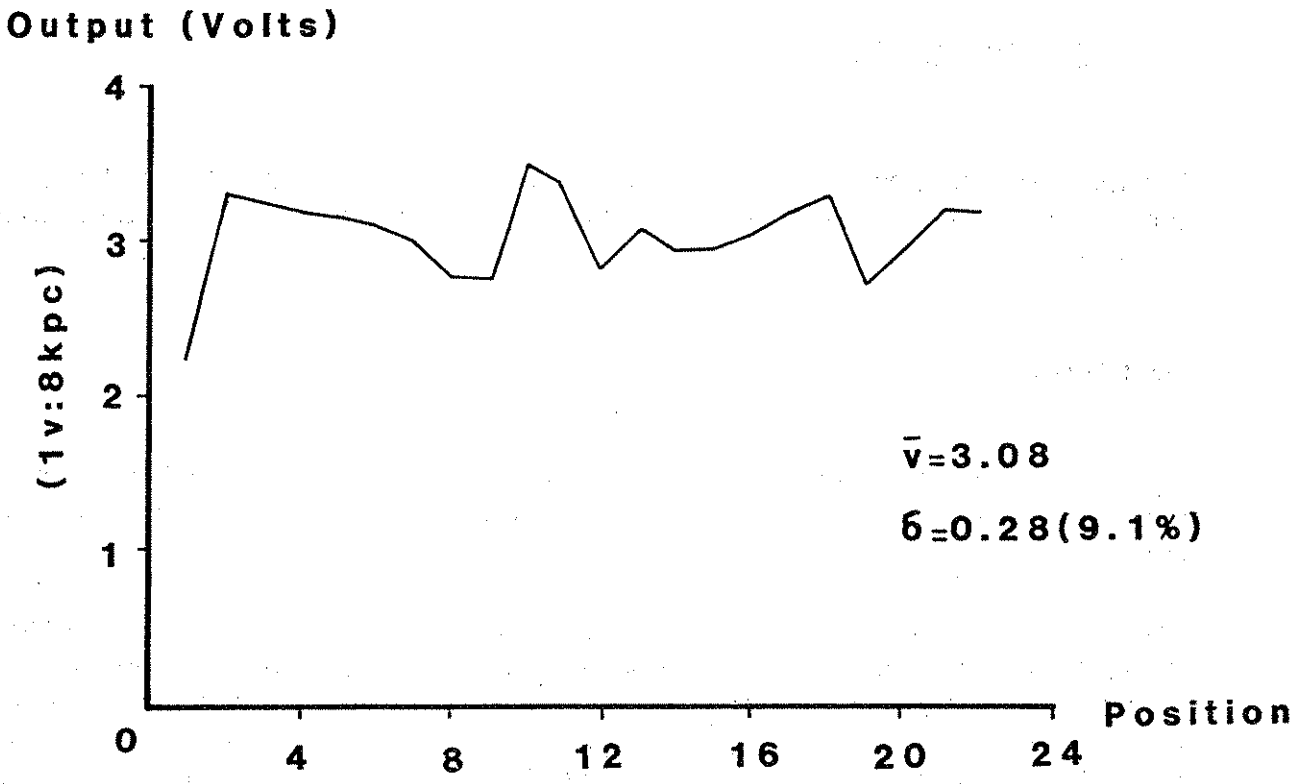


Figure 6.2 Unmounted Sensor Response to Dynamic Loads with Varying Position

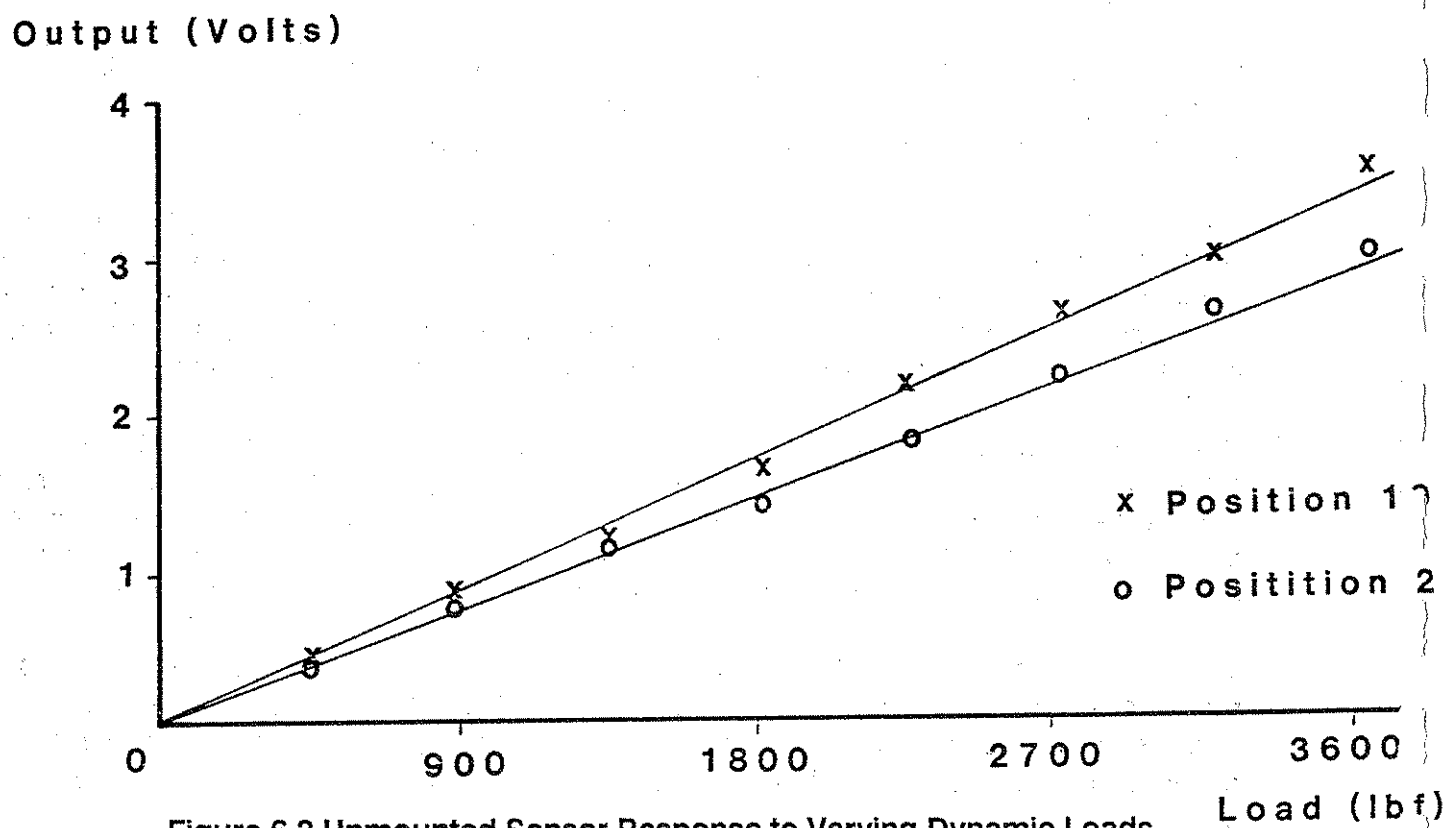


Figure 6.3 Unmounted Sensor Response to Varying Dynamic Loads

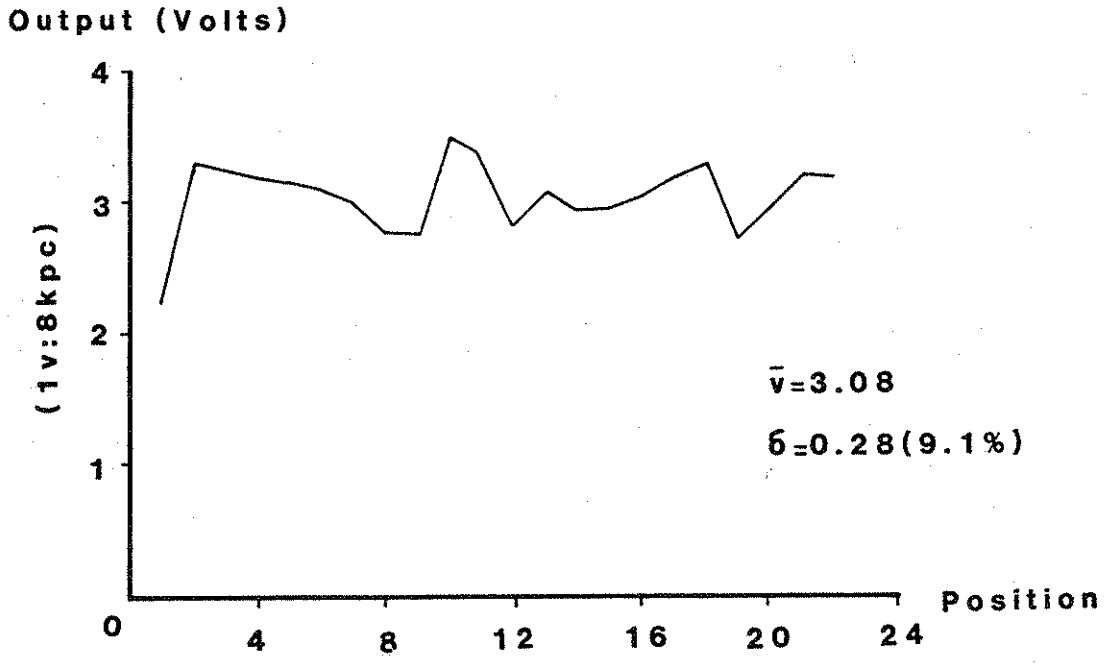


Figure 6.4 Mounted Sensor Response to Dynamic Loads with Varying Position

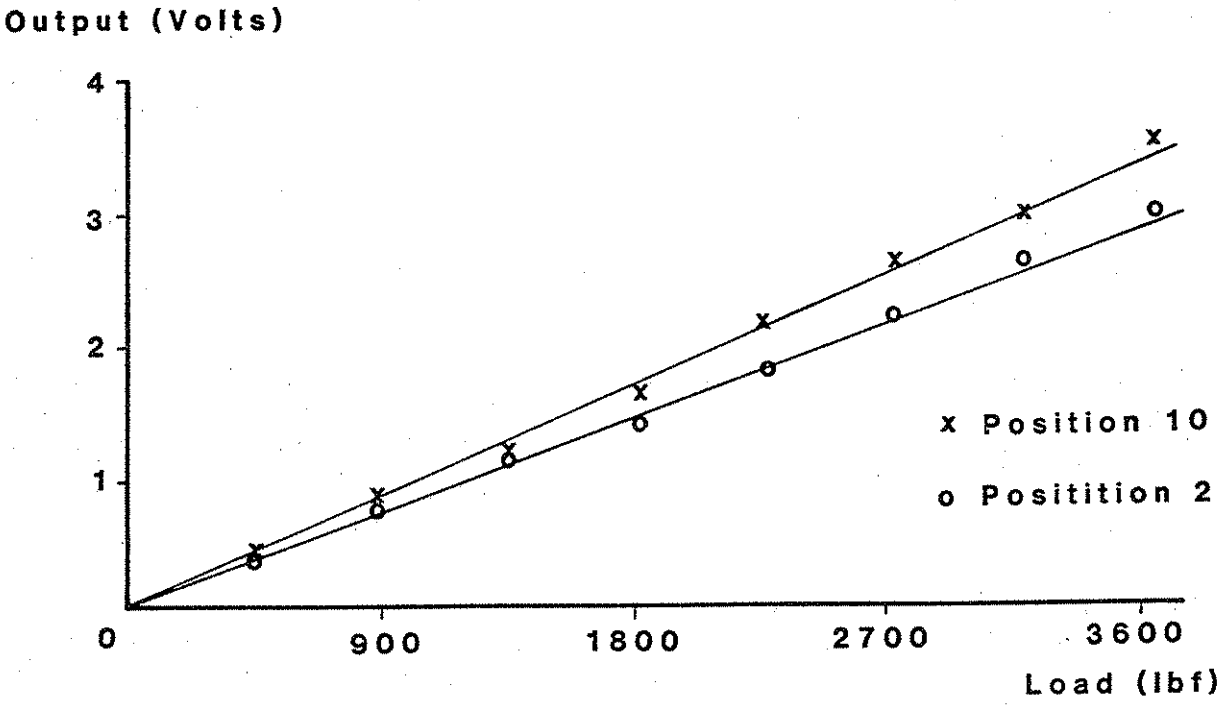


Figure 6.5 Mounted Sensor Response to Varying Dynamic Loads

Environmental Tests

Tests were undertaken to assess the performance of the axle load sensor in isolation, before environmental testing of the complete system. For this purpose, the sensor was subjected to varying environmental conditions and the resulting output was monitored. The response of the sensor to simulated wheel loads was observed directly using an oscilloscope. The output was also measured using the prototype AWACS equipment, via a charge amplifier.

Due to potential problems of using the servo-controlled hydraulic test rig under very extreme conditions, a portable rig was initially assembled and mechanical rather than electronically controlled, dynamic loading was used for some of the tests. In these tests, however, the response of the mounted sensors, which were simply supported in the rig, was affected by the mechanical properties of the sensor under load. Relative stiffness of the sensor was the main property which influenced the behavior of the sensor under load. When this was taken into account the sensor output appeared uniform across the range of temperatures tested.

Having established the performance of the sensor in isolation, the complete system was subjected to the same extremes of temperature and relative humidity. Finally, the electronic components were tested in isolation, with the load sensor maintained at a constant temperature and humidity. Throughout the tests the system continued to function across a temperature range of -30 degrees F to +165 degrees F and a relative humidity of up to 100%. The mean peak output from the system was 81 units, with a standard deviation of 4.4 which is 5.4% of the mean. This is shown diagrammatically in Figure 6.6.

At a later stage in the project, field results suggested that piezo sensor response might be varying with temperature. An extended series of further laboratory tests was undertaken to identify and quantify these effects. A second, portable test rig was developed for use in the environmental chambers, this time using full electronic-servo hydraulic load testing techniques. Several series of tests were performed with different sensor restraint conditions in an attempt to simulate as far as possible the fixing of the sensor in the pavement. The results of these tests are detailed in Figures 6.7 through 6.9.

In the first series of tests, the sensor was gripped over a length of 2 feet in a purpose-built vice incorporated in a standard loading frame. Various pulsed loads up to a level of 900 lbf were applied to the test sensor at different temperatures in the range +95 degrees to -15 degrees F, and the output from the sensor was noted. The loaded length was kept constant at 10 inches and only one sensor position was tested.

The results of these tests detailed in Figure 6.7 indicate a change in sensor sensitivity over the range of test temperatures. Sensitivity is measured in terms of the sensor output in volts per kN (1kN = 225 lbf) of applied load, averaged over a range of dynamic loads between 225 lbf and 900 lbf.

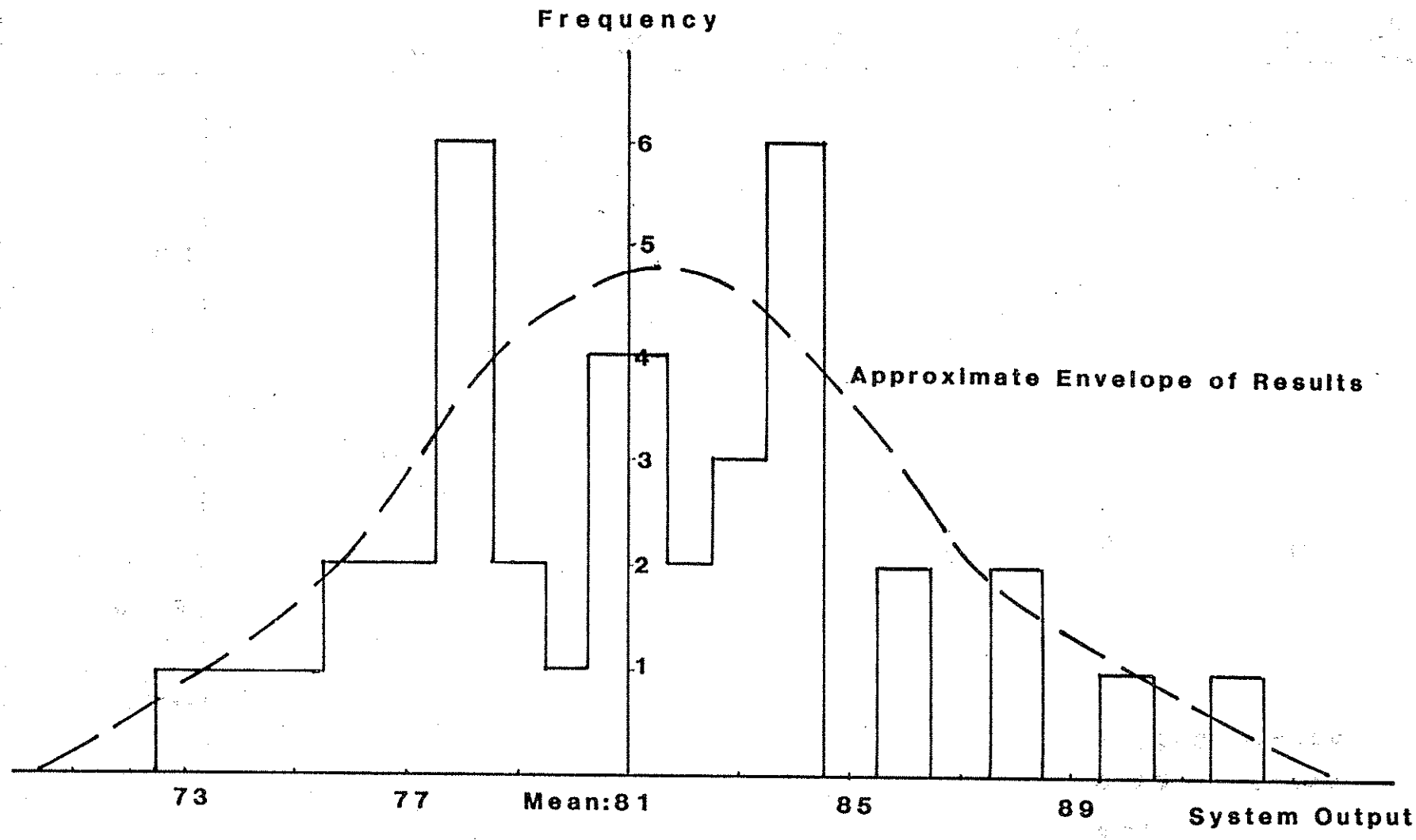


Figure 6.6 Mean peak system output

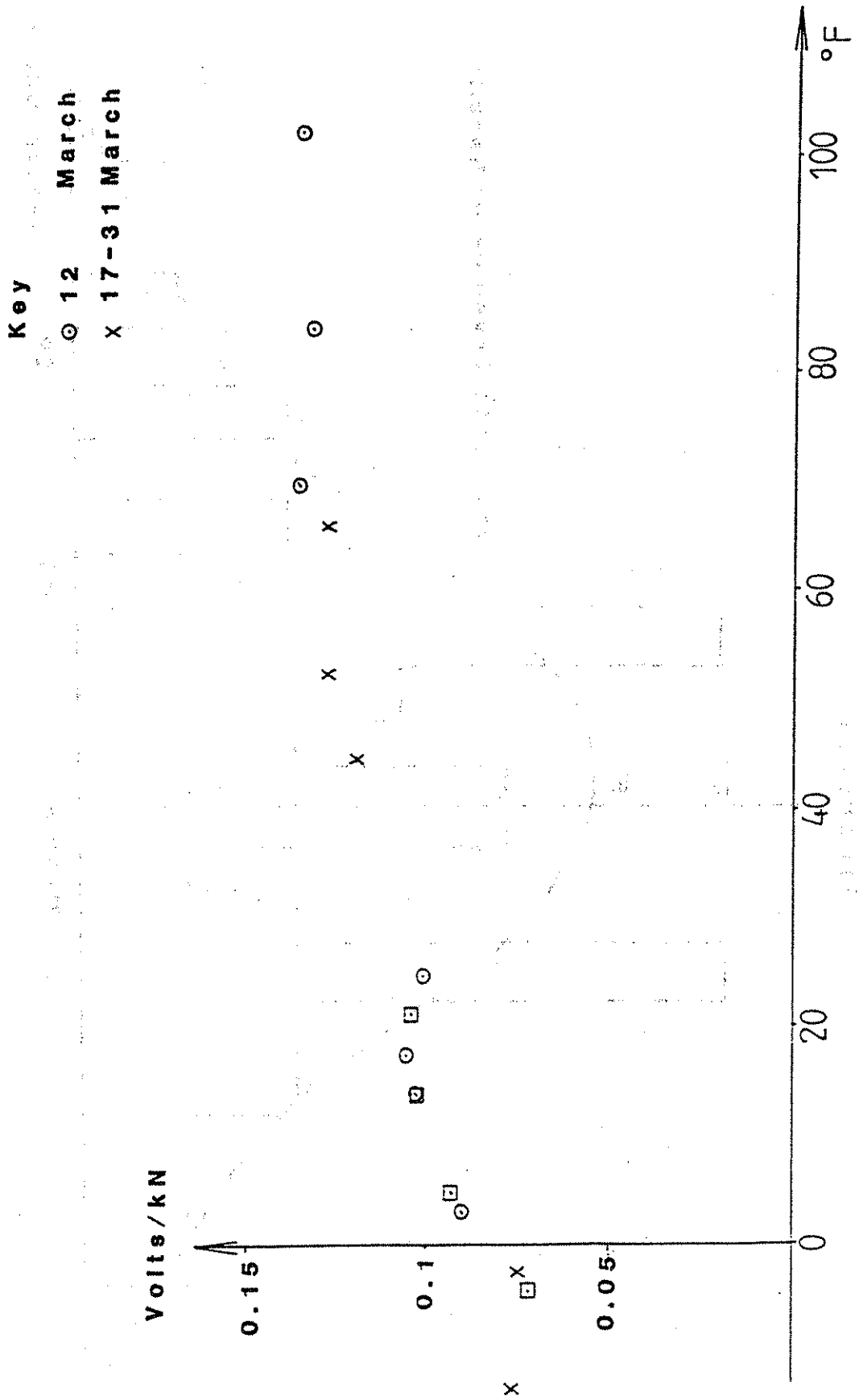


Figure 6.7 Sensor sensitivity v temperature (side clamped)

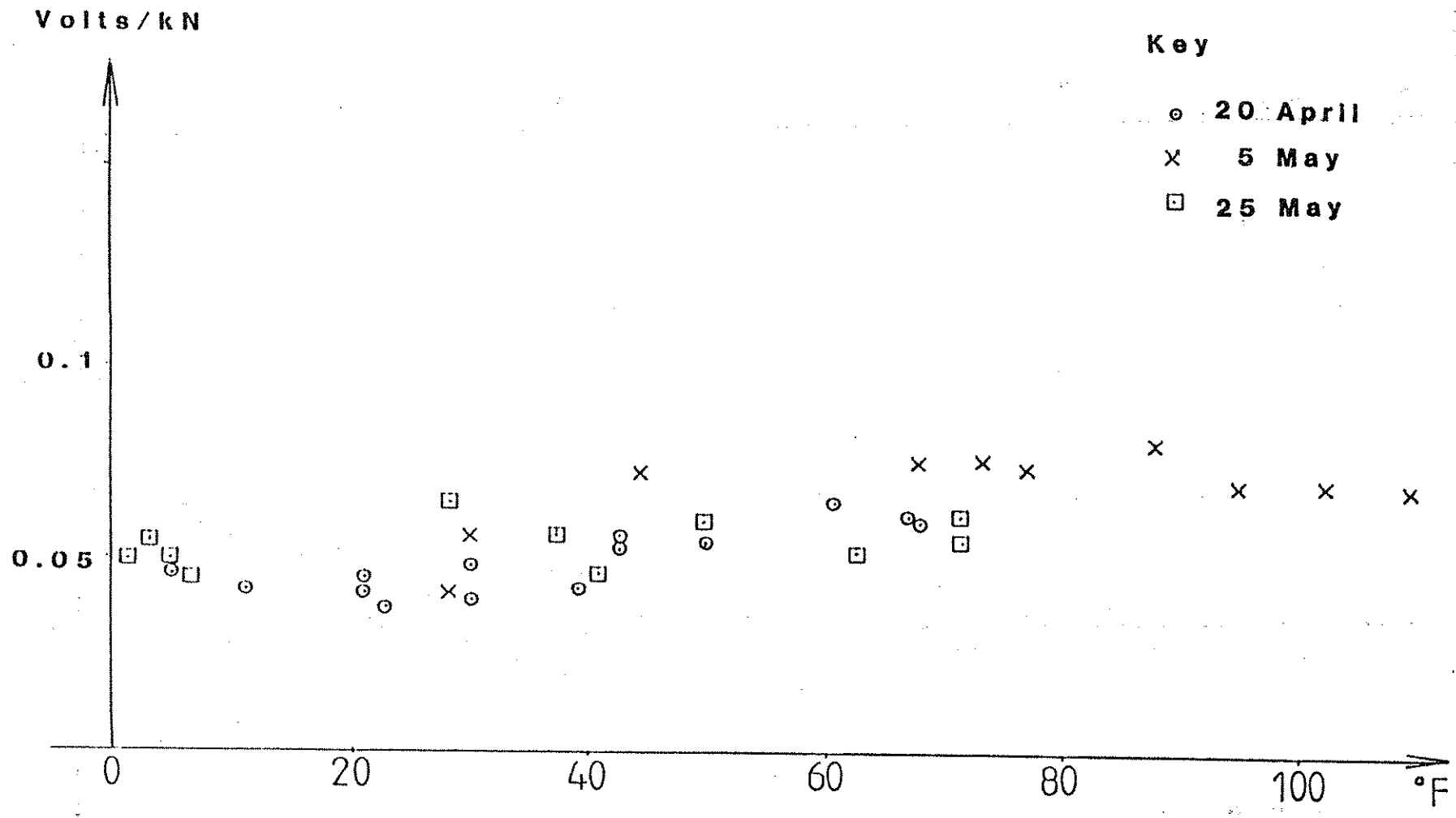


Figure 6.8 Sensor sensitivity v temperature (baseplate clamped)

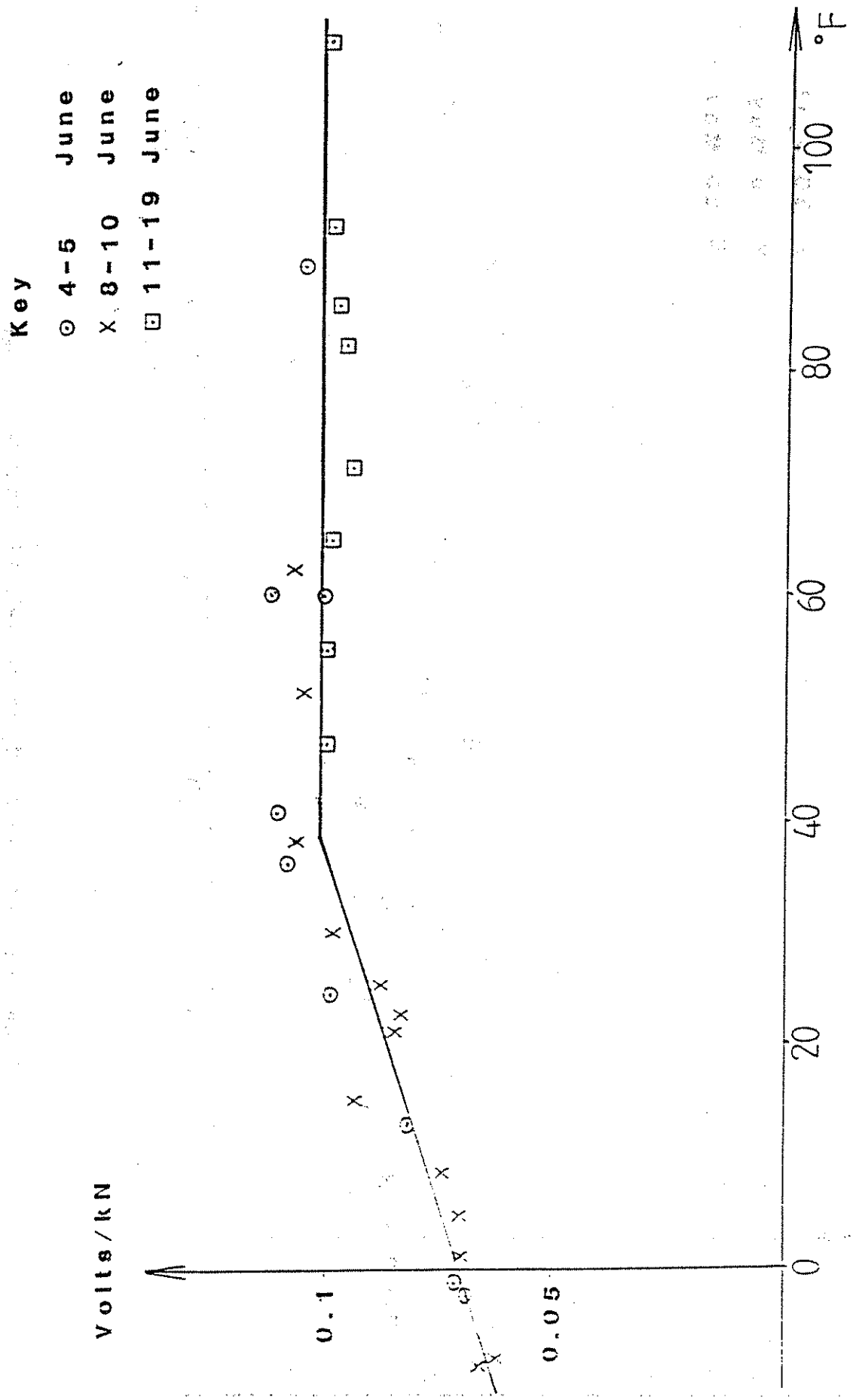


Figure 6.9 Sensor sensitivity v temperature (stuck down sensor with minimum side force)

In order to complete the full range of tests necessary the rig was kept in the environmental chamber for several days. Certain tests were repeated on different days. Output voltages were found to be different for the same load, although the temperature remained constant. This apparent change in sensitivity was thought to be due to the foam rubber on the side of the sensor creeping under stress, thereby loosening the grip between sensor and vice.

A second series of tests was undertaken with the sensor gripped on the side of the base plate which was not covered with foam. In all other respects the test procedure remained as before.

The results of these tests are detailed in Figure 6.8. Once again it was apparent that the amount of clamping used to hold the sensor in the rig had a significant effect on sensor sensitivity. This is demonstrated by the degree of scatter in the results.

In the final series of tests the original clamping mechanism was used, but only a minimal sideways force was applied to the sensor. The sensor was held in place by sticking the baseplate to the loading platform, thereby simulating the bond between the sensor and pavement when the sensor is installed in the highway. In all other respects the test procedures remained as before.

The results from the final tests are detailed in Figure 6.9. Unlike the previous tests, reasonably consistent results were achieved over a period of several days. The results indicate that sensor sensitivity remains constant at temperatures above 40 degrees F (5 degrees C). Sensitivity reduces steadily below this temperature at a rate of approximately 15% per 18 degrees F (10 degrees C). It is this relationship which is the basis of the temperature compensation used in the second generation AWACS.

Power Supply Tests

Experiments were undertaken to test the susceptibility of the preproduction systems to power supply fluctuations. Firstly, a variable power supply was provided through a variac and the system response to simulated wheel loads was observed as the applied voltage was incrementally reduced. During this time the back-up battery was disconnected.

Expressing the applied voltage as a percentage of the rated mains supply, the system output remained within the expected range down to 67% of mains voltage. The system failed to produce an output at approximately 55% of the rated mains voltage.

This result was confirmed by measuring the output from the system transformer with varying mains supply. Output voltage remained at or above the rated 6 volt level until the mains supply was reduced to 67%. The system continued to work satisfactorily until the output voltage dropped to approximately 5 volts.

The operation of the system with a total mains failure was also simulated. With the mains supply disconnected and the system powered by the battery alone, the output remained within the expected range during the period of the test. By measuring the current drawn by the system, it was calculated that it would be several days before the supply voltage dropped from the fully charged state of 6 volts to the minimum of 5 volts required to operate the system satisfactorily.

6.4 CONCLUSIONS

The laboratory and environmental tests undertaken were designed to investigate the fundamental operational characteristics of the piezo-electric cable sensors and the electronic hardware.

Both the unmounted cable and composite sensor operated satisfactorily across a wide range of conditions. Uniformity and linearity of response were such that reasonable results were projected from the field trials using the preferred sensor design.

The performance of the sensor and system electronics as a combined unit was also tested under varying environmental and operating conditions, indicating that the first generation preproduction system should perform within specification.

Subsequent laboratory tests indicated a reduction in sensor response at low temperatures, which was accommodated in the second generation AWACS equipment using a software compensation routine linked to an in-pavement thermocouple monitoring temperatures.

The overall conclusion of this chapter is that, so far as can be established from the laboratory test program, the first generation AWACS prototype equipment supplied by GK Instruments met the requirements of the procurement specification set out in Chapter 5.

7. Installation of equipment

7.1 INTRODUCTION

This chapter describes the installation of the two preproduction systems in the field in Iowa and Minnesota. It details the work undertaken, and installation procedures adopted.

Prior to the work commencing, detailed instructions were provided to the states for the installation of the two preproduction systems. The project team supervised transducer assembly and installation of all electronic equipment and interconnections by the states. Team members also supervised state calibration of the systems, testing all subsystem and system outputs before calibration.

Installation of sensor hardware involved slot-cutting and fixing of the piezo-electric sensors and inductance loops in the slots. Installation of system electronics followed this, using instructions and diagrams provided by the manufacturer. Members of the study team supervised the installations at both sites, which were completed as planned and to schedule.

7.2 SITE INSTALLATION INSTRUCTIONS

Detailed site installation instructions were prepared before fieldwork started, sufficient to allow states to install preproduction AWACS systems with appropriate supervision. Installation details are given in the following paragraphs, which specify both the methods of operation and the requirements for personnel, equipment and materials within a step-by-step guide to the installation of an AWACS system. A preferred method of installation is identified, though it is recognized that variations may be necessary due to local conditions, equipment availability and other external constraints.

A group of four operatives is envisaged for the safe and efficient installation of the equipment - two persons for loop cutting, a general laborer and a supervisor. Weather conditions must be dry, with pavement temperatures preferably in the range 50 degrees F to 80 degrees F. On arrival at the site, personnel should proceed in accordance with approved traffic control practices. The site should be coned well into the second lane, without undue detriment to passing traffic, to protect personnel when working at the edge of the array.

The precise site for the array is now identified and the proposed positions of the sensors marked onto the pavement with paint. Surface conditions such as rut depth can then be checked to confirm that a suitable site has been chosen. If a double-blade diamond saw slot cutter is to be used, which is the preferred method of operation, a single straight line is drawn indicating one edge of the sensor. If a single blade cutter is to be used then the sensors are laid alongside the first line and a second line drawn. In such a case it is preferable to cut just inside the line to avoid having too wide a hole for the sensor.

Having marked the positions of the sensors it is possible to start excavating the trench between the edge of the pavement and the site of the control cabinet or hut into which ducting will be laid for the feeder cables.

If a twin blade cutter is adopted for the piezo installation, the space between the blades should be set to the specified distance, typically 1 3/8". The depth of cut needs also to be set, typically to 1 1/4". A height control should be provided on the cutting machine, failing which it may be possible to mark the side of the cutting blade to indicate the necessary depth of cut. A single slot is also required for the coaxial cable feeder to each piezo sensor.

Having cut the twin slots for the piezo sensors, the intervening material is carefully broken out to avoid damaging the pavement surface at the edge of the hole. A hammer and stone chisel are required, breaking-out along the length of the cut. Having brushed out most of the debris, an air blower should be used to drive out finer material and some of the remaining water. A flame gun is then used to dry out the holes completely. This is most important as it helps achieve a good bond between the pavement and the sensor using Hermetite epoxy.

The sensors can now be placed in their respective holes to identify isolated high spots which are broken out. The sensors are then laid alongside the holes to identify high and low points across the pavement profile. These positions are marked on the sensors. Where the pavement is high, steel plates are attached to the top of sensors using fine tie wire. Where the pavement is low, plates can be laid across the sensor after it is installed and weights applied to hold it down to the pavement profile while the Hermetite epoxy acquires the necessary strength.

The bottom and sides of the sensors are then cleaned using a proprietary solvent. The Hermetite epoxy, prepared in accordance with the manufacturer's instructions, is then poured in the slot and spread up the sides. Only one sensor should be installed at a time. Typically 14 - 20 lbs of Hermetite is required for each sensor, depending on the final dimensions of the hole.

The sensor should be placed into the slot starting from one end, so that the bow-wave of Hermetite produced will ensure contact along its whole length. If necessary, a scraper can be used to spread adhesive down the sides of the sensor. Extra Hermetite may be necessary to fill the sides of the slot before weighting down the sensor. The untied plates are repositioned at the locations previously marked on the sensor and weights are placed to hold the sensor to the profile of the road.

The feeder cables can then be passed through the ducting to the control housing. It is important to tag the feeder wires to identify individual sensors. Where feeders pass through joints in the pavement, it is recommended that PVC sheaths are placed around the cable to minimize damage from movement along the joint. A second or subsequent sensor can now be installed.

Excess Hermetite should be removed while still wet. The actual time required for the Hermetite to set depends on the ambient temperature. Initial cooling may be necessary if the weather is hot but the manufacturer's instructions and specification should first be checked. On cold days, setting times can be much longer than normal.

When the Hermetite is hard, the weights and plates can be taken away. Any excess fixant must be carefully removed using a hand grinder and low spots filled with further Hermetite. It is essential that epoxy is not left on top of the sensors. Cold fill macadam or similar, sealed as necessary, can be used to hold the feeder cables where they enter the ducting in the verge.

The cables are then connected to test equipment and the sensors are tested by striking with a hammer, or similar. Given suitable signals, the trench to the control housing can now be backfilled. The site can then be cleared and the dimensions of the array, as installed, noted for future reference. The traffic control signs and cones should finally be removed and the sensors tested using random vehicles before commissioning the equipment and commencing the calibration process.

7.3 INSTALLATION

The actual installation in each state proceeded in accordance with the instructions detailed in section 7.2 above.

The first priority in installing the two preproduction systems was the connection of power and telephone supplies at each site. Roadside huts were provided by the states for housing the system electronics. In Minnesota, a garage was salvaged from a right-of-way purchase and utilized as an equipment hut. In Iowa, a small portable cabin was used to house the equipment.

The site plans provided before installation showed the sensor arrays, service ducts and positions for the equipment huts. The distance between the array and the hut was regulated by the length of the feeder cable to the sensors. At the Iowa site the need to maintain a right-of-way meant that the control hut needed to be a further 50' from the array than recommended. This meant joining an additional length onto each of the existing feeder cables. Where joints were made, the cables were set in a small inspection chamber to allow for possible future maintenance.

Site meetings were held prior to work commencing so that the precise location for the array could be identified and the proposed positions of sensors marked onto the pavement. Surface conditions such as rut depth were then checked to confirm that a suitable site had been chosen.

Installation of the sensors required slots to be cut in the pavement surface, both for the piezo-electric cables and for the inductance loop included in the first generation preproduction system. The piezo cables and inductance loop were then fixed in these slots using Hermetite adhesive, comprising an epoxy resin base with silicate fillers and a fixatropic agent to reduce settling.

Mixing and use of the adhesives was in accordance with the manufacturer's recommendations and previously established practices. However, the relatively high temperatures experienced at the first site in Minnesota affected the viscosity of the adhesive; rather than the gradual set experienced in the UK, the adhesive remained liquid for some time before setting rapidly. This presented major problems, creating difficulty in profiling the sensors to the pavement.

In particular, the slight gradient across the site caused the epoxy to flow while soft. The adhesive spread to cover a significant proportion of the sensors which had been set level with the existing pavement surface. Consequently, it was necessary to remove excess material from the tops of the sensors, which could only be done after bond between sensors and pavement was achieved. In the interim the epoxy had set hard and a grinder was needed to remove the skim of material.

At the second site in Iowa there was less of a problem, probably due to the learning process which occurred in Minnesota. Some excess material still had to be chiseled off the sensors. The pavement at Iowa is less flexible than that at the Minnesota site and is more uniform. As a result of these differences, the sensors were better profiled to the pavement than was the case in Minnesota.

As expected, valuable lessons were learnt from the experience of installing piezo sensors in the two states and the study team had specific recommendations to make regarding improved installation techniques. These recommendations are as follows:

1. During summer months, it is desirable to maintain the adhesive at a temperature of 45-55 degrees F before use. This should avoid the adhesive running downhill before setting. If this is impracticable, it would be prudent to install the sensors early in the day when the ambient temperature is low. UK experience also suggests that during Spring or Fall, the opposite approach may be necessary, keeping the epoxy at room temperature prior to installation.

2. A false top should be fitted to each sensor, to be removed once the sensor is installed. This would avoid the need to chip away any excess material covering the sensor. This top could be in the form of a rubber strip or adhesive tape which

can be peeled off the sensor while the epoxy is setting, bringing with it any excess material. The strip or tape will need to be strong enough to resist tearing when it is removed from the top of the sensor.

These modified techniques have since been applied to several subsequent installations supervised by Castle Rock Consultants, and have proved highly successful in avoiding the problems which were observed during the initial sensor installation. The Minnesota sensors were eventually removed and re-installed using the new techniques, resulting in considerably improved profiling over that initially achieved. These events are detailed in subsequent chapters.

8. First generation system performance

8.1 INTRODUCTION

This chapter concerns the performance of the first generation Automatic Weight and Classification System (AWACS) during approximately five months of system operation at field test sites in Iowa and Minnesota.

The chapter summarizes the results obtained from the first generation system, the analyses conducted, and the conclusions drawn from these analyses. Problems encountered with the operation of the preproduction systems are identified, together with the steps taken to solve those problems. Certain system modifications are outlined which were considered necessary or desirable, based on the interim results. Details are also given of the accuracy of the system and its ability to perform according to established specifications, such as those being developed for the HELP program.

The first section of the chapter outlines the procedures adopted to determine system accuracy. Subsequent sections are concerned with individual aspects of system performance, principally the accuracy of weigh-in-motion measurements and vehicle classification. Conclusions drawn from the analyses are given at the end of the chapter.

8.2 METHODOLOGY

Evaluation of the first generation equipment concentrated on system accuracy and reliability of sensors and electronics. Data collection and analysis was in accordance with the agreed test program described in Chapter 3. Random and test vehicle data were collected at both sites during September and December 1986. The major effort in data collection came from state personnel. The data analysis, undertaken by CRC, considered the system's accuracy and reliability in measuring the following:

* axle weights
* gross weights
* axle spacings
* vehicle speed

* vehicle class
* tire length and width.

Data on each of these aspects were collected and recorded along with information on appropriate variables that may affect the system performance in that particular area. The weight estimation accuracy of the system was determined by comparison of the weigh-in-motion system measurements with weights obtained from a static scale. Vehicle classification accuracy was determined by comparison of system output with manual observations. Axle spacing, and tire length and width accuracy of the system were determined by comparison of system measurements with manual measurements. Speed accuracy was determined by comparison of AWACS data with radar measurements.

8.3 RANDOM VEHICLE EVALUATION

Appraisals using random vehicles were the major type of field test undertaken during the initial stages of the WIM performance appraisal. They were used to calibrate the systems, to measure their systematic and random error components, and to identify differences in errors between various weight ranges. Random vehicle evaluations were conducted in Iowa and Minnesota over a period of two weeks in September and one week in December 1986 with data collected by state DOT staff, working with study team members.

WIM Calibration

Calibration of the WIM function of the AWACS was achieved by plotting the WIM output (normalized to a common speed) against static load for a random sample of individual truck axles and axle combinations. The calibration was then found by fitting the best straight line through these points and the origin.

The Iowa random vehicle data were initially analyzed to produce one calibration factor for each piezo-electric sensor. These calibration factors were calculated on the basis that the mean percentage difference (PD) between dynamic and static weights should be zero for the calibration data set. However, further analysis of the resulting error distribution indicated that separate calibrations were appropriate for lead axles and other axles. This could be due to the fact that nearly all lead axles have single tires, while many other axles are fitted with double tires, resulting in a significant difference in loading width on the WIM sensors. Other relevant factors might include aerodynamic behavior and suspension effects, interacting with pavement approach profiles.

The calibration factors calculated for lead and other axles for the Iowa AWACS system using the September field data are summarized in Table 8.1. These correspond to the multiplier M in the formula:

$$Y = M X$$

where Y = axle weight
X = raw signal area, normalized to a speed of 1 mph

Sensor	A	B	D
Lead axles (M1)	0.91	0.37	0.40
Other axles (M2)	0.82	0.33	0.35
Ratio M1/M2	1.12	1.11	1.14

Table 8.1 Iowa WIM calibration factors - September 1986

Sensors A, B and D were the three parallel sensors shown in Figure 4.1. Sensor C was the diagonal sensor, used to measure tire width and lateral position, and sensor E was the experimental buried sensor.

It can be seen from Table 8.1 that there is a reasonably consistent ratio between the calibration factors for lead and other axles for each piezo-electric sensor.

The Minnesota random vehicle data collected in September were analyzed utilizing the same techniques as those adopted for the Iowa system. However, the system output from Minnesota showed that certain sensors were not working correctly. The resulting variability in the data collected meant that little confidence could be attached to the calculated calibration factors.

There are three possible alternative causes of the initial system performance in Minnesota. Firstly, the epoxy fixative used to bed the mounted sensors was observed to have spread over the top of the sensors in several areas. This reduced the sensitivity of the sensors to loading in those areas, resulting in an unacceptable variation in sensor response with the lateral position of vehicles crossing the WIM site. The second possible cause was a system electronics fault in the equipment initially supplied to Minnesota. Several problems were caused by a voltage overload during system installation in Minnesota, which had not been rectified at the time of the September tests. A final reason could be associated with the very flexible pavement in Minnesota, confusing bending with direct load signals on the piezo sensors.

Remedial action was taken after the September testing period to improve the performance of the Minnesota AWACS system. The sensors were cleaned using a chisel and hand-grinder to remove excess epoxy fixative. Flexane was spread over certain parts of the sensors to improve their profiling to the pavement surface. Improvements were also made to the system electronics to reduce performance variability from this source.

Table 8.2 shows the calibration factors calculated for both lead and other axles using random vehicle data collected at both Iowa and Minnesota during December. The third column in this table shows the calibration factors calculated from the Iowa data collected in September for the same combination of sensors. The apparent change in calibration from September to December was due to software and hardware changes over the intervening period affecting charge amplifier sensitivity and signal tracking.

It can be seen from Table 8.2 that there is a reasonably consistent ratio between the calibration factors for lead and other axles.

Sensor Combination BD	Minnesota December 1986	Iowa December 1986	Iowa September 1986
Lead Axles (M1)	1.12	1.21	0.39
Other Axles (M2)	1.03	1.06	0.34
Ratio M1/M2	1.09	1.14	1.13

Table 8.2 WIM calibration factors (AWACS 1)

Axle Weight Accuracy

The axle weighing accuracy of the AWACS equipment was determined by direct comparison of static axle and axle group weights with WIM measurements obtained using the calibration factors calculated above. The WIM accuracy analysis concentrated on the distribution of percentage differences (PD) in accordance with the Chapter 3 recommendations. The percentage difference (PD) is defined by the following formula:

$$PD = \frac{\text{WIM weight - static weight}}{\text{static weight}} \times 100\%$$

In the analyses, the systematic difference is measured by the mean of the PD distribution. The random difference is measured by the standard deviation of the PD distribution. The term 'difference' is used in preference to 'error' since later analysis suggested much of the difference between static and dynamic weight is genuine; that is, the result of actual dynamic variations in vehicle weights.

In September, means and standard deviations of the PD distributions were calculated for the individual sensors A, B and D; for combinations of two sensor outputs AB, AD and BD; and for the combination of three sensor outputs ABD. This was necessary in order that a decision could be made on the number of sensors that should be included in a low-cost AWACS system.

An initial WIM accuracy analysis was performed using all the random vehicle data collected in Iowa during September. From this it was evident that a small number of vehicles (around 5% of the sample) was producing percentage weight differences well in excess of those obtained from other vehicles. The test data on these vehicles were re-examined to identify possible causes of the large differences.

One cause that was identified in a number of cases was that there were occasional recording mismatches between the vehicles weighed statically and dynamically. These were identified from axle configurations and spacings. A lateral position analysis was also conducted using the output from the diagonal sensor to determine whether any of the vehicles had passed offscale or over the ends of the sensors, causing a suspect output signal. By these means a total of eleven vehicles were eventually eliminated from the data set where they had been off-scale or where there was reasonable doubt that the static and dynamic weight data were from the same vehicle.

Analysis of the resulting data set gave the WIM accuracy figures summarized in Table 8.3. This table shows figures for lead axles and other axles, as well as giving overall figures for the Iowa AWACS system. Of the individual sensors, half-sensor A gave the largest spread of results about the mean. This is explained by the fact that it only weighs one wheel per axle, while the full sensors B and D weigh in both wheeltracks. Of the sensor combinations comprising two piezo-electric cables (AB, AD and BD) there was only a small difference in performance between combinations of half and full length sensors.

The results in Table 8.3 suggest that the piezo-electric AWACS system is sufficiently accurate to satisfy many user needs, particularly if combinations of sensors are used. The HELP system requirements for low-cost WIM provisionally specify the following limits in terms of standard errors, where standard error is the standard deviation of the error distribution:

1. Systematic differences in weight measurement shall not exceed the greater of 500 lbs or 5% for any weight range.

2. Random differences in axle weight measurement shall not exceed the greater of 1200 lbs or 12% for any weight range.

This specification utilizes the 'funnel' concept, with limits in pounds up to 10,000 lbs, and percentage limits at higher loads. Full details of the provisional HELP specification are presented in Appendix C.

The Iowa random vehicle evaluation indicated that combinations of two or three sensors were very likely to meet the random difference specification, with differences of around 9% and 8% respectively. Full length single sensor systems may also meet the HELP specification, although with higher random differences this is less certain.

	Half sensor	Full sensors		Sensor combinations			
Sensors	A	B	D	AB	AD	BD	ABD
Lead axles							
Sample size (axles/axle groups)	100	162	162	94	95	161	94
Systematic difference	0.1%	0.0%	0.1%	-0.2%	-0.2%	-0.1%	-0.2%
Random difference	11.4%	12.2%	8.1%	8.2%	7.2%	8.1%	6.5%
Other axles							
Sample size (axles/axle groups)	177	294	294	165	167	292	165
Systematic difference	-0.1%	0.1%	-0.1%	0.5%	0.1%	0.0%	0.3%
Random difference	15.7%	11.9%	11.2%	10.0%	9.4%	9.3%	8.1%
Overall							
Sample size (axles/axle groups)	277	456	456	259	262	453	259
Systematic difference	0.0%	0.1%	-0.1%	0.2%	0.0%	0.0%	0.1%
Random difference	14.3%	12.0%	10.2%	9.4%	8.7%	8.9%	7.6%

Table 8.3 Iowa axle weights from different sensor combinations - September 1986

Based on these results, tradeoffs between system accuracy and system cost were examined to determine whether 1, 2 or 3 sensors should be utilized in an AWACS system. A preferred system design was developed using two full-length sensors, which appeared to represent a satisfactory compromise, minimizing costs while giving a reasonable likelihood of satisfying currently specified user needs. This preferred design was implemented prior to the December tests.

Table 8.4 presents the September 1986 Iowa data for the preferred sensor combination BD in a form compatible with later analyses. It gives separate figures for lead and other axles; for axles above and below the HELP pivot point of 10,000 lbs; and for all axles/axle groups combined. As anticipated in the HELP WIM specification, the system is more accurate, in percentage terms, for axles over 10,000 lbs.

Sensor Combination BD	Lead axles	Other axles	0-10,000lbs	> 10,000lbs	All Axles
Sample size (axles/axle groups)	161	292	173	280	453
Systematic difference	-0.1%	0.0%	109 lbs	-0.9%	0.0%
Random difference	8.1%	9.3%	758 lbs	7.8%	8.9%

Table 8.4 Iowa axle weight measurement accuracy - September 1986

Analysis of the Minnesota random vehicle data collected in September revealed a wide range of results, due to the equipment problems previously described. Systematic differences were not calculated as the system could not be properly calibrated. However, the percentage random differences produced by the system varied from 8% to 67%, depending on which sensors were used.

A similar analysis was carried out on the axle weight data collected at both sites during December. The accuracy of the equipment was again determined by direct comparison of static weights with WIM measurements obtained from the AWACS system. The calculated means and standard deviations of the percentage difference distributions relate to the combination of the two full length sensor outputs, BD.

When analyzing the data it was once again evident that a small number of vehicles were producing percentage weight differences well in excess of those obtained from other vehicles. Using criteria established while analyzing the September field data a total of 6 vehicles were eventually eliminated from the Iowa data set and 12 vehicles from the Minnesota data set.

Analysis of the resulting data set gave the WIM accuracy figures summarized in Tables 8.5 and 8.6. These tables show figures for lead axles, other axles, axles above and below 10,000 lbs and overall weight measurement accuracy for Iowa and Minnesota respectively.

Sensor Combination BD	Lead axles	Other axles	0-10,000lbs	> 10,000lbs	All Axles
Sample size (axles/axle groups)	101	199	111	189	300
Systematic difference	-0.2%	-0.1%	-92 lbs	0.2%	-0.2%
Random difference	11.3%	10.2%	1018 lbs	9.4%	10.5%

Table 8.5 Iowa axle weight measurement accuracy - December 1986

Sensor Combination BD	Lead axles	Other axles	0-10,000lbs	> 10,000lbs	All Axles
Sample size (axles/axle groups)	79	117	66	130	196
Systematic difference	-0.2%	-0.1%	125 lbs	-0.9%	-0.1%
Random difference	14.0%	16.5%	1312 lbs	14.8%	15.5%

Table 8.6 Minnesota axle weight measurement accuracy - December 1986

The analysis of the data collected in Iowa during December shows an increase in random differences from those calculated using the September field data. Statistical tests suggest that this apparent deterioration is significant at the 1% level (Appendix A). This increase in error could be associated with a deterioration of the sensors, caused perhaps by loosening of the mountings in the pavement, or with a reduced ability to reject off-scale vehicles, due to the elimination of the diagonal sensor from the December AWACS

equipment. More data were needed before any final conclusions could be reached on the system performance in Iowa.

The analysis of the Minnesota data collected in December showed a higher random error than that obtained in Iowa. The results were, however, considerably better than those obtained in Minnesota during September. This suggested that the remedial actions taken to improve the sensor installation were only partly effective. Cracking of the pavement around the ends of the sensors suggested that they might be loosening as the pavement flexed under them. Further tests were scheduled to monitor the ongoing situation in Minnesota.

Gross Weight Accuracy

The gross vehicle weight accuracy of the AWACS system was assessed by direct comparison of static vehicle weights with WIM weights. The data set used to calibrate the system and for the axle weight accuracy evaluation was also used to determine gross weight accuracy. The analysis again concentrated on the percentage difference (PD) distribution, for which the results are summarized in Table 8.7.

The September gross weight accuracy results again show a significant improvement in accuracy using two sensors rather than one, with random errors of around 8% for single sensors and 6% for pairs of sensors. There is also an improvement using three sensors rather than two, though this is smaller. Table 8.7 suggests that the AWACS is potentially capable of satisfying user needs with respect to gross weight accuracy. Combinations of two and three sensors appear capable of meeting HELP requirements, while systems utilizing a single sensor may do so in some instances.

	Half sensor	Full sensors		Sensor combinations			
Sensors	A	B	D	AB	AD	BD	ABD
Sample size (vehicles)	100	161	160	93	94	159	93
Systematic difference	-0.6%	-0.3%	-0.3%	-0.2%	-0.2%	-0.1%	-0.1%
Random difference	9.4%	8.3%	7.3%	6.3%	6.2%	6.3%	5.3%

Table 8.7 Iowa gross weight measurement accuracy - September 1986

Sensor combination BD	Minnesota December 1986	Iowa December 1986	Iowa September 1986
Sample size (vehicles)	77	100	159
Systematic difference	-1.9%	-0.8%	-0.1%
Random difference	13.1%	8.1%	6.3%

Table 8.8 Gross weight measurement accuracy (AWACS1)

An assessment of gross vehicle weight accuracy of the AWACS at both sites was also carried out using the weight data collected during December. The gross vehicle weight is based on a combination of results from sensors B and D. Table 8.8 shows gross weight measurement accuracy from random vehicle data collected in Iowa during September and from both states during December.

An F test was used to determine whether there was any significant difference between the two sample sets from Iowa (Appendix A). The tests revealed that the deterioration in performance was significant at the 1% level. This could result from genuine deterioration in the sensors, or from differences in selection of the sample due, for example, to the ability to calculate lateral positions and reject off-scale vehicles in September 1986.

Weight Range Analysis

An analysis was undertaken to examine changes in systematic and random differences between various axle weight ranges using the test data. The calibration set was divided into four weight ranges, as follows:

1. Axles/combinations less than 10,000 lbs
2. Axles/combinations 10,000 - 20,000 lbs
3. Axles/combinations 20,000 - 30,000 lbs
4. Axles/combinations greater than 30,000 lbs.

The first range was chosen so that the funnel concept 'pivot point' of 10,000 lbs implicit in the provisional HELP system specification was recognized. The other range divisions were chosen so that significant quantities of data were available in each range.

The results of the weight range analysis for the Iowa data collected in September are given in Table 8.9. These results show similar patterns in weight accuracy variations between sensors for all weight ranges. Percentage random differences tend to reduce with axle weight. The observed pattern of variation in systematic difference is more complex than expected, with small positive errors at low weights and slightly larger negative errors at high weights. This suggests that further improvements to the calibration could be worthwhile.

Table 8.10 shows the results of weight range analyses carried out on the data collected in Iowa during December. The pattern of greater percentage accuracy at higher loads is maintained. Table 8.11 shows similar data collected in Minnesota during December. Random errors are higher than those obtained in Iowa. This is consistent with the poorer performance of the sensors in Minnesota.

Statistical tests were undertaken on the weight data to identify significant variations in both systematic and random differences between the weight ranges.The first statistical test carried out involved determining whether there was any significant variation in the systematic difference (mean percentage difference) between the weight ranges. Since more than two sample means were involved, the technique of analysis of variance was used. This tested the hypothesis that there was no significant difference between the sample means.

The results obtained for the data collected in Iowa during September indicated that for combinations of 1, 2 and 3 sensors, there were significant variations in systematic difference between the weight ranges, at the 5% level. The results for the December data in both Iowa and Minnesota showed no significant variation in systematic difference between weight ranges for a combination of two sensors (Appendix A).

The second statistical test undertaken determined whether there were significant variations in random difference between the weight ranges. Pairwise comparisons were made between the variances obtained for the PD distributions in each weight range. The F-distribution was then used to determine whether the variance ratios were significantly different at the 5% level.

The tests on the Iowa September data revealed that the PD distribution variances obtained for the two higher weight ranges were significantly less than those obtained at the two lower weight ranges, where sensors were considered singly. Where combinations of two sensor outputs were considered, the only significant result obtained was that the PD distribution variance at the highest weight range (>30,000 lb) was less than those obtained at the other three weight ranges. With the combination of three sensor outputs,

	Half sensor	Full sensors		Sensor combinations			
Sensors	A	B	D	AB	AD	BD	ABD
0-10,000 lbs							
Sample size (axles/axle groups)	112	175	174	109	110	173	109
Systematic difference	1.6%	1.9%	1.1%	1.6%	1.3%	1.4%	1.3%
Random difference	15.2%	13.4%	10.6%	9.9%	8.0%	9.7%	7.3%
10-20,000 lbs							
Sample size (axles/axle groups)	102	161	162	96	98	160	96
Systematic difference	-0.2%	0.6%	0.2%	0.3%	-0.4%	0.3%	-0.1%
Random difference	14.1%	11.5%	10.8%	8.9%	9.3%	8.9%	7.8%
20-30,000 lbs							
Sample size (axles/axle groups)	33	58	58	30	30	58	30
Systematic difference	-3.4%	0.1%	-0.4%	-1.8%	-0.8%	-0.1%	-0.8%
Random difference	12.3%	9.1%	9.5%	9.5%	8.4%	7.4%	7.6%
>30,000 lbs							
Sample size (axles/axle groups)	30	62	62	24	24	62	24
Systematic difference	-1.9%	-6.4%	-3.3%	-3.3%	-3.3%	-4.8%	-3.8%
Random difference	13.0%	8.9%	7.2%	7.6%	8.8%	5.3%	6.3%

Table 8.9 Iowa weight range analysis - September 1986

Sensor combination BD	0-10,000 lbs	10-20,000 lbs	20-30,000 lbs	>30,000 lbs
Sample size (axles/axle groups)	111	113	35	41
Systematic difference	-92 lbs (-0.9%)	0.3%	3.6%	-2.8%
Random difference	1018 lbs (12.3%)	10.3%	8.2%	7.9%

Table 8.10 Iowa weight range analysis - December 1986

Sensor combination BD	0-10,000 lbs	10-20,000 lbs	20-30,000 lbs	>30,000 lbs
Sample size (axles/axle groups)	66	81	16	33
Systematic difference	125 lbs (1.5%)	0.4%	1.7%	-5.5%
Random difference	1312 lbs (16.0%)	15.0%	18.6%	12.7%

Table 8.11 Minnesota weight range analysis - December 1986 data

no significant differences were observed (Appendix A). These findings tend to support the view that the system is more accurate, in percentage terms, for heavier axles.

The results of the F tests performed on the data collected in Iowa during December confirm the September findings, with four from six pairwise comparisons between weight bands showing a significant trend. The Minnesota data were less conclusive, with differences which were in most cases not significant. More data were required to investigate the Minnesota case in detail.

Axle Spacing Accuracy

The accuracy of axle spacing measurement was determined using random vehicle data collected in Iowa during September. Axle spacings measured using the AWACS were

compared with manual measurements taken using a tape measure at the weigh station. The difference distribution was calculated in terms of absolute differences. The absolute difference (AD) statistic was used because it was apparent that the magnitude of the difference between static and dynamic measurements was not dependent upon axle spacing.

Based on a sample of 53 axle spacing measurements, the systematic difference was -0.52 inches, with a random difference of 0.98 inches. We consider this to be a very high level of measurement accuracy, such that the errors may well be associated primarily with the static measurements.

The small systematic difference component may very well be due to errors in manual measurement, with tape sag the probable cause. The random difference can also be explained mostly by expected errors in manual measurements. This minimal random difference implies that speed measurements are also extremely accurate, since axle spacing calculations use speed as an input parameter. Any appreciable percentage error in speed measurement would certainly cause a corresponding error in axle spacing, proportionate to length. No such error was observed.

Speed Measurement Accuracy

Speed measurement accuracy was assessed using the Iowa random vehicle data. Absolute and percentage difference distributions were calculated, based on comparisons between AWACS and radar speed measurements. The results of the assessment, using a sample of 49 vehicles, are summarized in Table 8.12.

The calculated differences in speed measurement are very small. As discussed above, the percentage differences in AWACS speed measurement must be smaller than those calculated for axle spacing measurement, consisting essentially of rounding errors. Even the small differences displayed here are therefore likely to be mainly due to inaccuracies in the radar measurements.

	Absolute difference	Percentage difference
Systematic difference	0.67 mph	1.22%
Random difference	0.55 mph	1.03%

Table 8.12 Speed measurement accuracy (AWACS1)

8.4 TEST VEHICLE EVALUATION

Test vehicles were used during the September and December testing periods to investigate effects which could not be examined using random vehicles alone. The effect of speed on WIM accuracy was examined, and initial data were gathered toward investigating the effect of temperature on system accuracy.

Speed Trend Analysis

The speed trend analysis was performed as part of the WIM test vehicle evaluation, to investigate the effect of speed on WIM accuracy. Three test vehicles were used in Iowa and two test vehicles were used in Minnesota, to evaluate WIM performance in three speed bands. In Iowa, the speed bands considered were a low speed band of around 20 mph, a medium speed band of around 40 mph, and a high speed band of around 55 mph. The test vehicles used were a 2-axle, a 3-axle, and a 5-axle truck. In Minnesota, the speed bands used were around 30 mph, 40 mph, and 50 mph. The tests used 2-axle and 3-axle trucks.

Each vehicle was initially tested against the random sample for significant differences in the accuracy of the WIM results produced. This bias testing was performed for the high speed results, as this speed band corresponds with speeds observed in the initial random vehicle sample. The bias testing involved performing t-tests using the initial random sample and each vehicle's set of results at 55 mph. The results of the t-tests are summarized in Tables 8.13 and 8.14. These indicate that the results for the 2-axle and 3-axle trucks are not fully representative of the population observed in the random sample at Iowa. Results for the 5-axle truck are less conclusive. Table 8.14 indicates that no clear evidence of bias emerged from the Minnesota tests, probably due to the greater scatter in the data.

Sample	No of Axles	Mean of Percentage Differences	Variance of Percentage Differences	t	Biased
Random	1189	0.01	142.8	-	-
2 axle	45	-9.20	115.4	5.092	yes
3 axle	45	-8.87	224.5	4.844	yes
5 axle	33	-1.36	229.6	0.645	no

Table 8.13 Iowa t-test analysis (AWACS1)

Sample	No of Axles	Mean of Percentage Differences	Variance of Percentage Differences	t	Biased
Random	196	-0.14	241.0	-	-
2 axle	16	-1.86	142.5	0.434	no
3 axle	18	1.76	97.8	-0.509	no

Table 8.14 Minnesota t-test analysis (AWACS1)

The results of the speed trend analysis for static/dynamic weight comparisons using the Iowa test vehicle data are summarized in Tables 8.15 and 8.16. Minnesota test vehicle data are presented in Tables 8.17 and 8.18. The results suggest that random differences increase with vehicle speed, as expected for all WIM systems. Systematic differences appear to reduce with speed. However, when fluctuations in the individual vehicle results and the outcome of the bias testing are considered, the results are less conclusive. Further testing phases were required to yield more information on this aspect of AWACS performance.

Sample	Number of Axles	Systematic Difference (%)	Random Difference (%)
2 axle, 20 mph	90	-22.10	6.89
3 axle, 20 mph	82	-10.53	9.27
5 axle, 20 mph	45	0.53	9.74
2 axle, 40 mph	92	-15.04	8.99
3 axle, 40 mph	86	-4.55	10.29
5 axle, 40 mph	45	-8.29	9.34
2 axle, 55 mph	34	-9.20	10.74
3 axle, 55 mph	12	-8.87	14.98
5 axle, 55 mph	33	-1.36	15.15

Table 8.15 Iowa speed trend by vehicle (AWACS1)

Sample	Number of Axles	Systematic Difference (%)	Random Difference (%)
20 mph	216	-17.06	8.51
40 mph	180	-7.56	10.23
55 mph	123	-3.21	11.32

Table 8.16 Iowa overall speed trend analysis (AWACS1)

Sample	Number of Axles	Systematic Difference (%)	Random Difference (%)
2 axle, 30 mph	20	-9.97	10.26
3 axle, 30 mph	18	0.69	11.97
2 axle, 40 mph	20	-13.49	10.15
3 axle, 40 mph	20	4.95	11.10
2 axle, 55 mph	16	-1.86	11.94
3 axle, 55 mph	18	1.76	9.89

Table 8.17 Minnesota speed trend by vehicle (AWACS1)

Sample	Number of Axles	Systematic Difference (%)	Random Difference (%)
30 mph	38	-4.92	12.31
40 mph	40	-4.27	14.07
55 mph	34	0.05	11.05

Table 8.18 Minnesota overall speed trend analysis (AWACS1)

8.5 CLASSIFICATION ACCURACY

This section of the chapter is divided into four main subsections, dealing with the performance of the original FHWA Scheme F classification algorithm, the enhanced classification routine initially developed by CRC, subsequent testing of the GK classifier by the states, and performance of the GK classifier using the enhanced CRC logic.

The original aim of the initial tests was to establish the performance of the GK Instruments 6000 classifier, which is the basis of the Iowa/Minnesota AWACS equipment. This classifier utilized a Scheme F classification flowchart developed by Wyman and circulated by the FHWA in 1984. In the event, the GK equipment was not ready for testing in September 1986, so an existing classification routine developed by CRC was adapted to use the Wyman logic for the September testing.

The CRC classification routine was programmed on a Golden River Environmental Computer connected to a pair of piezo-electric axle sensors at right-angles to the traffic stream. For this appraisal, the classifier was connected to the second and fourth piezo sensors (B and D) at each site (Figures 4.1 and 4.2). Manual classification was used to check the accuracy of the Wyman algorithms, with a simultaneous video recording of traffic as a backup.

Following the September tests, the original GK 6000 classifier was tested by the states. After these tests, the GK classifier was upgraded, such that the December testing at both sites used the GK classifier programmed with the enhanced CRC logic. Manual classification was again performed as a check on accuracy.

Data were analyzed on a vehicle-by-vehicle basis using individual pairwise comparisons. In the course of the analysis, the following statistics were calculated:

Absolute accuracy

This is a measure of how well the AWACS classifies individual vehicles, considered one at a time, into their correct categories. The absolute accuracy can be defined for any particular category or for all of the categories taken together. Vehicles classified correctly lie on the leading diagonal of the classification matrix. For any class or group of classes,

$$\text{Absolute Accuracy} = \frac{\text{Number of vehicles classified correctly}}{\text{Number of vehicles recorded manually}}$$

Absolute accuracy is usually expressed as a percentage.

Compensated accuracy

This is a measure of how well the AWACS classifies a number of vehicles treated only as a group. It is a measure of how similar the manual classified totals are to the AWACS totals. This measure of accuracy allows compensation or canceling, in numeric terms, to occur between classes since vehicles lost from one particular class may be compensated for by those gained from another. Compensated accuracy may also be defined for an individual category, or for several categories together.

For an individual category:

$$\text{Compensated Accuracy} = 1 - \frac{\text{Absolute difference in manual and AWACS class total}}{\text{Manual total for that class}}$$

For several categories:

$$\text{Compensated Accuracy} = 1 - \sum^{N} \frac{\text{(Absolute difference in manual and AWACS class total)}}{\text{Overall manual total}}$$

Again, compensated accuracy is usually expressed as a percentage. Compensated accuracy is probably the more useful measure of accuracy in practical terms, since generally only the totals of the classified flows are of interest.

Wyman Algorithm

This algorithm, programmed in a Golden River Environmental Computer, was initially tested in both Minnesota and Iowa. The Minnesota data were used in establishing vehicle parameters for the enhanced classification routine subsequently tested in Iowa. In Minnesota, however, certain piezo sensors were malfunctioning during September, as documented earlier. This prevented the classifier from functioning effectively due to the poor quality of the input signals. In Iowa, the equipment functioned properly, giving a fair test of the accuracy of the Wyman algorithm. Analysis of the results has therefore concentrated on the Iowa data.

A sample of 1504 vehicles was collected in Iowa in September 1986 using the Wyman algorithm. This data set was called AMES 1. These data were analyzed by comparing manual and automatic classification records for individual vehicles. Where discrepancies occurred, the video record was checked to try to establish the cause. The AMES 1 accuracy matrix and accuracy statistics by vehicle class are given in Appendix B. Overall accuracies are summarized in Table 8.19.

	All vehicles	Trucks and buses
Sample size	1504	88
Absolute accuracy	85.7%	85.2%
Compensated accuracy	91.1%	86.6%

Table 8.19 Accuracies of Wyman algorithm

Only one of the four totals above satisfies the draft HELP WIM Performance Specification standard of at least 90% accuracy, with or without compensation. Classification accuracy was high for cars, and high for 3S2 trucks, but indeterminate or low for most other types of vehicle. Unfortunately, the sample sizes for other types of vehicle were generally small.

The largest single source of error was the misclassification of pickups as cars. The compensating error, of cars being classed as pickups, occurred less than half as often. Wyman's car/pickup boundary is an axle spacing of 10 feet. The AMES 1 results suggested that this value was too high for the Iowa situation.

To find the optimum car/pickup boundary, axle spacings for individual vehicles from Iowa were compared with the video record of vehicle classification. Frequency distributions of axle spacing were developed for cars and pickups, which indicated an optimum boundary value of 9.8 feet. This value would serve to ensure that compensating errors between cars and pickups would approximately cancel.

A second estimate of the optimum cut-off was made by assuming that car and pickup axle spacings are each normally distributed. From a sample of 985 vehicles, the mean car axle spacing was found to be 8.74 feet, with a standard deviation of 0.70 feet. For pickups, the mean was 10.13 feet, with a standard deviation of 1.12 feet. These values, illustrated in Figure 8.1, give an optimum boundary value which is in close agreement with the empirical figure above.

A similar problem occurred between pickups and 2-axle trucks. In this case, a 13 foot boundary had been utilized by CRC, after Startz (1985), rather than the 15 feet suggested by Wyman. In total, out of all the AMES data, 30 of these trucks were wrongly classified as pickups, while only four pickups were counted as trucks. These results indicate that the 13 foot value was still too large. Details of the analysis to determine an optimum pickup-truck boundary are included in a subsequent section of this chapter.

A third source of error in the AMES 1 data was the misclassification of vehicles for which only one axle is detected. This can occur due to lane changing, or to lack of sensor sensitivity in detecting very lightweight axles. Calculations suggested that a small improvement in absolute accuracy could be gained by assuming these vehicles to be cars.

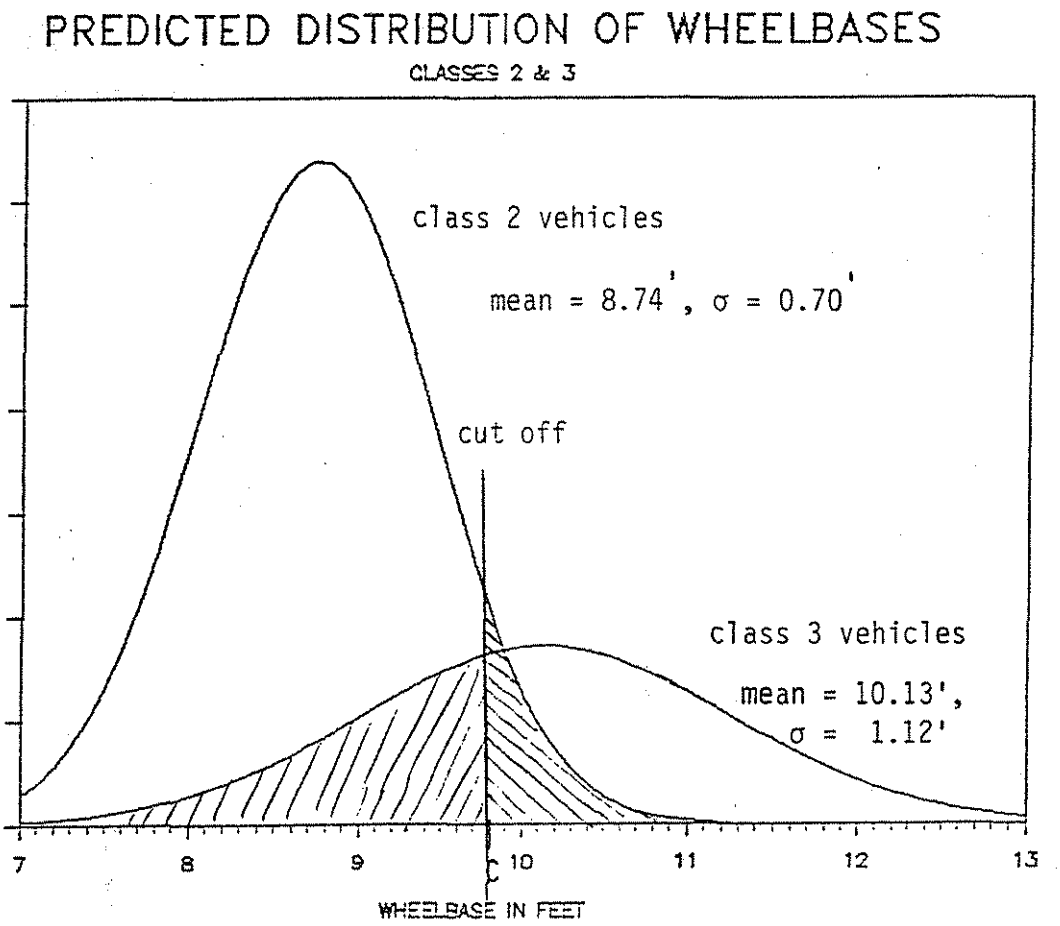


Figure 8.1 Predicted distribution of wheelbases

Finally, misclassification was observed in the AMES 1 data for various less common truck categories. The frequencies of these truck types were too low to quantify the problems precisely. To address this issue, an empirical approach was adopted. The Wyman axle spacing boundary values were modified and expanded to cover all axle spacings and all truck types observed over a 10 day period in Minnesota and Iowa. Values were adjusted manually as each new truck type was observed, until a reasonably comprehensive data base was felt to have been established. These vehicle dimensions formed the basis of the enhanced CRC classification routine tested during the remainder of the September appraisal in Iowa.

CRC Algorithm (Version 1)

An initial version of the enhanced CRC classification algorithm, developed during the first 10 days of the September testing in Minnesota and Iowa, was tested during the final three days in Iowa. This initial version of the algorithm incorporated revised truck dimensions and logic, but not the change in the car/pickup boundary. Classification checks were carried out during four sampling periods, creating data sets AMES 2 to AMES 5. A total of 3308 vehicles were surveyed in these samples.

Accuracy matrices and summary statistics for AMES 2 - AMES 5 are summarized in Table 8.20, with the AMES 1 data included for comparative purposes.

	All vehicles			Trucks and buses		
Data Set	Sample size	Absolute accuracy	Compensated accuracy	Sample size	Absolute accuracy	Compensated accuracy
AMES 1	1504	85.7%	91.1%	88	85.2%	86.6%
AMES 2	847	89.0%	93.4%	189	93.1%	92.6%
AMES 3	985	87.3%	90.8%	161	91.9%	90.0%
AMES 4	351	86.0%	88.6%	71	90.1%	87.3%
AMES 5	1125	85.1%	90.4%	200	92.0%	90.5%
Total 2-5	3308	86.9%	91.4%	621	92.1%	92.3%

Table 8.20 Accuracies of CRC Algorithm (Version 1)

Note: AMES 1 = Wyman algorithm; AMES 2-5 = CRC algorithm (Version 1)

The enhanced logic produced significant improvements in the classification of trucks and buses. Their absolute accuracy of classification increased from 85.2% to 92.1%, a figure statistically significant at the 5% level. Compensated accuracies for trucks and buses also showed a tendency to increase. These changes suggest that the classification logic amendments produced many of the desired effects.

The changes produced little impact on the overall accuracy statistics. This is because the overall figures are dominated by cars and pickups, whose logic had not been changed. A further, manual analysis was therefore undertaken to predict the effects of changing the car/pickup classification boundary from 10 feet to 9.8 feet. This was simulated by manually reclassifying vehicles on the computer printout within the relevant range. Some 2500 vehicles were analyzed in this investigation, which showed that the overall compensated accuracy of vehicle classification would increase from 91.1% to 95.1%, a statistically significant change. This amendment was therefore implemented in subsequent versions of the enhanced logic.

The AMES 2 - AMES 5 data sets are in total sufficiently large as to be practicable for subdivision by time period. Nominal 15 minute time periods were utilized to establish system accuracy variations with recording interval. Separate accuracy matrices were prepared for each 15 minute period.

This disaggregated method of data analysis has several advantages. Firstly, by subdividing samples, a distribution of accuracy statistics was derived, allowing 95% confidence limits of the mean accuracies to be estimated. Secondly, subsamples can be tested to see if accuracy varies with sample size, or by time period; and finally, apparent changes in accuracy following enhancements to the classification logic can be tested for significance. The statistical analysis is presented in Appendix B.

Figures 8.2 and 8.3 show the results of these analyses of percentage accuracy against sample sizes, for all vehicles and trucks/buses respectively. The figures show that, in general, absolute accuracy is independent of sample size, while compensated accuracy tends to increase with higher flows or longer time periods. This is an expected result, which indicates that hourly or daily flows will be more reliable than very short period counts.

A final analysis of the September Iowa data shows that the overall counting accuracy of the system is very high, with less than 1% of vehicles being missed or double-counted. These results are summarized in Table 8.21.

Data set	Count accuracy
AMES 1	100.0%
AMES 2	99.1%
AMES 3	99.7%
AMES 4	99.4%
AMES 5	100.0%
Total 2-5	99.6%

Table 8.21 Overall count accuracy

Pickup/Truck Boundary Analysis

This section details the analysis carried out to determine the optimum pickup/truck threshold. During the September field trials, as stated in the previous section, CRC incorporated the Startz (1985) amendment for the pickup/truck boundary at 13 feet, rather than the original Wyman algorithm value of 15 feet. The 13 feet boundary still misclassed many pickups and trucks, however, and further redefinition of this boundary was required.

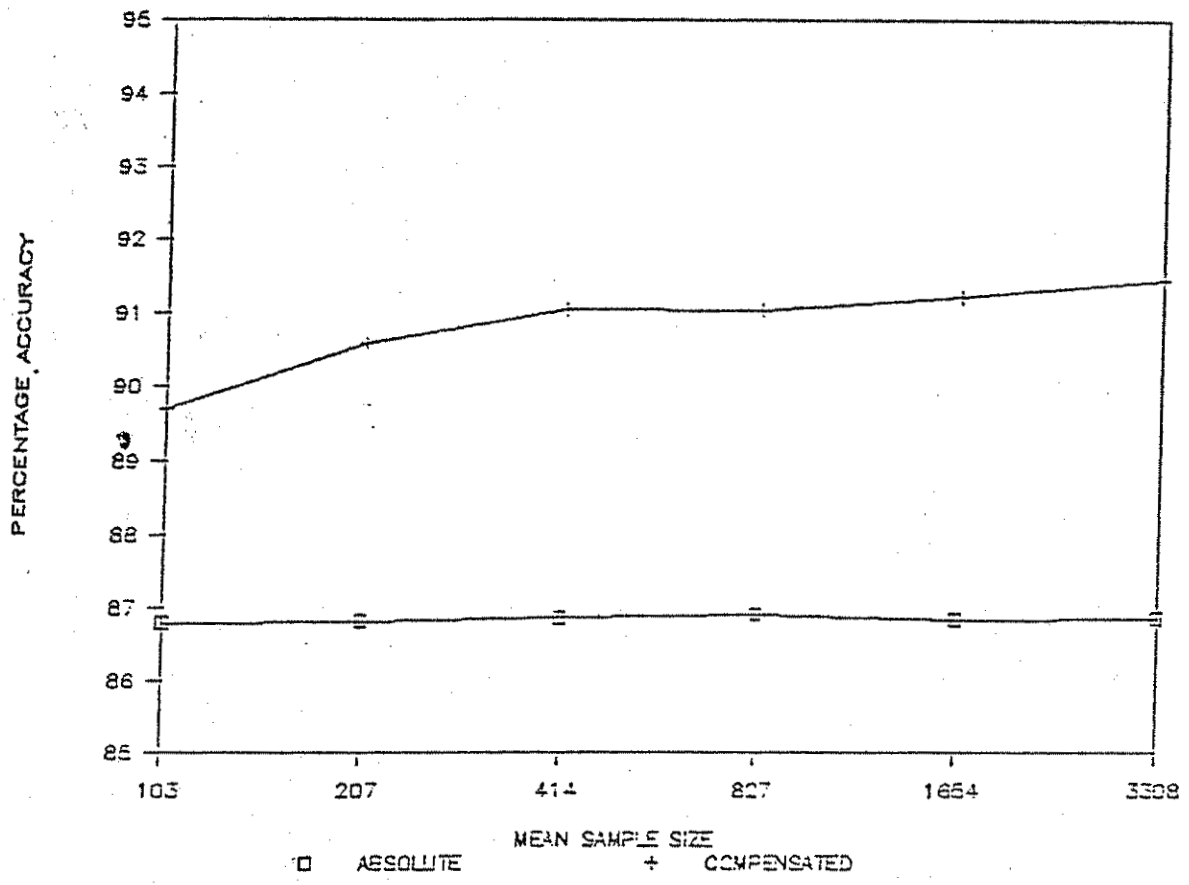


Figure 8.2 Percentage accuracy versus sample size (all vehicle classes)

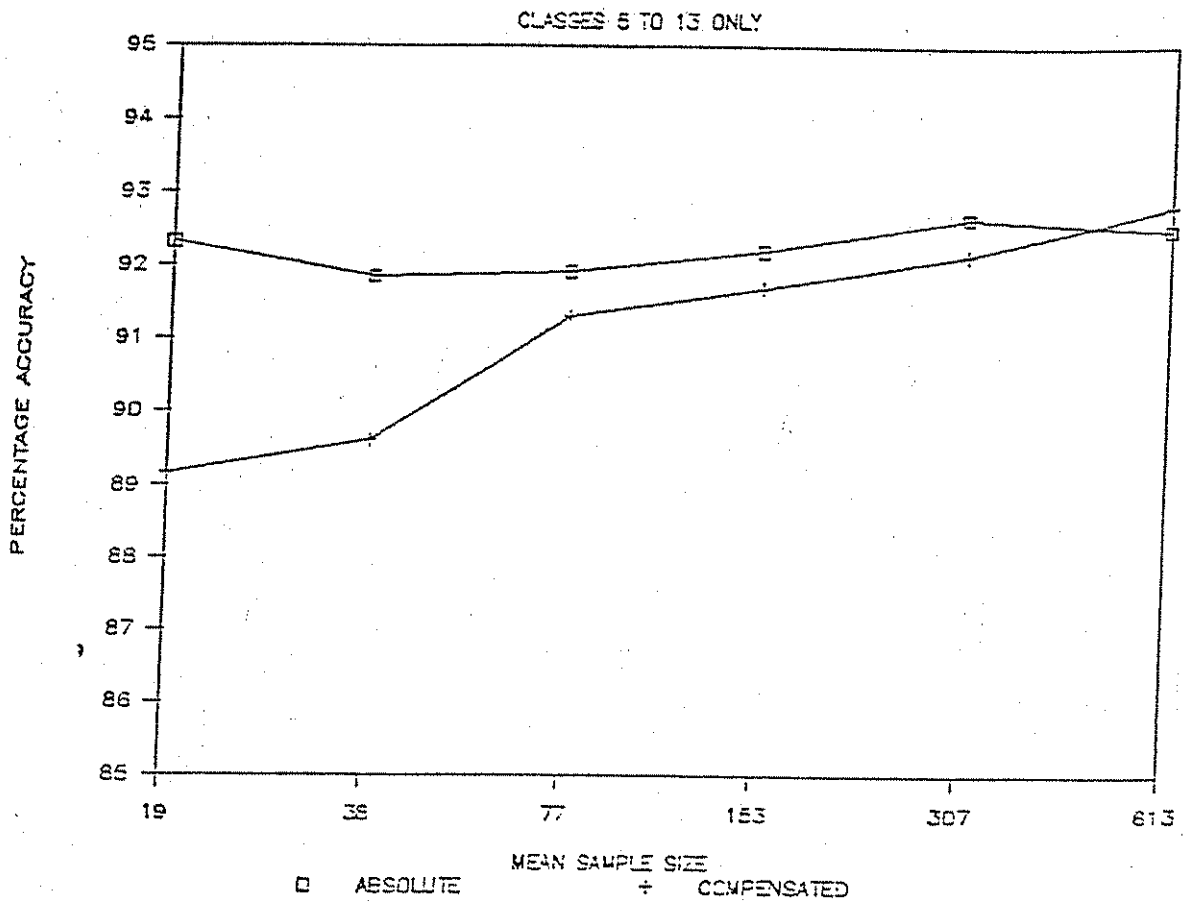


Figure 8.3 Percentage accuracy versus sample size

In September, a total of 870 Class 3 vehicles and 110 Class 5 vehicles were recorded. The wheelbase information for these vehicles was used as the basis of determining the revised car/pickup boundary, The boundary was determined by considering the number of Class 3 vehicles recorded as Class 5 and vice versa at different incremental cut-offs. Table 8.22 shows the results of the computer analysis.

Cut-off (feet)	Class 3 recorded as Class 5	Class 5 recorded as Class 3
11.8	59	19
11.9	50	19
12.0	41	21
12.1	34	24
*12.2	28	26
12.3	23	27
12.4	19	27
12.5	15	29
13.0	5	31
15.0	0	77

Table 8.22 Pickup/truck cut-off table

Table 8.22 illustrates that the optimum pickup/truck boundary occurred at 12.2 ft where 28 Class 3 vehicles were classified as Class 5, and 26 Class 5 vehicles were recorded as Class 3.

Figure 8.4 is a graph of the percentage misclassification of Class 5 as Class 3 vehicles for the same sample used in this analysis. It shows that the original Wyman pickup/truck boundary of 15 feet would result in 70% of the Class 5 vehicles being recorded as Class 3, while the CRC Version 1 algorithm (after Startz, 1985) would result in 28% of Class 5 vehicles being recorded as Class 3. The steep climb in the slope of the graph between 13 and 13.5 feet indicates that most Class 5 vehicles have wheelbases between these limits.

State Classification Testing

GK 6000 classifiers were delivered to both Iowa and Minnesota in late September, 1986. Both states began preliminary testing of the equipment during September/October. Various initial, minor problems were reported by both states which were examined and rectified wherever possible.

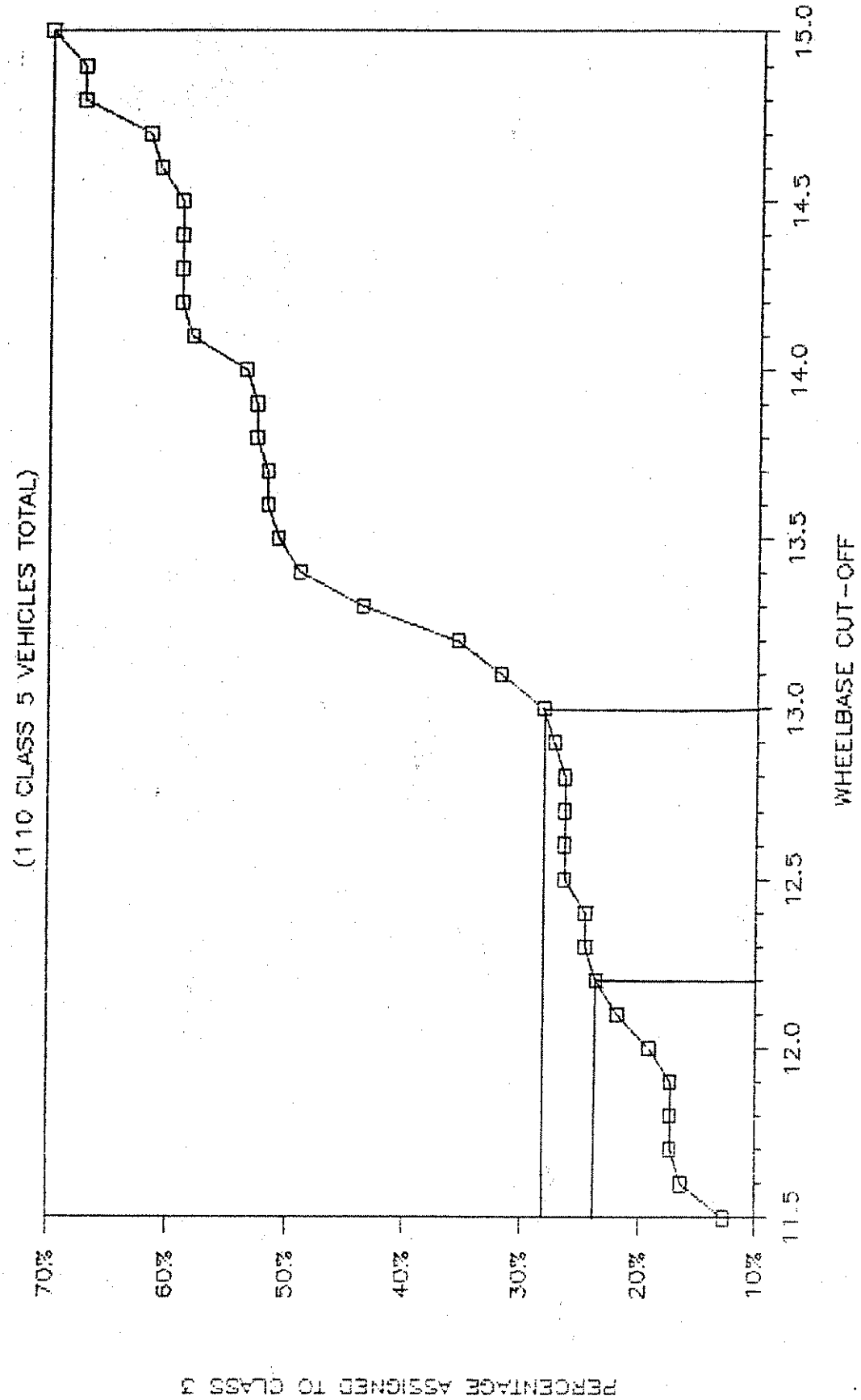


Figure 8.4 Percentage misclassification of class 5 as class 3

Iowa operated the equipment successfully and provided detailed feedback on its performance. On September 29, 1986 and October 17, 1986, a total of 2268 vehicles were classified using the GK Instruments classifier with the inductive loop connected. On October 21, 1986, 1575 vehicles were classified with the loop disconnected. Simultaneous manual classifications were also performed during these observation days.

For each set of data, the manual and classifier results were compared, and the absolute and compensated accuracies of the classifications calculated. A summary of these results is presented in Table 8.23, together with the earlier results for comparison.

	All vehicles			Trucks and buses		
Data Set	Sample size	Absolute accuracy	Compensated accuracy	Sample size	Absolute accuracy	Compensated accuracy
Wyman (AMES 1)	1504	85.7%	91.1%	88	85.2%	86.6%
CRC Version 1 (AMES 2-5)	3308	86.9%	91.4%	621	92.1%	92.3%
GK - loop	1575	84.9%	93.1%	320	80.6%	80.9%
GK + loop	2268	82.3%	89.9%	338	69.5%	63.6%

Table 8.23 Accuracies of GK 6000 Classifier

There are no significant differences in the overall accuracy statistics for the Wyman algorithm, CRC Version 1 algorithm or the GK classifier working without an inductive loop. This is not surprising, as all the systems used the same 10 foot axle spacing boundary for the cars and pickups which dominate the overall accuracy figures. The GK classifier working with an inductive loop was less accurate than the other systems, but the differences were not great.

The accuracies of truck and bus classification differ substantially between the systems. The differences are highly significant, statistically. The GK system without loop, based on the original Wyman algorithm, is significantly worse than CRC's implementation of the Wyman algorithm. This may be because CRC incorporated Startz' 1985 amendment with a pickup/truck boundary of 13, rather than 15 feet.

Truck classification accuracies with a loop drop into the range 60% to 70%. This is mainly due to the loop splitting 3S2s into two separate vehicles. These two separate vehicles are normally a three-axle single unit truck, and a motorcycle or car. The presence of

reinforcement in the pavement in Iowa is probably a significant factor in reducing loop performance and producing these poor results.

The implications of this finding for the low-cost AWACS system design are considerable. We have consistently recommended that a loop is not a necessary component of a low-cost piezo WIM system, as it was not expected to add significantly to classification accuracies. In the event, it was shown to make classification significantly worse. We therefore recommended that further development should concentrate wholly on system designs without a loop.

December Classification Testing

GK classifiers using the enhanced CRC logic were delivered to Iowa and Minnesota for the trials performed in early December. The new software, however, contained a number of bugs which caused the equipment to misclassify or miss certain vehicle types.

Testing proceeded at both sites, although it was realized that the software faults would have a substantial effect on the accuracies obtained. The equipment classified 1575 vehicles in Iowa and 1448 vehicles in Minnesota. Simultaneous manual classifications were also performed at both sites.

Manual and classifier results were compared for the two sets of data. The absolute and compensated accuracies were calculated and are summarized in Table 8.24. The accuracy values reflect the fact that the equipment was not functioning correctly due to the errors in the software. The problems that were recognized during the December testing were, however, rectified by new software sent to Iowa and Minnesota in mid-December 1986.

	Iowa Classification	Minnesota Classification
Sample size	1644	1514
Absolute accuracy	81.8%	82.8%
Compensated accuracy	89.6%	79.7%

Table 8.24 Accuracies of AWACS classifier in December 1986

8.6 TIRE LENGTH AND WIDTH MEASUREMENT

The aim of these initial tests was to establish the scope for using piezo sensors in the determination of the dynamic tire lengths and widths. For this appraisal, the output of the first and third sensors (A and C) for the Iowa site (Figure 4.1) were used. The AWACS tire lengths and tire widths were then compared with static lengths and widths measured manually at the weighscale.

Tire lengths were determined dynamically from the AWACS system by timing the duration of wheel passages across the half-piezo sensor 'A'. Sensor 'A' was used rather than full-length sensors B or D to avoid imperfectly overlapping signals caused by vehicle skew. Vehicle speeds were measured separately by timing wheel passages between piezos B and D. Dynamic tire contact length was given by the product of wheel passage duration and speed.

Tire widths were calculated from the duration of wheel passages across the 60 degree piezo sensor 'C'. Wheels take longer to cross the diagonal sensor 'C' than the half-length sensor 'A' by an amount proportional to tire width. The Task G1 report gave the derivation of a formula used for the calculation of dynamic tire widths.

Tire Lengths of Random Vehicles

This study was conducted at the Iowa test site on a sample of random trucks. A sample of 41 trucks had their static tire lengths measured at the weighscale using a specially constructed tire measurement gauge. The gauge comprised three steel strips forming three sides of a rectangle. One of the strips was free to slide, changing the length of the rectangle, and thereby measuring the tire contact length. Of the 41 random trucks, a subset of 26 were measured using the AWACS system, yielding a total of 112 dynamic tire length measurements.

The dynamic tire lengths obtained from the AWACS system were compared with the static tire lengths in order to investigate the relationship between the two sets of results. Figure 8.5 is a graph of the dynamic tire lengths against the static lengths. This graph shows that the dynamic lengths are typically 5" less than the static measurements.

This large systematic difference may result from a number of reasons. Firstly, the gauge measurements for static lengths may contain significant measurements errors due to uneven pavements, small stones and multiple tires (Figure 8.6). Secondly, it is likely that tire shape changes with speed due to centripetal force. This would result in lower tire contact lengths and higher tire contact pressures at speed. Thirdly, there may be an uneven pressure distribution over the contact length, with the leading and trailing edges only superficially in contact with the road, supporting little or no load (Figure 8.7). The final

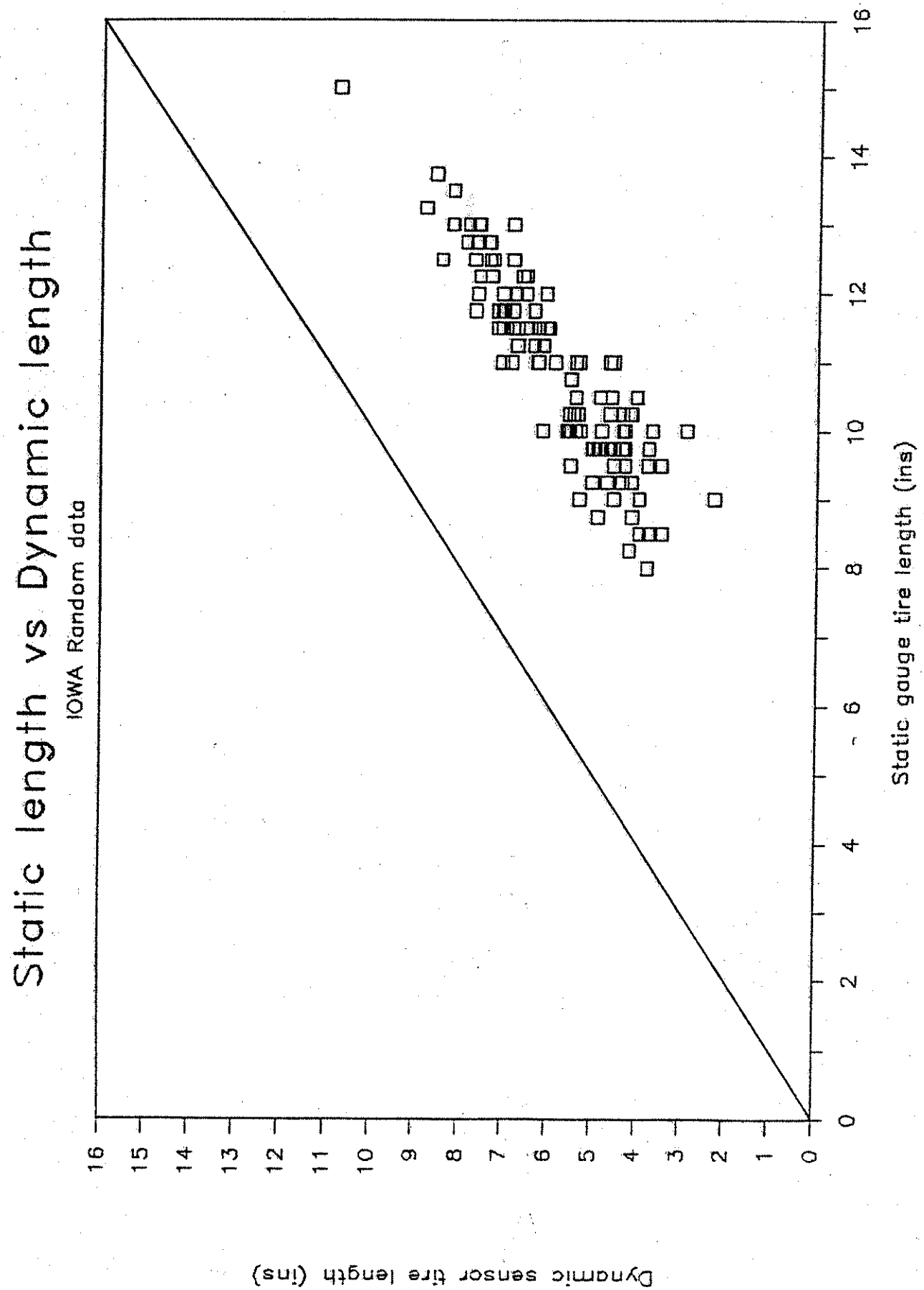


Figure 8.5 Static tire length v dynamic tire length (Iowa random vehicles)

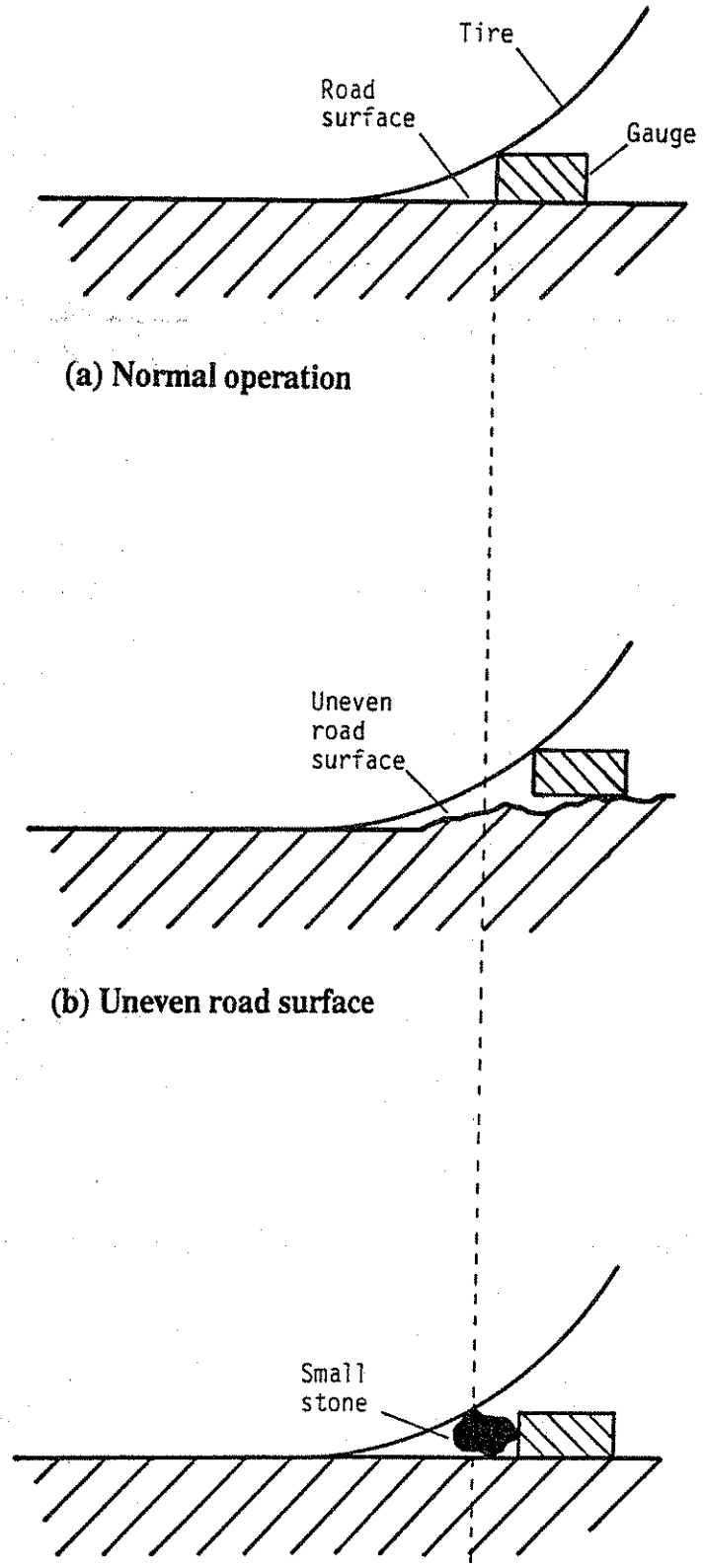


Figure 8.6 Schematic representation of measurement errors

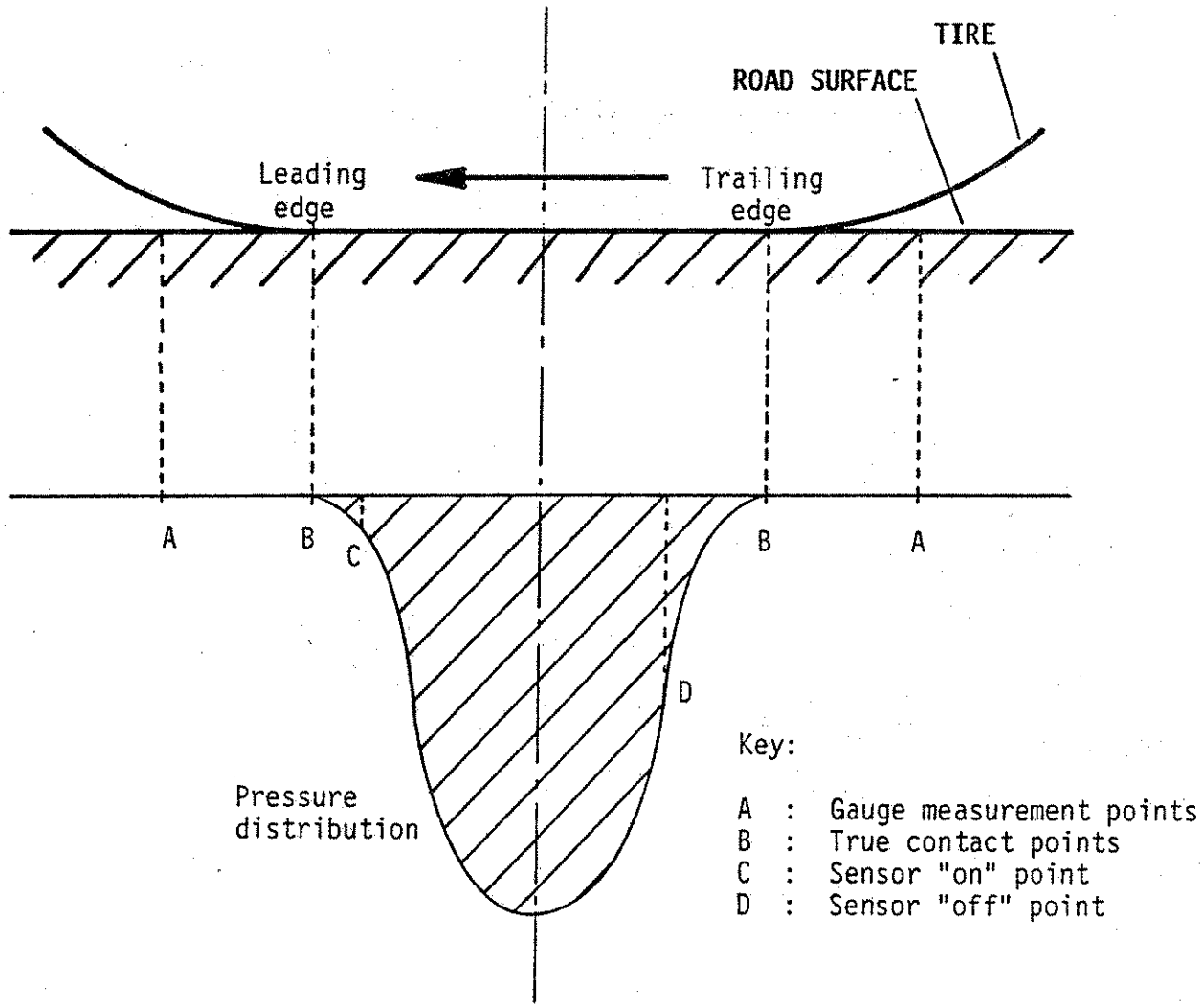


Figure 8.7 Pressure distribution under a tire

reason for the discrepancy between AWACS measured lengths and static tire lengths may be that the algorithm for processing the tire contact signals routinely underestimates the contact time.

Detailed analysis of the static and dynamic results shows that there is a systematic difference of -5.05" and a random scatter of 0.64". Calibration of the dynamic lengths using a simple additive correction factor gives results illustrated in Figure 8.8. This graph shows the calibrated dynamic tire lengths plotted against the static lengths. The calibrated dynamic lengths have a systematic difference of zero and a random difference of 0.64".

Tire Lengths of Test Vehicles

This study was similar to that performed on random vehicles, except that in this case the dynamic tire lengths were measured for test vehicles with a range of tire pressures. The vehicles used were a 2-axle and a 3-axle test truck with tire pressures of 60 and 100 psi. The two test vehicles were run over the piezo sensors five times at each tire pressure providing a total of 50 dynamic tire length readings.

Table 8.25 gives the tire length measurements for the test vehicles at the different pressures. The table shows that for the 2-axle truck, static tire lengths change by about 1.5" between tire pressures of 60 and 100 psi. The differences for the 3-axle truck are less consistent.

Analysis of the dynamic tire lengths gave a systematic difference of -4.82" and a random scatter of 0.90". Calibrated dynamic lengths were calculated as for the random vehicle tests detailed above, by adding a constant factor to each dynamic length. These results corresponded very closely to those obtained using the random data set.

	Axle	Static tire length at 60 psi (ins)	Static tire length at 100 psi (ins)	Difference in Static tire length (ins)
2-AXLE TRUCK	1	14.25	12.50	1.75
	2	14.00	12.50	1.50
3-AXLE TRUCK	1	17.50	15.50	2.00
	2	14.50	13.75	0.75
	3	13.75	13.75	0.00

Table 8.25 Static tire lengths at different tire pressures

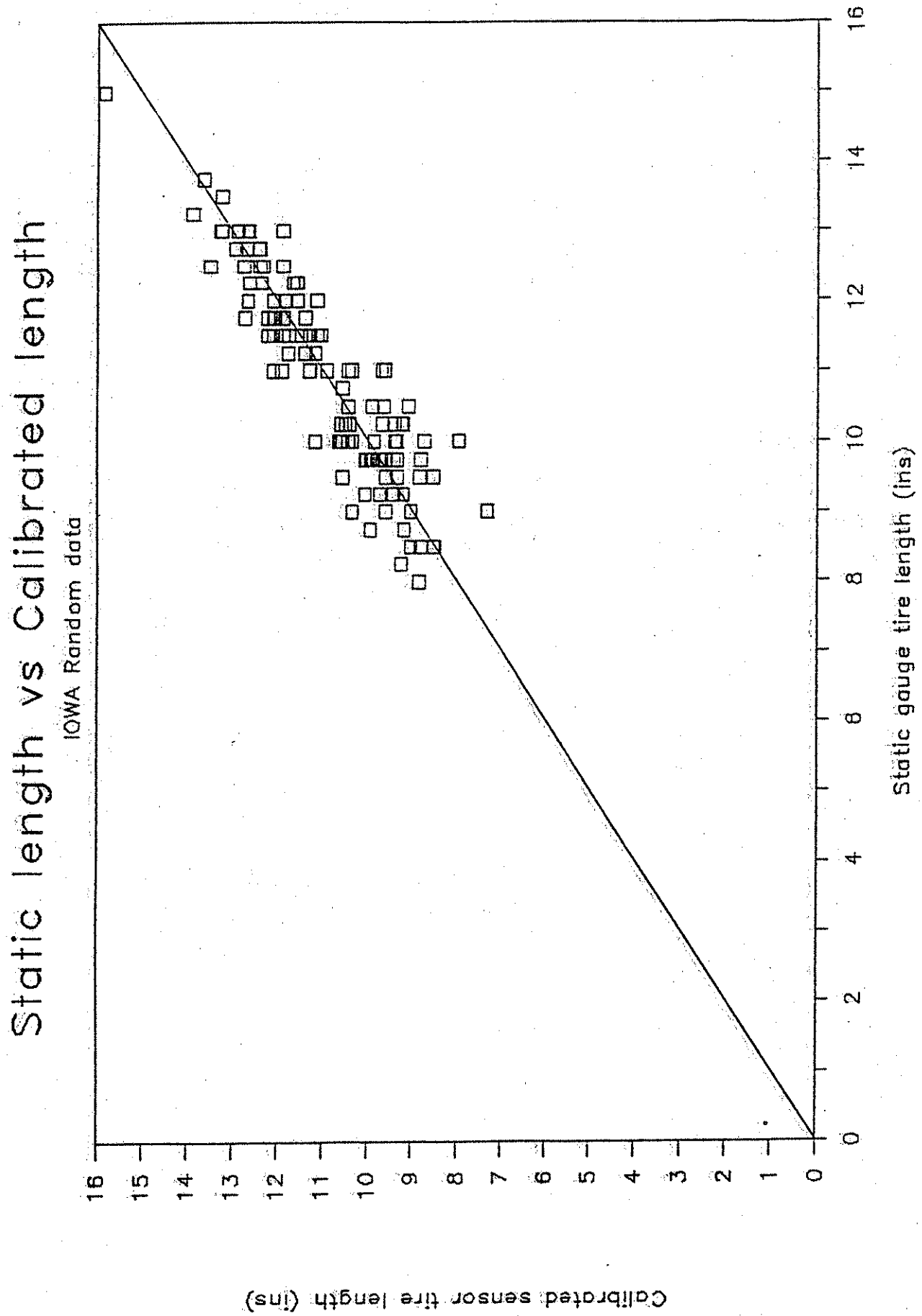


Figure 8.8 Static tire length v calibrated tire length (Iowa random vehicles)

Paint Spray Measurements

This study was performed at the weighscale in Minnesota on three test vehicles having a total of 30 tires, during the period of the September field trials. The method involved spraying paint on thick paper laid on the pavement surface underneath the vehicle tires. The paint spray measurements were then compared with the gauge measurements, to investigate the errors inherent in the gauge method of tire length determination.

The systematic difference between the paint spray and gauge methods was -1.88" and the random difference was 0.67". The difference of -1.88" indicates that the paint spray penetrates much further underneath the tire than the gauge. This result supports the supposition that the true contact length of a tire is significantly less than that measured by the gauge method.

Tire Width Determination

This section details the measurement of the dynamic tire widths. It presents preliminary findings of the tire width measurements and gives initial recommendations based on the results.

The vehicles used for the determination of the tire widths formed part of the Iowa random truck data. Examination of these data showed that the 60 degree diagonal sensor typically measured each half of a double tire as a separate wheel passage. Therefore, an 18-wheel semi would ideally produce 9 separate wheel passages, from all 9 tires on the right side of the vehicle. However, in some cases, wheels were missed by the system entirely, even though the remaining axles had been measured correctly. For the initial analysis, these cases were edited from the data set.

Dynamic tire widths were initially compared with static widths. The systematic difference between static and dynamic widths was -3.06", which is lower than the 5" obtained for the tire length measurements. This could be caused by several factors. Firstly, the point where the sides of the tire come into contact with the road is more clearly defined and therefore more easily measured using the gauge. Secondly, dynamic effects on tire contact area may be smaller across the width than along the length. Finally, the pressure distribution across the tire width may be more uniform than that along its length.

Figure 8.9 shows the calibrated dynamic tire widths obtained by adding a constant factor onto each dynamic measurement, to make the systematic error zero. The random difference associated with the results in 1.73", which is larger than that obtained for the tire length result. This is partly due to the use of the tire lengths in the calculation of the tire widths, as errors associated with these lengths are "added-in" to the tire widths.

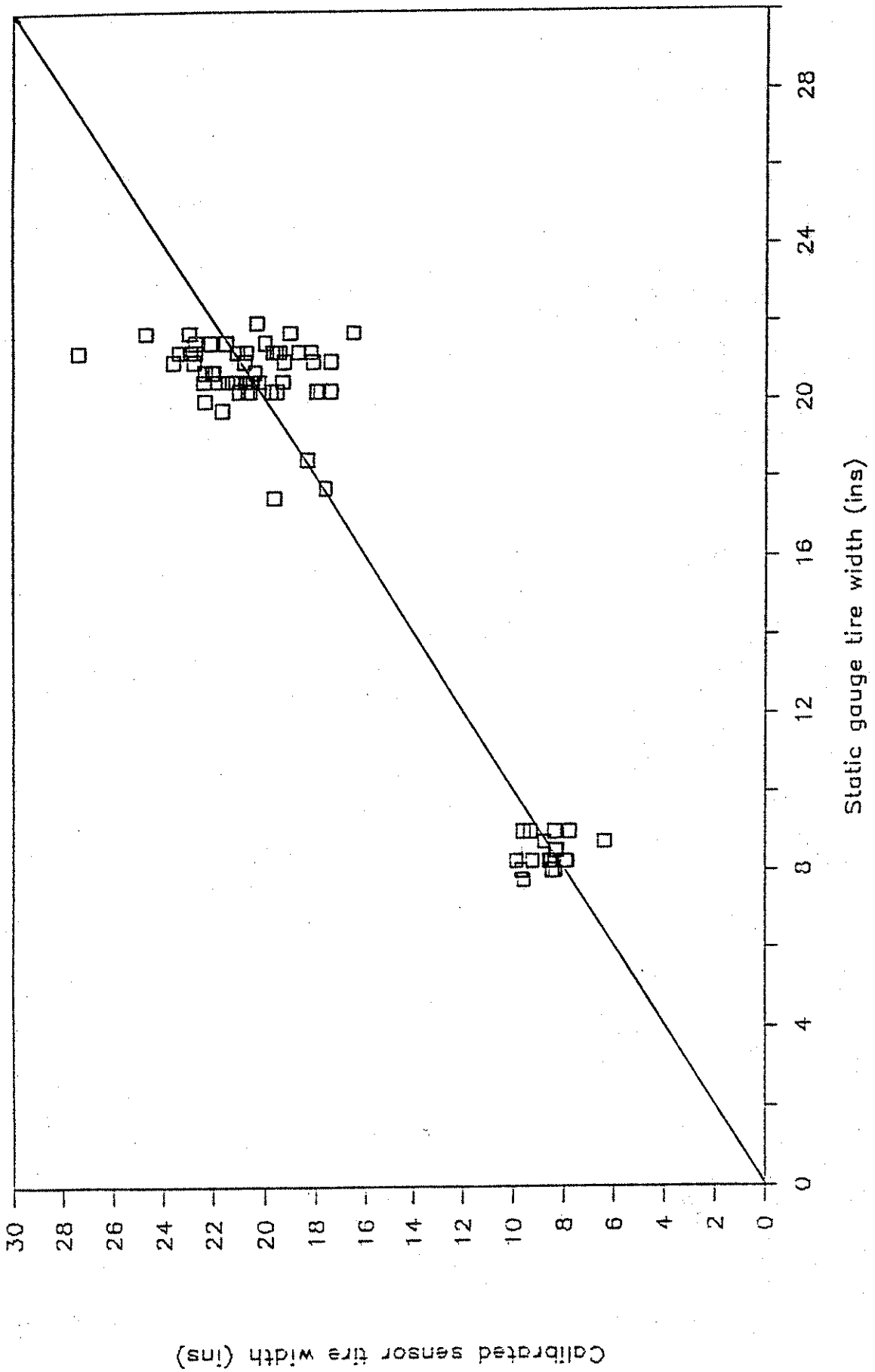


Figure 8.9 Static tire width v calibrated tire width (Iowa random vehicles)

Both the systematic and random differences were affected by the relatively poor definition of the piezo output on the angled sensor. Each tire on the tandem produces a peak on the output, but individual durations are confused by the overlapping of bending signals from pavement deflections. These overlapping signals could cause some wheels to be missed altogether, which explains why some vehicle data sets were incomplete. Another effect of poor signal definition is to introduce errors in duration timing on the diagonal sensor.

These problems were not unexpected for an experimental prototype tire width measurement system. The signal processing algorithm, designed for sensors set at right angles to the traffic flow, needed significant modifications for reliable use with a diagonal sensor. Several modifications to the algorithm were made as a result of this initial analysis.

8.7 SUMMARY AND CONCLUSIONS

Weigh-in-Motion Accuracy

Random and test vehicle data collected during September and December 1986 in Iowa and Minnesota were analyzed, leading to the following main conclusions.

1. Based on the 1986 Iowa test results, the AWACS should satisfy user requirements on axle weight and gross weight measurement accuracy, using a system configuration combining outputs from two or three sensors. In September, random differences between static and dynamic weights with two full-length piezo sensors were 8.9% for axle weights and 6.3% for gross weights. In December, the random difference was 10.5% for axle weights and 8.1% for gross weights.

2. Expressed in terms of the HELP WIM performance specification's 'funnel' concept, September 1986 random differences for two full-length sensors were 758 lbs below 10,000 lbs, and 7.8% above this value. In December 1986 the equivalent values were 1018 lbs and 9.4%. Systematic differences were less than 1% above 10,000 lbs.

3. The Minnesota data were less satisfactory, with large percentage static/dynamic differences in weight measurement for certain combinations of axle sensors. During September, random differences in axle weights ranged from 8% to 67% in the best and worst cases. The provisional conclusion was that certain sensors and/or electronic components were not functioning correctly during these tests. Modifications were made at the Minnesota test site, but the sensors continued to perform less well than those in Iowa during December tests. Random differences were found to be 15.5% on axle weight and 13.1% on gross weight. In terms of

the 'funnel' concept, these axle weight differences equate to 1312 lbs and 14.8% below and above 10,000 lbs. Systematic differences were less than 1%.

4. The tradeoff between system cost and system performance utilizing one, two or three sensors was examined. A system with two weight sensors appeared to represent an optimum, meeting user needs while minimizing costs.

5. Differences in weighing accuracy between weight ranges were found in the Iowa data. These differences indicate that the AWACS equipment showed least random difference, in percentage terms, for weighing heavy axles.

6. Axle spacing measurement accuracy using the first generation AWACS was very high (±1") and should satisfy all user needs.

7. AWACS speed measurement accuracy was also very high (±0.5 mph), and should also satisfy all user needs.

Vehicle Classification Accuracy

Vehicle classification data collected in Iowa and Minnesota during September and December 1986 were analyzed, leading to the following major conclusions.

1. In Iowa, the accuracy of FHWA Scheme F classification using the Wyman algorithm was low. In Minnesota, sensor problems during the September tests prevented reliable vehicle classification results from being obtained.

2. Analyses suggested that reducing the car/pickup threshold from 10 feet to 9.8 feet would significantly improve the overall compensated accuracy of classification.

3. Analysis of the Iowa pickup and truck wheelbase information showed that the Startz pickup/truck threshold misclasses significant numbers of these vehicles. Reduction of the pickup/truck threshold for 13 feet to 12.2 feet would significantly improve the overall compensated accuracy of classification, for the vehicle samples observed in Iowa.

4. Where only one axle of a vehicle was detected, due to lane changing or lightweight vehicles, a small improvement in accuracy could be obtained by assuming the vehicle to be a car.

5. The enhanced CRC logic for truck and bus classification gave a statistically significant increase in accuracy for commercial vehicle categories.

6. The overall counting accuracy of the CRC prototype classifier was very high, with less than 1% of vehicles being missed or double-counted. With the GK 6000 equipment, missed vehicles and double counting were more common.

7. State tests in Iowa confirm that the Wyman algorithm did not give satisfactory results for truck classification. These results showed that more accurate classification was obtained when the inductive loop was not connected.

8. Software problems with the GK equipment using the enhanced CRC logic meant reliable vehicle classification results were not obtained during the December testing in Iowa and Minnesota.

Tire Length and Width Measurement Accuracy

Finally, tire length and width data collected during September 1986 in Iowa and Minnesota were analyzed, leading to the following main conclusions.

1. The first generation AWACS equipment was capable of measuring tire contact lengths with a random error of less than one inch. Most of the difference between static and dynamic measurements could be explained by problems with the manual method of tire length measurement using a mechanical gauge.

2. Tire width measurements with the first generation AWACS had a random error of less than two inches. This was easily sufficient to distinguish single from double tires. Systematic width differences may be representative of actual reductions in dynamic contact areas, or may result from AWACS measurement errors.

3. Several refinements to signal processing algorithms were suggested as a result of the first generation measurements, which aimed to increase the reliability of tire contact measurement. These were implemented in the second generation equipment and are discussed in Chapter 11.

9. System modifications

9.1 INTRODUCTION

This chapter concerns system modifications made to the first generation AWACS, under Task H of the demonstration project. The modifications were made prior to testing the second generation systems in Iowa and Minnesota.

The first part of the chapter gives details of system modifications and the reasons why these modifications were considered necessary. Modifications included changes to the sensor configuration at the Minnesota site, with existing sensors resited upstream of the original test site. Additional short sensors for off-scale detection were installed at both sites. Thermocouples were incorporated into these short sensors to monitor temperature at the sites. The experimental buried sensor at the Iowa site was modified by replacing the epoxy cover with a rubber compound. Other modifications were intended primarily to increase the efficiency of the diagonal sensor.

The second section of the chapter concerns installation of the modified equipment at the sites in Iowa and Minnesota. Various hardware and software developments were also made to the system electronics to provide the additional functions required for the second generation preproduction systems. These system developments are described in Chapter 10, which includes a specification prepared for the procurement of equipment from GK Instruments.

9.2 SYSTEM MODIFICATIONS

Several modifications were made to the initial AWACS systems following an analysis of the first generation system performance over a five-month trial period at test sites in Iowa and Minnesota.

The performance of sensors at the Minnesota test site throughout the first phase of system testing was consistently poorer than that of the Iowa sensors. Chapter 8, concerning first generation preproduction system performance, determined that variability in sensor output was probably due to inadequate profiling of the sensors to the pavement surface, and that a contributing factor was the presence of epoxy on the tops of the sensors. A further concern was caused by cracking of the pavement around the sensor ends in Minnesota.

Remedial action to remove excess epoxy material from the sensors and reprofile their surface with Flexane proved only partially successful in improving system performance. It was decided, therefore, that the Minnesota sensors would be removed and reinstalled in such a way as to profile the sensors more closely to the pavement surface.

An analysis of the test data from both field sites indicated that a cost- effective basic AWACS system should comprise two parallel, full-length sensors without an inductance loop. This would provide both weight and classification data. An enhanced system, including off-scale detection and tire contact data, would require an additional short sensor and a diagonal sensor set at 60 degrees to the traffic flow.

Based on the above findings, the Minnesota site was modified to consist of two parallel full-length sensors, and one short and one diagonal sensor, with array dimensions the same as the Iowa test site. At the Iowa site, a short sensor was installed and the epoxy material encapsulating the experimental buried sensor was replaced with a softer rubber compound. Modified arrays for both sites are shown in Figures 9.1 and 9.2.

The objective of installing short sensors, positioned within the nearside wheeltrack, was to determine whether or not vehicles are off-scale. Off-scale detection concerns the identification of vehicles which partially avoid the load transducer cables. This function is highly desirable within a WIM system in order that accurate distributions of weight measurements can be produced. For example, in the case of a truck crossing the sensor array with one wheel of each axle on the shoulder, only a proportion of its real weight could be recorded by the WIM system as valid data unless off-scale detection is included.

An analysis of field trial data of first generation equipment suggested that at least 2% of vehicles surveyed were off-scale or had passed over the ends of the sensors, causing a suspect output signal. The site selection criteria developed in Chapter 4 considered lane discipline as a relevant factor in the choice of suitable AWACS site. Lane discipline at the field test sites is generally good but even a small number of off-scale vehicles has a significant detrimental effect on weighing accuracies.

To determine the optimum length and position for the short sensor, truck wheel separation data and laboratory data on longitudinal variations in sensor response were considered. The intention was that vehicles crossing the last 6" either end of the full length sensor would not cross the short sensor. Modifications to the software were implemented such that if a signal is produced from the short sensor, the vehicle is on-scale and the weight data are binned. If the vehicle is off-scale this is identified in the vehicle-by-vehicle mode, but vehicle weight is excluded from the memory module. In all cases the vehicle is classified and recorded in memory to permit subsequent scaling-up.

In view of the many variables involved it was decided that two different lengths of sensor would be tested to determine their effectiveness in off-scale detection. An 8" sensor was therefore installed in Minnesota, and a 12" sensor in Iowa.

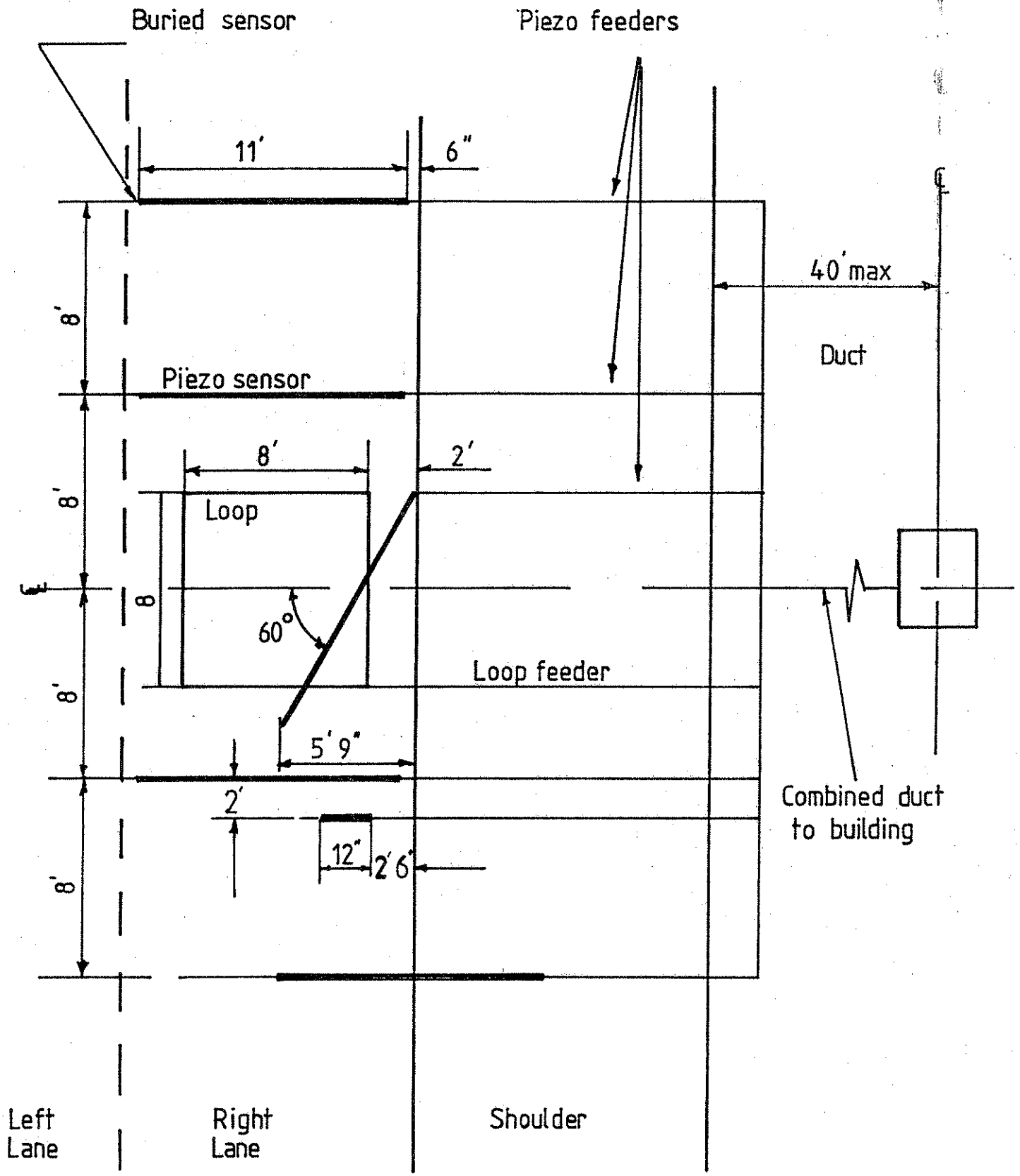


Figure 9.1 Modified sensor array - Iowa

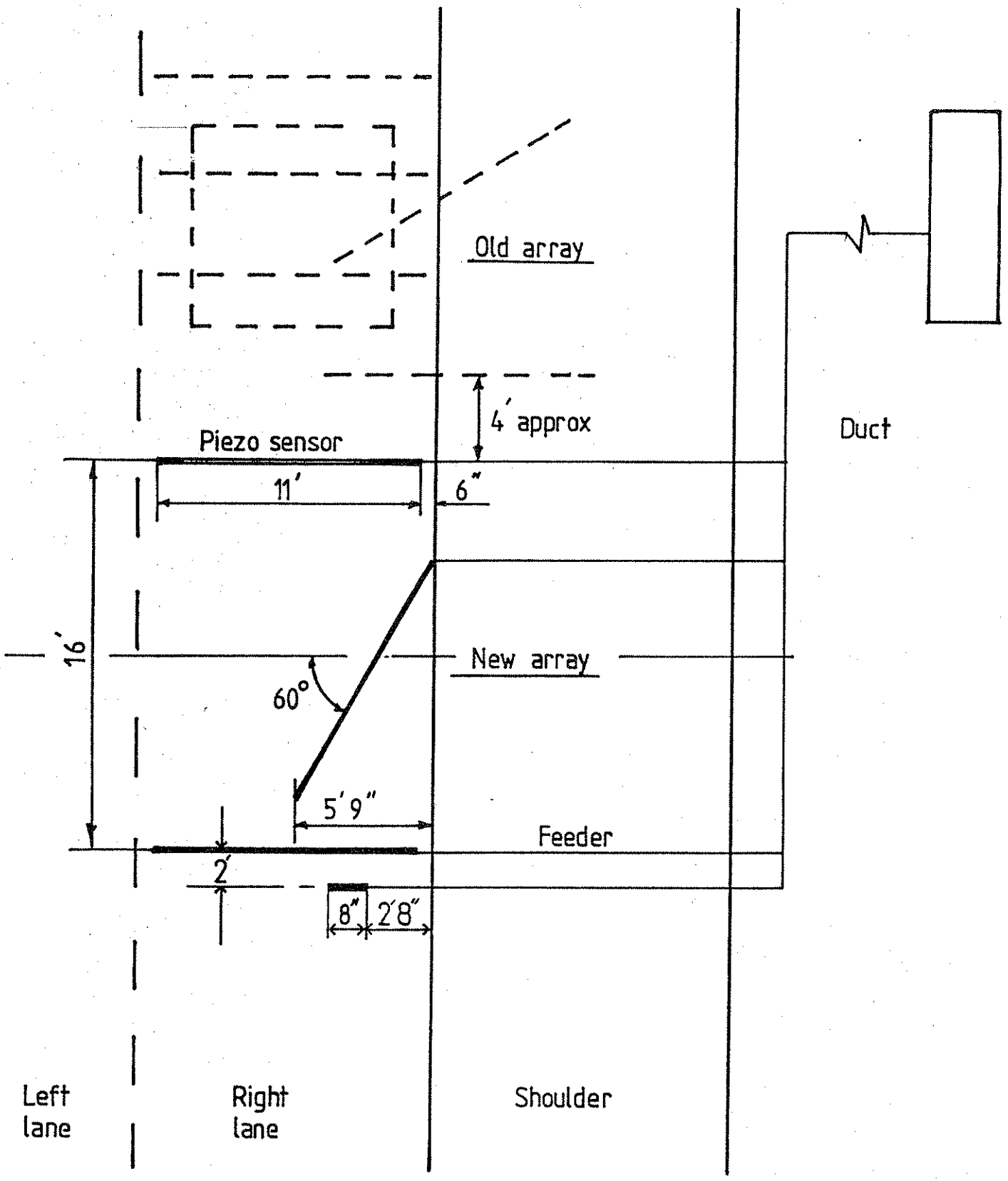


Figure 9.2 Modified sensor array - Minnesota

A second type of modification to the first-generation AWACS concerned the treatment of calibration factors for lead and other axles. The initial calibration of the preproduction systems was carried out prior to their installation in order to obtain an approximate weight-related output from the electronics. Subsequent refinement of the calibration, to optimize the gradient of the static/dynamic weight relationship, resulted from the evaluation of first generation system performance.

Initially, a single calibration factor was derived for each sensor on the basis that the mean percentage difference between dynamic and static weights should be zero for the calibration set. However, further analysis indicated that separate calibrations were appropriate for lead or other axles. Furthermore, overall system accuracy was improved significantly by combining results from pairs of sensors.

These facts were taken into account during the development of second generation system electronics. The calculation of axle weight was based on the output from pairs of piezo sensors, and a single site-specific calibration factor was used for the two sensor outputs combined. A further factor of 1.12 was then applied to lead axle signals only. Operation of the equipment required the site-specific calibration factor to be manually input. This factor was initially set at 1.00.

Results from the Iowa site with the first generation equipment suggested the sensitivity of the sensors reduced when the temperature dropped below freezing. This may be due to changes in the hardness of the encapsulating rubber. Another possible cause is that the lateral restraint of sensors within the pavement changes with temperature. To monitor this type of temperature effect, thermocouples were incorporated into the short sensors during manufacture.

Following the initial identification of this temperature effect, a series of laboratory tests was instigated. The tests were described in Chapter 6. The object of the tests was to simulate in the laboratory the type of lateral pressure or clamping to which the sensors are subjected in the pavement, resulting from temperature changes. Results suggest that these clamping forces can affect sensor sensitivity, as can changes in the hardness of the rubber. The monitoring of temperature throughout future field trials will provide data to investigate this effect further.

An analysis of the first generation system performance data concluded that both systematic and random errors associated with tire width determination were affected by relatively poor definition of the piezo output on the diagonal sensor. For example, each axle on a tandem passing over the diagonal sensor produces a peak in the output. A double tire on a single axle also produces two peaks, but with less separation. Individual durations are confused by the overlapping of bending signals from pavement deflections. These overlapping signals can cause some wheels to be missed altogether. Another effect of poor signal definition is to introduce errors in duration timings.

To address these problems the signal processing algorithms, designed for sensors set at right angles to the traffic flow, needed significant modifications for reliable and consistent

use with a diagonal sensor. Firstly, the 'on' threshold for signals from the diagonal sensor was reduced so that tracking of the signal would begin at a lower value. This recognized the fact that the diagonal sensors were subjected to only half-axle loads as opposed to full axle loads on the full-length, straight sensor. A slower tracking rate was required for the same reason.

The separation of individual signal peaks and the calculation of signal duration was enhanced by increasing the sensitivity of the charge amplifier used with the diagonal sensor, and adjusting the technique used to determine when the wheel has passed. This was estimated by noting when the signal reduced to half its peak value.

The experimental buried sensors installed at both test sites had not been used with the first generation AWACS equipment because of their very low sensitivity. The sensors were buried during the initial installation to a depth of 3/4", to assess what effect this might have in protecting the sensors from possible snowplow damage. An epoxy material (Hermetite) was used to cover the sensors. The hardness of this epoxy did not allow axle loads to be transmitted satisfactorily to the transducers. Replacing the epoxy with a softer material (Flexane) as a part of the system modifications in Iowa was expected to improve the sensor's response to axle loads considerably.

9.3 INSTALLATION

Having established that modifications were necessary to sensor arrays in Iowa and Minnesota, short sensors were fabricated and arrangements made with the states for the installation work. Site layouts were supplied showing the sensor arrays and service ducts, and installation details sufficient to allow DOT personnel to install the equipment with appropriate supervision. Methods of operation and requirements for equipment and materials were specified within a step by step guide to the installation, as detailed in Chapter 4.

A preferred method of sensor removal and installation was identified based on experience of similar work in the UK and the installation of first generation equipment in the US. The method included the use of PVC tape to protect the sensors from excess epoxy during installation, since considerable effort had previously been necessary to remove epoxy which had flowed over the top of the sensors. Other measures were also included in the method statement to ensure that sensors were profiled to the very flexible Minnesota pavement more precisely. Specifically, a reduction in the stiffness of the sensors was incorporated by cutting notches in the baseplate before reinstallation, and additional support plates and weights were used to hold the sensors in place while the adhesive cured.

Site meetings were held at both sites prior to the work commencing. In Minnesota, the precise site for the new array was identified and the proposed position of sensors was

marked onto the pavement. Surface conditions such as rut depth and cracking were then checked to confirm that the new site was suitable. Having discovered some minor reflection cracking, the array was moved slightly further upstream from the original site than had first been proposed.

Two of the original Minnesota sensors were damaged during their removal from the pavement. This occurred when excess Flexane was being stripped from the sensor prior to reinstallation. The Flexane had been used for earlier remedial work to help profile the sensors to the pavement surface. The bond between the Flexane cast in the laboratory and that added on site was found to be extremely good and considerable force was required to remove the excess material.

The fact that such a good bond was achieved between the laboratory-cast and site-cast material may allow an alternative method of installation to be adopted in the future, whereby the sensors are set below the surface and the final profiling is achieved by the application of Flexane once the adhesive holding the sensors in the pavement has set. Further tests would be needed to establish whether this method holds significant advantages over the current approach.

Removal damage to the sensors occurred in the area where the coaxial feeder entered the fixing block holding the piezo cable. To avoid damaging the remaining three sensors, they were reinstalled with fragments of old pavement attached to the end of each. This required large and irregular holes close to the shoulder line. Further damage to the coaxial cables was observed where they crossed the joint between the pavement and the shoulder. Care was taken therefore to provide extra protection to the cables in this area when the sensors were reinstalled, using a flexible joint-filler. This joint-filler remained soft for a long time after installation and by reducing pavement integrity may have contributed to subsequent cracking of the bond around the sensor ends.

The buried sensor at Iowa was exposed and recovered with Flexane. Subsequent examination of the sensor output suggests the modification has had the effect of increasing its sensitivity, to an extent where the output signals appear comparable with those from the other sensors in the array. This improved output from the modified buried sensor again suggests it may be feasible to adopt this method of installation in future arrays, to prolong the operational life of the sensors without significantly affecting the system's performance.

Although no visible damage was evident to the three piezo sensors removed and reinstalled in Minnesota, two of the three sensors subsequently failed within three months. Like the earlier sensors installed in Minnesota, all three sensors tended to break bond with the pavement around their ends, suggesting that the sensors were too stiff for this very flexible pavement. No other piezo sensors failed at any stage of the project. This gave a very clear indication that removal and reinstallation is not a procedure to be recommended in future.

The most likely reason for these sensor failures is microscopic damage to the coaxial feeder cables, occurring while the sensor is being removed or cleaned. Minute punctures

of the PVC sheath on the coaxial feeders were shown to have allowed moisture to creep into the feeders over a period of some weeks or months. Eventually, corrosion and loss of insulation between the metal sheath and central conductor caused the sensors to become unusable.

All three recycled sensors were replaced with new sensors and feeders in August, 1987. In constructing the new sensors, a further experiment was instigated to see if mountings could be modified to better suit the very flexible pavement construction in Minnesota. The 1-inch square aluminum channel used for previous sensors was replaced by a lighter, 3/4 inch channel, giving increased flexibility. The installation was successful in producing smoothly profiled sensors in a very clean surround, free from excess epoxy or other irregularities.

9.4 CONCLUSIONS

Several modifications to both sensors and electronics were accommodated within the original budget and contingency of the Iowa/Minnesota demonstration. These had been anticipated in principle when the project was established, though details of actual changes could only be determined in the light of experience with the first generation systems. The end result of the modifications was a standard site configuration in both Iowa and Minnesota, with some additional sensors remaining in Iowa which could be the subject of further investigation. Modifications to the system electronics and signal processing were also defined and incorporated in the second generation system detailed in the next chapter.

10. Second generation system procurement

10.1 INTRODUCTION

This chapter concerns the hardware and software components and system characteristics of the second generation preproduction AWACS equipment. Two systems were supplied by GK Instruments for installation and field testing in Iowa and Minnesota. The chapter covers the specification followed by GK Instruments in the procurement of second generation systems, and the development plan used to help ensure that the systems could be delivered on schedule.

The second generation AWACS equipment was developed from the first generation systems tested in both Iowa and Minnesota between August 1986 and February 1987. The results of the data analyses from the first phase of testing were used to develop a second generation system in cooperation with the manufacturer. The outcome of this technology transfer was the development of a system with increased capabilities, very close to the ultimate procurement specifications.

The first part of the chapter is in the form of a specification for the procurement of second generation preproduction systems. This documented the characteristics of the systems for evaluation in the test program, including software and hardware components.

The second part of the chapter describes the plan used to ensure that the second generation AWACS systems were developed in a manner compatible with requirements of Iowa and Minnesota. Tasks which were to be performed to complete the second generation systems on schedule are detailed, together with their relative timings.

10.2 SECOND GENERATION PREPRODUCTION SYSTEMS

The second generation preproduction systems were developed to include additional functions such as tire width measurement, provision for the calculation of contact pressures, diagnostic checks and self-calibration. Modifications were also made to the functions provided in the first generation systems based on analysis of the results obtained during the first phase of the test program, as described in Chapter 9. The other changes made for the second generation system were principally concerned with increasing the capability of the signal processing software.

The second generation systems offer the full data output and display capabilities specified and/or subsequently agreed with Iowa/Minnesota DOT staff. The systems were designed on a modular basis, to be potentially capable of monitoring several traffic lanes simultaneously. The states agreed that full implementation of the multi-lane system will be made by GK Instruments and other manufacturers in response to market forces, and is outside the scope of this project. In addition, however, dynamic tire width and length data were output, in a suitable format for further analysis, with the other data.

A prototype self-calibration feature was included in the second generation preproduction systems, the principle of which is that the loads on certain axles of specific truck categories show relatively little variation, regardless of the loading condition of the truck. A database can be built up by the system utilizing axle load measurements for these particular axles. The system calibration factor can then be adjusted to force the mean output to agree with an expected long-term population mean.

The particular axle category used as the basis for the self-calibration feature is the steering axle of 3S2 trucks. The dimensions of 3S2s are such that the kingpin is located close to the center of the rear tandem axle. Therefore, the loading on the vehicle has very little effect on the steering axle load.

To test this hypothesis, a database of vehicle dimensions and weights was analyzed from the biennial Truck Weight Study in Arizona. The vehicle weights in the database were obtained from portable static weighing scales, accurate to $\pm$ 2%, and collected during a period when no enforcement weighing was in progress.

A computer program was written to analyze the database by firstly selecting only the vehicle type under consideration and then examining the axle weight of the steering axle. Each of the weights examined were sorted into classes of 400 lbs in the range 6400 lbs to 14000 lbs. In total, 512 vehicles were used in the analysis.

From these data, the mean and standard deviation were calculated. The mean weight of the steering axles for the vehicles examined was 9950 lbs, with an associated standard deviation of 1126 lbs. If the assumption is made that the standard deviation of the sample is representative of the population as a whole, it is then possible to determine the sample size required to give a specified standard error of the mean for a given confidence level. Using 95% confidence limits and a standard error of the mean (SE) of 100 lbs, the sample size needed was calculated as:

$$SE = \frac{\sigma}{\sqrt{n}}$$

where σ = standard deviation
n = sample size

95% confidence = 1.96 SE (normally taken as 2 SE)

$$100 = \frac{1126}{\sqrt{n}}$$

$$n = 127$$

There is therefore a 95% chance that the population mean should lie within $\pm$ 200 lbs of the sample mean for the specified sample size. If a smaller standard error of the mean were considered necessary then obviously a larger sample would be needed. In the prototype self-calibration system, n is set to a minimum value of 150 3S2s.

Once a database of size n has been recorded, the mean system response for that sample is compared with the assumed population mean value. When there is a significant difference between the two, the system automatically readjusts the calibration factor to the required value. This occurs at the beginning of the next recording interval, or immediately if the system is recording individual vehicles.

From the analysis of the limited data initially available, it appeared that the use of steering axle weight data from 3S2 vehicles for calibration purposes is a practical proposition, although a number of issues remained to be considered in the system appraisal. In particular, it is possible that the data employed for the above analysis were biased, as a result of illegally overloaded vehicles bypassing the weighing location, even though no citations were being issued. The data may also be site dependent, and time dependent as the construction of the vehicles changes. The accuracy of the vehicle classification, particularly for the class used in this technique, is another consideration. For these reasons, the 'target' assumed population mean is user-programable.

Because of these factors, it is expected that self-calibration will not remove the need for individual site calibration on a regular basis, but it should be useful for improving the accuracy of axle load measurements between calibrations.

10.3 SYSTEM SPECIFICATION

Most of the changes to the first generation system specification related to the additional features of diagnostic checks, self-calibration, off- scale detection, and tire width and length data. Also, summary data were made available in addition to individual vehicle data. Other changes related to the sensor arrays used for the second phase of testing, with either two, three or four sensors being monitored simultaneously in one lane.

The modes of operation also changed from those adopted for the first generation equipment testing. The Selection Mode, used to gather random and test vehicle data during the first phase of testing, was no longer required. Individual vehicle data, as well as summary data, are available in the Remote Mode, via the telemetry link, or can be gathered on-site in the Continuous Mode, via the RS232 port. In Continuous Mode, either summary or individual vehicle data can be stored in memory, up to the capacity of the memory module.

The principal features specified for the second generation system which differ from the first generation equipment are as follows.

System Versions

1. Basic AWACS system to use two parallel piezo sensors.

2. Advanced system to additionally include one short piezo sensor for off-scale detection and one diagonal sensor for obtaining tire width data.

Classifier

1. Weighing of individual axles, tandems, triples, and gross vehicle loads.

2. Classification to Scheme F using enhanced CRC logic (Version 5).

3. Data output modes: summaries by time period, or vehicle-by-vehicle.

4. All data always output to memory module, and optionally to telemetry/RS232.

5. Variable time periods for summary data - user selectable in the range one minute to 24 hours.

6. Summaries available by time period:

   (a) Classified count by FHWA Scheme F category;
   (b) Weight histograms with user-programmable weight intervals, for each of single axles, tandems, triples and gross vehicle weights.

7. Additional data produced in vehicle-by-vehicle mode: time, vehicle speed, and axle spacings.

8. Option to ignore motorcycles, cars and pickups in the vehicle-by- vehicle mode, listing vehicles of classes 4-13 only.

9. 48 hour data retention in memory in summary mode. Memory capacity in vehicle-by-vehicle mode depends on traffic flow levels.

Self-Calibration

1. Assumed weight for steering axle of 3S2 vehicles to be user programable.

2. Calibration factor to be changed only at the beginning of the next time period.

3. Calibration factor to be output whenever changes occur and/or at the head of each summary.

Temperature Compensation

1. Pavement temperature to be monitored using a thermocouple mounted in the short sensor at each site.

2. Axle weights to be scaled by a programable amount per degree above or below freezing, optionally applied over the full temperature range or only below 41 degrees F.

Off-Scale Detection

1. In vehicle-by-vehicle modes, off-scale vehicles to be identified by a gross weight of zero; all other data to be displayed as calculated. (Gross weight can still be determined by summing axle weights.)

2. In summary modes, weight data to be included in bins only when an output signal is identified from the short sensor. All vehicles are to be recorded in the classification bins, whether on or off-scale.

Tire Width and Length Data

1. Event times and durations taken from the diagonal and the leading sensor are to be output in a special mode of vehicle-by-vehicle operation, together with axle weights, axle spacings, speed and classification, for FHWA Classes 4-13 only.

Initializing Data

1. Time, date and site number.

2. Sensor spacing, initial calibration factor, and self-calibration 'target' weight.

3. Mode of operation required - summary or individual vehicle data.

4. "All vehicle" or "truck only" data required.

5. Time interval for summary data, from menu.

6. Units for output data (US or metric).

Diagnostic Checks

1. Low battery power.

2. Axle sensor failure - checking axle counts on successive sensors.

3. Data consistency - checking axle weights on successive sensors.

4. Telemetry error.

5. Condition of module data.

The software and hardware required to include these diagnostic functions were developed during the first phase of the test program. The data from this first phase were analyzed and used as an input into development of the diagnostic features. The first and third of these checks require specific actions on behalf of the user, the others being fully automated.

Sensor failure and sensor malfunction are initially identified through the "Class 00" feature. Class 00 vehicles are indicated when different numbers of axles are detected on each piezo cable. Occasional Class 00 vehicles will occur naturally due to lane changing or extreme vehicle dynamic effects on light axles causing wheels to skip over the sensor. More frequent Class 00 vehicles are indicative of a sensor malfunction. If all vehicles are classed as Class 00, the probable cause is a failure of one sensor.

Further diagnostics are then available from the front port of the weight card, relating to data consistency. The weight card output identifies the unprocessed signals seen by each axle sensor individually. Sensor malfunction and failure will generally be recognized by the form of the output from the weight card, corresponding either to a distorted signal or no signal at all. More complex diagnoses would require an input from the manufacturer.

Data storage errors are checked automatically within the data module. Whenever a module is removed or reinserted, and whenever the display is brought into operation, a checksum in the module is compared with a similar checksum in the recorder. A "module invalid" message is displayed if any discrepancy occurs. Similar internal checks determine whether data are already present in the module when modules are changed, to avoid inadvertent loss or corruption of data.

Data transmission errors are checked by echoing all characters back over the telemetry link or connection to the adjacent microcomputer. If discrepancies are found between transmitted and received characters, they are automatically re-transmitted up to three times, after which an error message is generated. This error checking is fully automated and requires no specific action from the user.

A check on data consistency has been implemented in the self-calibration routine. Successive lead axles of 3S2s are averaged and a new calibration factor calculated after a minimum of 150 such vehicles. If this factor changes substantially or systematically over time it could be indicative of equipment problems with hardware or software, calling the calibration process into question. A major change would call for a repeat manual calibration to establish the reasons for the drift in self-calibration values.

10.4 DEVELOPMENT PLAN

A development plan was agreed with GK Instruments detailing the requirements for the second generation preproduction system. Starting from the equipment used in the first phase of field trials, a number of modification and development tasks were identified to complete the production of a second generation prototype AWACS system within the contract timescale. An outline schedule of tasks was produced in conjunction with GK Instruments, allowing for testing of the equipment prior to field installation. The development tasks, which are shown in Figure 10.1, were as follows:

Phase A Integrate weight boards with basic classifier

Phase B Develop simple AWACS system for 1 lane using 2 sensors, giving basic vehicle weight and classification data.

1. Combine speed-corrected weight data with classification data.

2. Scale weight data with manually-input calibration factor. Output individual vehicle data; gross weights, axle weights, axle spacings, speed and event time, with an option to exclude cars and pickups.

3. Incorporate enhanced CRC classification logic.

4. Put weight data into bins; gross weights, single axle weights, tandem axle weights, and triple axle weights, optionally grouped according to vehicle class. Store bin data in memory.

5. Implement diagnostic checks and telemetry.

Phase C Develop advanced AWACS system for 1 lane using up to 4 sensors, including additional short and diagonal sensors.

1. Develop self-calibration feature.

2. Implement off-scale detection.

3. Output data for tire width and tire length calculations.

Phase D Expand system to produce a multi lane AWACS.

As agreed with Iowa and Minnesota DOTs, Phase D will be accomplished by GK in response to market forces, being outside the scope of this contract.

10.5 OUTCOME

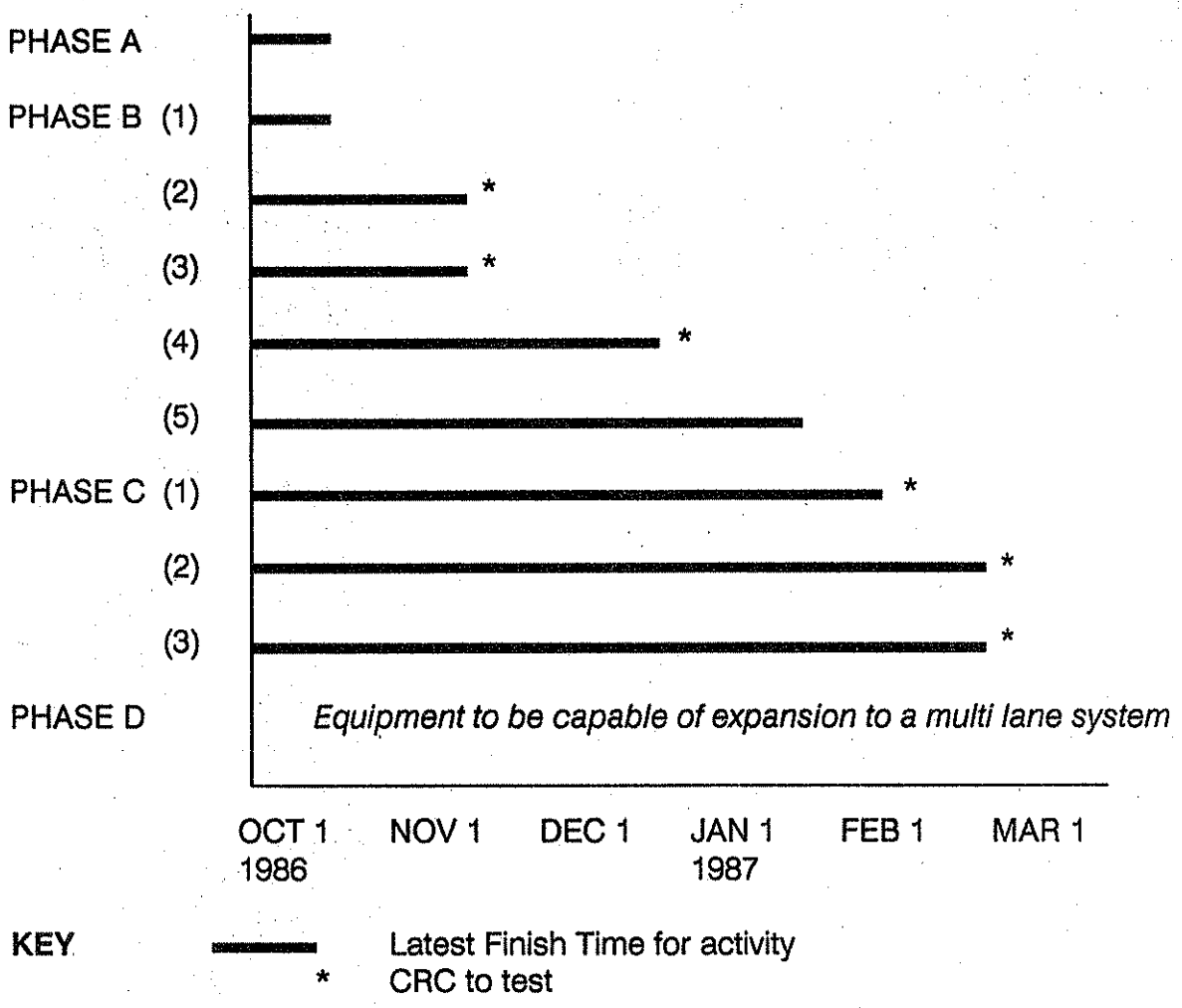


Figure 10.1 Development timeplan for second generation preproduction AWACS

Delivery of the second generation system was phased over an extended period, as additional functions were incorporated and field-tested. Specific software and hardware problems were identified at several points within this process, whose resolution absorbed a great deal of effort from the states, consultant and manufacturer alike. The second generation system specified in this chapter was initially implemented close to the scheduled time in May 1987. Fully operational, de-bugged second generation equipment was not available, however, until September 1987.

Along this road, several milestones are notable. Initial features of the second generation system were implemented in system upgrades during March 1987. However, off-scale detection and self-calibration only became possible after modifications to the sensor configurations in April, and were fully implemented during May 1987. Automated temperature compensation was subsequently implemented in July 1987. Final, minor problems with software and hardware compatibility between the AWACS and modems took until September/October 1987 to overcome.

The outcome of the program fitted very well with the original timescale envisioned for the project. No major revisions to the timing of key events in the program were necessary at any time over the 19-month period, once the activities defined as first and second generation were clearly agreed. The second generation equipment was available for testing as required by the program, with the results detailed in the next chapter.

11. Second generation system performance

11.1 INTRODUCTION

This chapter concerns the performance of the second generation Automatic Weight and Classification System during field testing in Iowa in May and June, 1987, and in Minnesota during June and September 1987.

The first generation AWACS was modified following the evaluation presented in Chapter 8, which identified several desirable alterations. Implementation of these changes was detailed in Chapters 9 and 10. This chapter summarizes the results obtained since then, as well as analyses conducted, and the conclusions drawn from these analyses. The chapter also gives details of system accuracy and its ability to satisfy established specifications, such as those being developed for the HELP Project.

The methodology followed in these tests was the same as that utilized in the first generation system performance appraisal, described in Chapter 8. The methodology is detailed in Section 8.1 and Chapter 3 of the report, which describe test procedures used in each of the appraisals. Statistical tests are presented in Appendix A.

11.2 RANDOM VEHICLE EVALUATION

As in the first generation system appraisal, random vehicle tests were used to calibrate the system; to measure the systematic and random error components; and to identify differences in errors between various weight ranges. Test data, recorded using three different types of test vehicles, were used to determine any speed trends in the system measurements and for comparison with the results obtained during the random tests. Random and test vehicle evaluations were conducted in Iowa over a three day period in May 1987 and in Minnesota over similar periods in June and September 1987. Data were collected by State DOT staff working with study team members.

The Minnesota data collected in May/June 1987 showed that the software signal processing was not working correctly at that time due to excessive pavement bending. Increases in charge amplifier sensitivity to 10 nC/volt caused signals to go negative at certain points during the passage of heavy axles, preventing normal signal integration.

The resulting variability in the data collected prevented an effective calibration of the system at that time. This problem was rectified by experimentally reducing charge amplifier sensitivities to 15 nC/volt, 20 nC/volt and 25 nC/volt for the September 1987 trials. The September data indicated that system operation was satisfactory at these amplifications.

WIM Calibration

Calibration of the WIM function of the second generation AWACS was achieved by plotting the WIM output against static load for the random vehicle data, and fitting the best straight line through these points and the origin. This was performed on data sets with and without offscale vehicles to calculate one calibration factor for all axles. The calibration factors given in Table 11.1 indicate that excluding off-scale vehicles does not change the calibration.

Sample	Charge Amplification	All random vehicles	Excluding off scale vehicles
Iowa (May 1987)	10 nC/volt	0.80	0.80
Minnesota (Sept 1987)	15 nC/volt	0.87	0.87
	20 nC/volt	1.11	1.11
	25 nC/volt	1.33	1.33

Table 11.1 WIM calibration factors (AWACS2)

The calibration factors shown in Table 11.1 differ from those calculated using random vehicle data collected in December 1986, namely 1.06 in Iowa and 1.03 in Minnesota. The apparent change in calibration is due to software and hardware changes over the intervening period affecting charge amplifier sensitivity, tracking rates and signal threshold levels at which a pulse is detected.

Axle Weight Accuracy

The axle weight accuracy of the AWACS equipment was determined by direct comparison of static axle and axle group weights, with corresponding calibrated WIM measurements obtained using the calibration factors calculated above. In all analyses, off-scale vehicles were excluded from the data set. The WIM accuracy analysis again concentrated on the distribution of percentage differences (PD) as defined on page 75. Below 10,000 lbs a different analysis was performed in accordance with the 'funnel' concept implicit in the HELP system specification.

The results of the analysis are given in Table 11.2, for all axles of all on-scale random vehicles weighed statically and dynamically. These show that below the 'pivot point' of 10,000 lbs, the system satisfies the HELP specification of systematic and random differences not exceeding 500 lbs and 1200 lbs respectively. Above this boundary the system also satisfies the specification, with systematic and random differences not exceeding 5% and 12% respectively.

Range	0-10,000 lbs	> 10,000 lbs	All Axles
Sample size (axles/axle groups)	415	783	1198
Systematic difference	240 lbs	-1.8%	0.0%
Random difference	1126 lbs	11.8%	12.3%

Table 11.2 Iowa axle weight measurement accuracy - May 1987

An 'F' test was used to determine whether there was any significant difference between the December 1986 (Tables 8.9 and 8.10) and May 1987 data sets. Below 10,000 lbs, the apparent deterioration is significant at the 5% level, though not at the 1% level (Appendix A). Above 10,000 lbs, the deterioration is significant at the 1% level. When the September, December and May results are taken together, the evidence for a gradual deterioration in performance appears to be strong. However, changes in the electronics systems and the methods of rejecting off-scale vehicles make it difficult to be certain that the samples are wholly comparable. Further monitoring is recommended, to see if a trend continues.

Further analysis of the Iowa random data indicated that certain vehicles were producing percentage weight differences well in excess of those obtained from other vehicles. In particular, three-axle vehicles with two axle 'pups' were repeatedly identified as producing significantly higher percentage differences. Nineteen such vehicles were identified, and were removed from the main sample, with the result that the standard deviation reduced by approximately 1% from the values quoted in Table 11.2. A separate analysis of these nineteen vehicles, providing fifty-seven axle combinations, gave a high mean and standard deviation for the percentage differences (Table 11.3). Statistical tests indicate that the sample mean of these particular vehicles is significantly different from that of other vehicles at the 1% level (Appendix A). This difference appears to be a function of the design particular to that type of vehicle.

When individual axle groups are considered, it can be seen from Table 11.3 that the rear tandem, or 'pup', behaves differently from the rest of the vehicle. The large random differences in static and dynamic weight measurements for the pups suggest that they are pitching heavily as they move along the highway, producing dynamic weights which are often unusually high or low. Large systematic differences are also evident, suggesting that the vehicles tend to pitch in a repeatable way as they interact with the pavement profile.

Sample Set	Lead Axle	Tandem	Rear Tandem (Pup)	All Axles
Sample size (axles/axle groups)	19	19	19	57
Systematic difference	-4.0%	16.8%	14.6%	9.1%
Random difference	9.4%	14.0%	27.7%	20.9%

Table 11.3 Iowa axle weight measurement accuracy (3 axle vehicles with 2 axle pups)

A similar analysis was undertaken for a sample of 158 3S2 vehicles, which are the most common truck type within the random vehicle data set. The results of the analysis are shown in Table 11.4.

Sample Set	Lead Axle	First Tandem	Rear Tandem	All Axles
Sample size axles/axle groups	158	158	158	474
Systematic difference	-6.0%	-0.8%	5.8%	-0.4%
Random difference	8.3%	10.9%	14.9%	12.7%

Table 11.4 Iowa axle weight measurement accuracy (3S2 vehicles)

Although the effect is less marked than for three-axle trucks with two axle pups, the data suggest that the rear tandems of 3S2s again demonstrate above-average dynamic variations in load.

The effect of charge amplifier sensitivity on weighing accuracy was investigated at the Minnesota test site. Random vehicle test data were collected over a period of 4 days, during which time the charge amplifier sensitivity was set to 15, 20 and 25 nC/V. The results of the analysis are given in Table 11.5.

Charge amplification (nC/V)	15	20	25
Sample size (axles/axle groups)	238	67	151
Systematic difference:			
Axles < 10,000 lbs	-56 lbs	-453 lbs	349 lbs
Axles > 10,000 lbs	0.1%	2.5%	-1.8%
All Axles	0.0%	0.0%	0.0%
Random difference:			
Axles < 10,000 lbs	1418 lbs	1526 lbs	1845 lbs
Axles > 10,000 lbs	16.7%	14.4%	16.4%
All Axles	16.5%	15.0%	17.6%

Table 11.5 Minnesota axle weight measurement accuracy - September 1987

Random differences are higher than those obtained in Iowa. This could be due to differences in the approach profile, which was not measured in Minnesota, or to the severe road bending component observed at the Minnesota site. Changing the charge amplification has little effect. An 'F' test shows that the apparent changes in weighing accuracy with different charge amplifications are not significant at the 5% level (Appendix A).

Overall, these results are similar to those of December 1986, taken before the sensors were replaced (Table 8.11). In order to assess the relevance of the results to the selection of future AWACS sites, Falling Weight Deflectometer readings should be taken in both Iowa and Minnesota to establish whether the Minnesota site is typical.

Gross Weight Accuracy

The gross vehicle weight accuracy of the AWACS system was assessed by direct comparison of static vehicle weights with calibrated WIM weights. The data set used was the same as that for calibration and for the axle weight accuracy analysis, both exclusive of offscale vehicles. Results of the Iowa analysis, which again concentrated on the percentage differences (PD) distribution, are summarized in Table 11.6.

Sample size (vehicles)	409
Systematic difference	-0.1%
Random difference	9.4%

Table 11.6 Iowa gross weight measurement accuracy - May 1987

The systematic and random differences in gross vehicle weight accuracy for random vehicle data collected in December 1986 were -0.76% and 8.1% respectively (Table 8.7). An 'F' test analysis revealed that the two samples differ significantly at the 5% level, though not at 1% (Appendix A). When viewed in conjunction with the September 1986 results of -0.1% and 6.3%, a gradual deterioration in sensor performance appears to be a stronger possibility. Further monitoring is again required for more definite conclusions to be drawn.

The effect of charge amplifier sensitivity on the measurement of gross vehicle weights was investigated at the Minnesota test site. The results of the analysis are given in Table 11.7. Random differences are higher than those obtained in Iowa and do not meet HELP system

requirements. The apparent changes in weighing accuracy with different charge amplifications are again not significant.

Charge amplification (nC/V)	15	20	25
Sample size (vehicles)	84	28	55
Systematic difference	0.3%	-1.0%	0.8%
Random difference	14.2%	17.9%	15.8%

Table 11.7 Minnesota gross weight measurement accuracy - September 1987

Weight Range Analysis

An analysis was undertaken to examine systematic and random differences for various weight ranges. The data set used to evaluate accuracy in these weight ranges was the same as that used in other random vehicle appraisals.

Table 11.8 confirms that the random differences, in percentage terms, tend to reduce with axle weight; that is, the system is more accurate for heavy axles. Four of the six possible pairwise "F" test comparisons between weight bands show significant differences at the 1% level (Appendix A). There is also an apparent systematic tendency to underestimate heavy axle weights and overestimate light axles, with five out of six pairwise comparisons showing significant biases. A similar trend was evident in the September 1986 Iowa data (Table 8.8) but was not obvious in December 1986 (Table 8.9).

Statistical tests on Table 11.8 show that two of the three apparent departures from provisional HELP system requirements are not significant at the 5% level (Appendix A). The random difference of 12.6% for the 10-20,000 lb weight band is not significantly greater than 12%. Similarly, the systematic difference of -5.9% in the 20-30,000 lb weight band is not significantly outside 5%. However, the systematic difference of -7.8% for axles over 30,000 lbs does lie outside provisional HELP system specifications, and brings present calibration procedures into question.

The weight range analysis undertaken for the largest random vehicle data set collected in Minnesota during September 1987 is given in Table 11.9. The results do not support the trends in weight measurement accuracy observed in the Iowa data, with random differences in the higher weight ranges being smaller than those in lower weight ranges. Moreover, there is no clear trend in systematic difference with axle weight.

Range	0-10,000 lbs	10,000-20,000 lbs	20,000-30,000 lbs	>30,000 lbs
Sample size (axles/axle groups)	415	519	100	164
Systematic difference	240 lbs (3.1%)	0.8%	-5.9%	-7.8%
Random difference	1126 lbs (14.7%)	12.6%	8.6%	7.3%

Table 11.8 Iowa weight range analysis - May 1987

Range	0-10,000 lbs	10,000-20,000 lbs	20,000-30,000 lbs	>30,000 lbs
Sample size (axles/axle groups)	53	57	25	103
Systematic difference	-56 lbs (-0.6%)	0.4%	-1.1%	0.2%
Random difference	1418 lbs (15.9%)	17.4%	16.4%	16.4%

Table 11.9 Minnesota weight range analysis - September 1987

When considered in isolation, the weight range analyses for Iowa taken from September 1986 and May 1987 data suggest a consistent bias, with systematic differences increasing with axle weight. This bias could be reduced by applying a regression analysis to the data. The calculation of dynamic weights would then take the form

$$Y = mX + C$$

where
- Y = dynamic axle weight (lbs)
- m = revised calibration factor
- X = raw AWACS axle weight (lbs)
- C = constant (lbs)

An analysis of this form was carried out experimentally on the Iowa May 1987 data and did effectively remove the bias, producing a reduced gradient and an intercept of 1719 lbs. Such a system would clearly comply with provisional HELP specifications.

When the results of the Iowa December 1986 and Minnesota September 1987 weight range analyses are also considered, however, the merits of the regression approach are less obvious. There appears at present to be no clear justification for adopting the more complex regression analysis approach, with its additional software and calibration parameters. Further sites will need to be appraised before this question can properly be re-examined, to see if an alternative calibration procedure would be worthwhile.

Offscale Analysis

The offscale analysis examined the distribution of errors for vehicles classed as offscale during random vehicle testing. The systematic and random differences for offscale vehicles are shown in Table 11.10. The desirability of rejecting offscale vehicle data is illustrated by the large random differences associated with these vehicles.

Sample set	Iowa (May 1987)	Minnesota (Sept 1987)
Sample size (vehicles)	26	71
Systematic difference	-6.2%	-5.5%
Random difference	29.8%	22.6%

Table 11.10 Axle weight measurement accuracy for offscale vehicles

To examine the results in more detail it is necessary to refer to Figures 9.1 and 9.2, giving the layout of sensors in Iowa and Minnesota. Of the complete random sample of 435 vehicles in Iowa, 26 were classed as offscale, with 18 sufficiently close to being onscale to give an output from the diagonal sensor. The other 8 vehicles totally missed the diagonal sensor. Vehicles classed as offscale on the shoulder side of the sensor had their right wheels within 9" of the shoulder. Those classed as offscale toward the center of the highway had their right wheels at least 4'6" from the shoulder. Offscale vehicles were therefore running more than two feet left or right of the wheeltracks.

Of the complete random sample of 527 vehicles in Minnesota, 71 were classed as offscale. The offscale detector at Minnesota is shorter than that of Iowa, which is the likely reason for the higher proportion of offscale vehicles. Vehicles classed as offscale were running at least 22 inches left or right of the wheeltracks.

The random error component for offscale vehicle weighing is smaller in Minnesota than in Iowa. This would suggest that, when compared with Iowa, a higher proportion of vehicles identified as offscale in Minnesota were in fact weighed with accuracies approaching those achieved for onscale vehicles. This is consistent with the fact that the offscale detector in Minnesota is shorter than that used in Iowa. Vehicles which were only just offscale at Minnesota were still within the effective length of the weighing sensor.

Axle Spacing Accuracy

The accuracy of axle spacing measurements was determined using a sample of 33 vehicles in Iowa and 66 vehicles in Minnesota, selected randomly from the complete set of vehicles used in previous evaluations. Axle spacings measured using the AWACS were compared with manual measurements recorded using a tape measure at a weigh station. The error distribution was calculated in terms of absolute differences, because it was apparent from the analysis of September 1986 field data that the magnitude of the difference between static and dynamic measurements was not dependent on axle spacing.

The results of the axle spacing analysis are shown in Table 11.11. The small differences are within those attributable to errors in manual measurement. This implies that speed measurements are also extremely accurate, since axle spacing calculations use speed as an input parameter. An assessment of speed measurement accuracy using Minnesota random vehicle data shows that both systematic and random errors in speed measurement are less than 1 mph when compared with measurements taken using a hand held radar gun. These findings confirm the results of earlier tests.

Sample set	Iowa (May 1987)	Minnesota (Sept 1987)
Sample size (axle spacings)	109	217
Systematic difference	-0.26"	-0.19"
Random difference	1.51"	1.44"

Table 11.11 Axle spacing measurement accuracy (AWACS2)

11.3 TEST VEHICLE EVALUATION

Test vehicles were used to investigate effects which could not be examined using random vehicles alone. The test vehicles used were 2-axle and 3-axle trucks in both Iowa and Minnesota, plus a 6-axle truck in Iowa only.

Speed Trend Analysis

The speed trend analysis involved the use of test vehicles in 3 speed bands; a low speed band of around 20 mph, a medium speed band of around 40 mph, and a high speed band of around 55 mph. Axle weights measured using the AWACS for each of the speed bands were compared with static weights. Tables 11.12, 11.13 and 11.14 show the results of the speed trend analysis for Iowa for all separate axles and axle groups, test vehicles, and speed bands. Table 11.15 shows combined test vehicle results in each speed band.

Speed	20 mph	40 mph	55 mph
Sample size (axles)	15	15	16
Lead Axle:			
Systematic difference	13.1%	10.0%	-13.4%
Random difference	3.0%	7.6%	4.2%
Rear Axle:			
Systematic difference	-9.0%	-9.4%	-17.3%
Random difference	3.3%	5.1%	3.2%

Table 11.12 Iowa speed trend analysis (2 axle test vehicle) AWACS2

Speed	20 mph	40 mph	55 mph
Sample size (axles/axle groups)	16	15	16
Lead Axle:			
Systematic difference	6.8%	6.2%	10.2%
Random difference	6.4%	9.0%	4.8%
Tandem:			
Systematic difference	-8.4%	-10.3%	-9.9%
Standard difference	1.7%	2.6%	4.9%

Table 11.13 Iowa speed trend analysis (3 axle test vehicle) AWACS2

Speed	20 mph	40 mph	55 mph
Sample size (axles/axle groups)	18	15	10
Lead Axle:			
Systematic difference	10.0%	-4.0%	-4.9%
Random difference	7.5%	2.7%	4.5%
Tandem:			
Systematic difference	3.8%	-4.9%	-2.0%
Random difference	8.1%	2.6%	6.8%
Triple:			
Systematic difference	-7.8%	-10.8%	-6.0%
Random difference	3.5%	1.5%	3.9%

Table 11.14 Iowa speed trend analysis (6 axle test vehicle) AWACS2

Sample set	Sample size (axles/axle groups)	Systematic difference	Random difference
20 mph	116	1.2%	10.2%
40 mph	105	-3.3%	9.3%
55 mph	94	-10.0%	6.6%

Table 11.15 Iowa overall speed trend analysis (AWACS2)

Each test vehicle was tested against the initial random sample for significant differences in the accuracy of the WIM results. This bias testing was performed using results from the high speed band of around 55 mph, as this speed band most realistically represented speeds observed in the random sample. The results of these t-tests indicate that the 2 and 3-axle test vehicles were not representative of the vehicles observed in the random sample (Appendix A.3).

Tables 11.16 and 11.17 show the results of the speed trend analysis in Minnesota for all axles and axle groups, test vehicles, and speed bands. Table 11.18 shows combined test vehicle results in each speed band. As in Iowa, the test vehicles are not representative of the vehicle population as a whole (Appendix A.3).

Speed	20 mph	40 mph	55 mph
Sample size (axles)	10	10	17
Lead Axle:			
Systematic difference	-4.1%	-9.3%	-12.7%
Random difference	4.9%	10.6%	8.0%
Rear Axle:			
Systematic difference	6.1%	-1.7%	-8.2%
Random difference	12.9%	11.2%	13.5%

Table 11.16 Minnesota speed trend analysis (2 axle test vehicle) (AWACS2)

Speed	20 mph	40 mph	55 mph
Sample size (axles/axle groups)	9	14	17
Lead Axle:			
Systematic difference	-20.3%	-16.1%	-16.8%
Random difference	11.0%	7.1%	10.1%
Rear tandem:			
Systematic difference	11.8%	-11.9%	-15.9%
Random difference	4.3%	11.4%	9.4%

Table 11.17 Minnesota speed trend analysis (3 axle test vehicle) (AWACS2)

When the results for individual vehicles are considered it can be seen that at both sites, random differences for specific axle groups are small and compare favorably with results obtained from the random vehicle tests. Systematic differences, however, are greater and vary considerably with speed and between axles of individual vehicles. The relatively high random differences observed in the combined results are caused by these large discrepencies in the systematic differences of the separated axle results; i.e. the vehicles effectively come from different populations. This same phenomenon was observed in the analysis of individual axle groups for three axle vehicles with two axle pups, described previously.

Sample set	Sample size	Systematic difference	Random difference
20 mph	38	-7.5%	14.6%
40 mph	48	-9.2%	10.0%
55 mph	68	-12.7%	10.6%

Table 11.18 Minnesota overall speed trend analysis (AWACS2)

These results, which hold for each of the test vehicles in both states, as well as for the three axle trucks with two axle pups, constitute one of the most significant findings of the Iowa/Minnesota project. The results show that for specific vehicles, the WIM sensors do in fact give highly repeatable results, with single-figure random differences at a site with high pavement rigidity such as Iowa. Even in Minnesota, where the random differences are higher, most of the results still fall within HELP specifications.

The implication of the highly repeatable results with large systematic differences is that specific trucks really do behave this way as they move along the highway. Individual axles of specific trucks interact with the pavement profile, speed and suspension system of the vehicle in such a way as to consistently pitch upward or down at the instant of crossing the sensor array. Although some averaging is introduced through the use of two piezo sensors, it is not sufficient to ensure cancelation of the effect.

A second factor which supports this interpretation is the way the effect changes dramatically with speed. In Iowa, for example, the lead axle of the two-axle truck shifts from being about 13% heavier than static at 20 mph, to being over 13% lighter than static at 55 mph. The spread of results at both speeds is very small - around 3 or 4%. This highly significant shift in recorded load does indeed seem to be a genuine effect of vehicle dynamics.

The results of this section also show that the calibration factors used in the analysis, calculated from the random vehicle test data, were not optimal for the test vehicles used. This supports the view that test vehicles would not constitute a satisfactory approach to the WIM calibration problem.

Temperature Trend Evaluation

The temperature trend analysis looked at the possibility of any significant change in axle weight measurement with temperature. During the period of testing in Iowa there was only a very small range of temperatures noted (80 degrees F - 100 degrees F) and no significant effect was observed. The temperatures during the Minnesota tests varied between 70 degrees F - 100 degrees F, and again no significant effect was discerned over this relatively small range of values.

11.4 CLASSIFICATION ACCURACY

Tests were also undertaken to establish the classification accuracy of the second generation AWACS. Testing occurred in Iowa in May and June, 1987, during which time a sample of 3160 random vehicles were collected. Similar tests were undertaken in Minnesota in August and September, 1987, during which time a sample of 2683 vehicles were collected. Vehicles were classified manually to check the AWACS, and data were analyzed on a vehicle-by-vehicle basis using individual pairwise comparisons. In the course of the analysis, the same statistics were calculated as were utilized in the first generation AWACS appraisal (Section 8.5).

The results of the classification study carried out in Iowa in May and June, 1987, are summarized in Table 11.19, along with corresponding results from data that were collected in September 1986 using first generation equipment with GK classification software. Table 11.19 also shows the results of the classification study carried out in Minnesota in August/September 1987.

	All vehicles			Trucks and buses		
	Sample size	Absolute accuracy	Compensated accuracy	Sample size	Absolute accuracy	Compensated accuracy
Iowa September '86 AWACS 1	1575	84.9%	93.1%	320	80.6%	80.9%
Iowa May '87 AWACS 2	3160	95.2%	98.9%	576	94.8%	97.6%
Minnesota September '87 AWACS 2	1713	89.4%	98.9%	267	90.3%	94.0%

Table 11.19 Classification accuracy (AWACS2)

The results shown in Table 11.19 show substantial improvements in both absolute and compensated accuracies at the Iowa site since September 1986 which are significant at the 1% level. The system clearly satisfies the draft HELP WIM specification of 90% accuracy in all of the above categories in Iowa and three out of the four categories in Minnesota. These results indicate that the classification logic amendments implemented since September 1986 have produced the desired results.

The absolute accuracy performance in Minnesota of 89.4% is not significantly below the HELP threshold of 90% in statistical terms. Chapter 8 and Appendix B show that for absolute accuracies of all vehicles, the standard error of the percentage accuracy is approximately

$$\sigma = 44.6\, n^{-0.51}$$

where n is the number of vehicles in the sample.

The error function is approximately normal for accuracies more than two standard errors below 100%. Substitution in this formula shows that the standard error of the percentage accuracy is in the case approximately ±1%, giving 95% confidence limits on the classification accuracy in Minnesota of 87.4% and 91.4%. For this reason there is insufficient evidence to reject the hypothesis that the system meets HELP requirements for vehicle classification on all counts in both states.

Finally, Table 11.20 shows the extremely high count accuracy of the system.

Data set	Count Accuracy
Iowa	99.9%
Minnesota: sensitivity 15 nC/V sensitivity 20 nC/V	 99.9% 99.6%

Table 11.20 Overall count accuracy (AWACS2)

11.5 TIRE LENGTH AND WIDTH MEASUREMENT

Tire length and width measurement accuracy were analyzed by direct comparison between static measurements and dynamic measurements calculated using the AWACS. This involved 27 random trucks in Iowa, yielding a total of 117 tires, and 26 random trucks in Minnesota, with a total of 123 tires.

Tire Length Accuracy

The results of the tire length accuracy analysis are provided in Table 11.21. Random and systematic errors are shown in terms of absolute differences in inches, rather than percentage differences, as it was apparent that differences between static and dynamic measurements were not dependent on tire length.

The random error in tire contact length measurement of between one and two inches is greater than that observed in Iowa with the AWACS1 equipment. The systematic difference in tire contact lengths calculated dynamically and measured statically is significantly less than that of AWACS1, however. Both changes may be the result of revisions to the signal processing algorithms within AWACS2.

Sample set	Iowa (May 1987)	Minnesota (Sept 1987)
Sample size (tires)	117	123
Systematic difference	-2.7"	-2.9"
Calibration factor	2.8"	2.8"
Systematic error	0.1"	-0.1"
Random error	1.1"	1.6"

Table 11.21 Tire length measurement accuracy (AWACS2)

There are several reasons why tire lengths could be systematically underestimated by the AWACS. Part of the differences shown in Table 11.21 may be explained by the genuine differences that exist between static and dynamic tire footprints, with the latter being dependent on the behavior of the tire under centrifugal forces. Manual measurements at the weigh station will also be a source of random and systematic errors.

Detailed analysis of the data suggest however that the algorithm used by the AWACS to sense the beginning and end of the wheel's passage across the sensor could be the major cause of the systematic differences. In order to help distinguish between tires, the tracking routine tends to underestimate the time taken for the tire to cross the sensor, which in turn leads to an underestimation of tire footprint length. Analysis shows that the underestimate caused by the tracking routine could be of the order of two or three inches. When a calibration factor is applied, the systematic errors in both states are reduced to very small values.

Tire Width Accuracy

Tire widths were calculated dynamically by timing the wheel passage across the diagonal and straight sensors. Random and systematic errors are again expressed in terms of absolute differences, for reasons detailed previously. The results from the overall analysis, consisting of both single and double tires, are given in Table 11.22.

Sample set	Iowa (May 1987)	Minnesota (Sept 1987)
Sample size (tires)	117	123
Systematic difference	-4.3"	-5.0"
Calibration factor	4.6"	4.6"
Systematic error	0.3"	-0.4"
Random error	1.5"	1.7"

Table 11.22 Tire width measurement accuracy (AWACS2)

As for tire length measurements, the tracking routine used by the AWACS may introduce a systematic error into the estimation of tire widths. This is because the algorithm used in the processing of diagonal sensor signals is necessarily different from that used for straight sensors. Analysis suggests that the tire width could be systematically underestimated by as much as four to five inches. When a calibration factor is applied, the systematic errors are reduced to less than 0.5".

A separate analysis was performed for tires on lead and other axles, the results of which are shown in Table 11.23. This shows a larger random error for tire widths on other axles than for lead axles. These errors are approximately proportionate to width, since lead axles are always single tired, while other axles are frequently double tired. The errors are small enough to ensure that single/double tire discrimination should be accurate.

Test Vehicle Evaluation

Test vehicles were used to investigate the effects of varying speed and tire pressures. The analysis involved comparison of AWACS tire lengths and widths with those recorded statically at the weigh station. Each vehicle was tested initially with high tire pressures (100 psi), before being reduced to allow low pressure testing (60 psi). Tire lengths and widths were remeasured statically after each reduction in pressure.

Sample set	Iowa		Minnesota	
	Lead axle tires	Other axle tires	Lead axle tires	Other axle tires
Sample size (tires)	27	90	26	97
Systematic difference	-4.2"	-4.3"	-5.0"	-5.0"
Calibration factor	4.6"	4.6"	4.6"	4.6"
Systematic error	0.4"	0.3"	-0.4"	-0.4"
Random error	1.0"	1.6"	1.2"	1.8"

Table 11.23 Tire width differences for lead and other axles

Table 11.24 shows tire length and width measurement accuracies for test vehicles in Iowa, processed using the same calibration factors as the random vehicles. Test vehicle systematic errors are generally larger than those of random vehicles, while test vehicle random errors are smaller. This is to be expected when between-vehicle variations are eliminated. Actual changes in contact length and width with pressure were similar to those detailed in Chapter 8, relating to AWACS1. The data were insufficient to identify any clear relationships between tire pressure and contact pressure.

11.6 SUMMARY AND CONCLUSIONS

Weigh-in-Motion Accuracy

Random and test vehicle data collected in Iowa during May 1987 and in Minnesota during September 1987 using the second generation AWACS equipment were analyzed, leading to the following main conclusions.

				Tire length		Tire width	
Test Vehicle	Speed band	Tire pressure	Sample size	Systematic error	Random error	Systematic error	Random error
2-axle	Low	High	32	-0.6"	0.7"	0.6"	0.9"
	Medium	High	28	-0.2"	0.7"	-0.1"	0.6"
	High	High	10	-1.2"	0.4"	0.4"	0.8"
	Medium	Low	18	-0.9"	0.4"	0.3"	0.8"
3-axle	Low	High	45	-1.7"	0.4"	-0.3"	1.0"
	Medium	High	42	-1.6"	0.5"	-1.0"	1.6"
	Medium	Low	33	-1.0"	0.3"	-1.2"	1.2"
5-axle	Low	High	90	-1.7"	0.5"	1.4"	0.9"
	Medium	High	90	-1.6"	0.5"	1.2"	0.9"
	Medium	Low	66	-1.5"	0.6"	1.2"	0.9"
	Low	Low	18	-2.5"	0.6"	1.4"	0.6"

Table 11.24 Tire length and width accuracy for test vehicles

1. Based on the Iowa test results for May 1987, the random differences between static and dynamic weights were 12.3% for axles and axle groups of all weight ranges combined. Random static/dynamic differences in Iowa were calculated to be 1126 lbs below 10,000 lbs, and 11.8% above this value.

2. The second generation AWACS should be capable of satisfying user needs for gross weight accuracies. Iowa test data indicate that these have a random difference between static and dynamic weight of 9.4%.

3. The Minnesota data are less satisfactory, with larger percentage differences in weight measurement. With charge amplification of 15 nC/volt, random differences between static and dynamic weight were found to be 1418 lbs below 10,000 lbs, and 16.7% above this value. Overall random differences for all axles and axle groups were 16.5%. These differences may result from characteristics of the approach profile, or could be related to the low pavement rigidity at this site.

4. Systematic differences for random samples of vehicles were generally less than 2%, due to the calibration procedure utilized in the tests associated with the need to recalibrate after each equipment upgrade. Longer-term appraisal of calibration factor stability is now required, including an assessment of self-calibration performance.

5. Axle spacing measurement accuracy is very high (+ 1.5") and should satisfy all user needs.

6. Test vehicle results indicate that individual test vehicles are generally not representative of the vehicle population. For this reason, calibration of the AWACS using test vehicles is considered inappropriate.

7. Unusually large systematic and random differences associated with certain vehicles may be a function of the design particular to that type of vehicle. This has important implications for WIM performance specifications, vehicle design and pavement loadings.

8. Analysis suggests that in the temperature range in which tests were conducted (70 degrees F - 100 degrees F), there is no appreciable change in axle weight accuracy corresponding to changes in temperature.

9. Random errors for offscale vehicles are higher than for those which are onscale. From a sample of 435 in Iowa, 26 vehicles were identified as offscale. Analysis indicated that they were approximately 2 feet right or left of the wheel track. From a sample of 527 vehicles in Minnesota, 71 were classed as offscale, where a shorter offscale detector was used. The shorter sensor did not create any increase in weighing accuracy over that achieved in Iowa.

Vehicle Classification Accuracy

Vehicle classification data collected in Iowa during May and June 1987 and in Minnesota during September 1987 were analyzed, leading to the following major conclusions.

1. The second generation system in Iowa, enhanced using the results from testing in September and December 1986, achieved absolute and compensated vehicle classification accuracies of 95.2% and 98.9% respectively for all vehicle categories combined. The classifier also gave excellent results for trucks and buses, with absolute and compensated accuracies of 94.8% and 97.6% respectively.

2. The second generation system in Minnesota gave absolute and compensated accuracies of classification for all vehicle types combined of 89.4% and 98.9% respectively. Trucks and buses have absolute and compensated accuracies of 90.3% and 94.0% respectively.

3. The overall count accuracy is very high, with less than 0.1% of vehicles being missed or double counted in Iowa and less than 0.4% of vehicles being missed or double counted in Minnesota.

4. Results indicate that modifications implemented following the tests in September and December 1986 improve compensated accuracies between particular categories of vehicle, particularly between cars and pickups.

5. The enhanced classification logic for trucks and buses gave a statistically significant increase in accuracy for these classes of vehicle.

Tire Length and Width Measurement

Tire length and width data collected in Iowa in May 1987 and in Minnesota in September 1987 were analyzed, leading to the following conclusions.

1. The second generation AWACS equipment is capable of measuring tire contact lengths with a random error of between one and two inches. Systematic differences in static and dynamic tire length can be reduced to less than half an inch by the use of a simple additive correction.

2. The second generation AWACS equipment is capable of measuring tire widths with a random error of between one and two inches. Again, systematic differences can be reduced to less than half an inch by the use of a simple additive correction.

3. The results suggest that the accuracy of tire contact widths on lead axles is greater than that on other axles. This may be due to the incidence of single and double tires on lead and other axles respectively.

4. Tire length and width results obtained using test vehicles are similar to random vehicle results.

5. There is no apparent trend in the accuracy of tire length or width measurement with changes in tire pressure. Actual changes in length and width with pressure were small. The data were insufficient to determine a conclusive relationship between tire inflation pressure and contact pressure with the pavement.

12. Procurement and costs

12.1 INTRODUCTION

This chapter presents the life-cycle cost analyses and final procurement specifications for the low-cost automatic weight and classification systems (AWACS). The overall purpose of the demonstration project was to prepare for the availability of proven, production AWACS equipment ready for immediate procurement. This has been accomplished.

The chapter contains information on the long-term system assessment carried out during the Iowa/Minnesota demonstration, in the form of a detailed fault log. It goes on to evaluate life cycle costs for three alternative specifications of low-cost AWACS. These life cycle costs were utilized in the final preparation of procurement specifications.

The procurement specifications presented in this chapter were developed at the conclusion of the study. They are for complete systems including sensors, electronics hardware, software and all other components. They aim to provide sufficient detail to enable manufacturers to follow necessary approaches and reach the required standards of performance without restricting peripheral areas of technical design.

12.2 LONG TERM APPRAISAL

Incidents and equipment failures were logged during the test program and the data were used in the development of a performance standard for the procurement specification. A log of operational problems is given at the end of this section.

The majority of corrective actions shown in the log relate to software development problems, which are inherent with a project of this nature and complexity. They are in no way representative of long-term production system performance.

Hardware and firmware changes relating to sensor sensitivity were also part of the system development process. Very few incidents relate to actual equipment failure and most of these can be easily avoided in future installations.

The piezo electric sensors have proven to be both reliable and durable. The only failure occurred in Minnesota with sensors which were moved from the existing array to another location nearby. Damage to the feeders happened during the removal and reinstatement

of the sensors, as described in section 9.3. In Iowa the sensors remained fixed within the pavement and no sensor failures occurred.

Except for a specific incident, when a lightning strike caused minor damage to certain components, the system's electronics have also proven to be both reliable and durable. Problems relating to data transmission via telemetry were associated with the operation of the modem used with the AWACS. The careful selection of such peripherals, connecting cables, etc. by the user should avoid similar problems occurring with the production systems.

12.3 LIFE CYCLE COSTS

The life cycle cost analysis for production systems considered the following items:

1. Site establishment cost
2. Procurement cost
3. Installation cost
4. Test and calibration cost
5. Operating and labor support cost
6. Maintenance cost
7. Spare parts cost
8. Staff training cost

Three levels of AWACS were evaluated: a basic system, a standard system, and an enhanced system. These are fully described in the procurement specifications. A separate analysis has been undertaken for each system type. Alternative costs have been calculated according to whether an existing WIM site is utilized or a completely new site is established.

Most of the life cycle costs have been estimated from data collected during the twelve month testing and analysis program, such as procurement, installation, and testing/calibration costs. However, the operation of the prototype AWACS systems was not typical of the long term performance assumed for production systems, in several respects. The type and cost of system operations, maintenance and corrective actions undertaken during the test period cannot be taken as a true indication of longer-term costs for these particular parts of the life cycle cost analyses. Additional data from a number of piezo-electric systems installed on highways in Britain over the past eight years have therefore been utilized in the life-cycle cost analyses. Previous work undertaken as a part of the HELP Concept Development Study also provided useful data on certain life cycle costs for traffic monitoring systems.

Life cycle costs represent the total cost of owning and operating a system over its useful life. The physical durability of a system is not always the critical factor in determining its

Problem	When first reported	Further feedback	When resolved	Solution	Corrective action taken	Comments
Low sensor sensitivity	Sept 8 1986		Oct 15	Sensitivity increased, tracking rate adjusted	Sensors 'cleaned', new charge amplifiers issued plus revised software Nov 6	
Vehicles not classified/ misclassified	Sept field trials	Oct - Dec	Sept - Dec	Sensitivity increased, algorithms to be improved	Sensors 'cleaned' and loop disconnected	CRC enhanced classification developed
			May		Minnesota sensors removed, cleaned and reinstated	
Insufficient operating instructions	Oct 2	Various enquiries		Revised classifier handbook required	Handbooks delivered to the States Nov 6	Single page updates issued during system development phase
Minnesota's classification problem (unspecified)	Oct 2	Nov 13				Short sensor used in error
Telemetry inoperative	Oct 2	Various enquries up till Dec 5		Telemetry to be re-established	System enhanced mid December. One way communication available	Complete telemetry link available by mid January 1987
"Module invalid" message	Oct 2	Oct 10, 13	Oct 16	Replace faulty component on mother board	New racks delivered to the States Nov 6	
		Nov 12	Nov 16			Subsequent occurance consistent with mode of operation. Correct mode of operation explained
Failure of battery check function	Unknown	Oct 13	Unable to reproduce in the UK		New racks delivered to the States Nov 6	
Classifier dead when first called	Oct 6	Various dates Oct 6-21	Oct 15	New software (memory overflow)	New software delivered Nov 6	
Classifier dead when first called		Nov 12, 13				Further software changes made. New chips delivered Nov 29
Lack of hardware and software to analyze data from memory module	Oct 6	Oct 13	Oct 19	Data port, cables and IBM software supplied	Hardware and software delivered Nov 6	Software for summary vehicle data only
Failure of Iowa's classifier (unspecified)	Oct 27	Oct 28, 31			Trouble shooting by GK Engineer Nov 29 - Dec 2	
Data port error messages	Nov 12	Nov 13	Nov 17	Connecting cable to be wired correctly	Pin details for cable given Nov 17	

Table 12.1 Operational problem log

Problem	When first reported	Further feedback	When resolved	Solution	Corrective action taken	Comments
Inability to extract single vehicle WIM data from memory module	Nov 22		Dec 29	Data analysis program	Program disk and operating instructions issued Jan 12	
'Frozen' display - Iowa	Dec 5			Cold boot required to restart recorder		Problem resolved in second generation equipment
Temperature effect on sensor sensitivity	Dec	Laboratory simulations	June	Monitoring of pavement temperature	Thermocouple installed with sensors	Thermocouple reading used to calibrate sensor output
"Activity overflow" message	Jan 19 1987		Jan 21	Software to be amended		System message to highlight irregularities
Periodic system lock-up	May 8	Various dates June 2-25	Aug 12	Cold boot required to restart the recorder	New software and hardware issued	Combination of several problems, unable to reproduce some in U.K
Erratic telemetry output	May 12	Various dates June 2-25	July 1	Change mode of system operation	System operation amended	
		Aug - Sept	Oct 1		New modem purchased	Proprietory software used to interrogate memory module
Lightning damage	Assumed to have occurred in June		July 29	Repair equipment	Equipment returned to manufacturers, repaired and reinstated	
Sensor failure Minnesota	Aug 10		Sept 1	Replace sensors	New sensors manufactured and installed	Failure caused by damage to sensors when sensor array was moved
			Related Software Problems			
Vehicles misclassified	Sept field trials 1986	Oct - Dec	Sept - Dec	Classification logic enhanced	CRC enhanced logic incorporated Nov 29	Software errors identified. Classification boundaries altered
			Dec Trials	New software issued	New software incorporated Dec 12	
Individual axle weights wrongly summed for gross weights >80000 lbs	Dec 11	Dec 23 Jan 5	Jan 14	Software to be amended		
Failure to log classes 4-13 only	Feb 3 1987		May	Software error corrected	New software issued May 30	
Delay in recorder	June 2		Aug 12	Removal of diagonal sensor input to weight card	Previous version of software reinstated during July	
					New software issued August	

Table 12.1 Operational problem log (continued)

useful life span. Technological advance often renders systems obsolete before the limit of their physical durability is reached. This concept of planned obsolescence has been taken into account in producing overall estimates of life cycle costs.

For this reason, a conservative value has been assumed for the useful life of the AWACS systems. While system electronics might achieve a life of ten years or more, continuing progress in low-cost WIM could result in system electronics being replaced after only 5 years. Alternative estimates have been made for the useful life of the piezo sensors. The optimistic scenario assumes sensor replacement after five years, and the pessimistic scenario a life of two years.

In the following analysis, the whole life cost for each alternative and level of system is calculated over a five year period.

1. Site establishment costs

These costs are based on estimates made in the HELP 1C Concept Development Study. Actual site establishment costs will vary widely according to the site location and the availability of power and phones.

Basic	$1000
Standard	$1500
Enhanced	$1500

2. Procurement costs

The original target of a $5000 procurement cost referred to AWACS equipment with only one piezo sensor per lane. The target was revised to around $6000 when it was determined that a two-piezo system offered worthwhile benefits in terms of increased accuracy.

These estimates assume production levels of over a thousand systems in total within a period of around five years. They also assume that the international value of the dollar will not change significantly from its average value over the period of the demonstration.

	Sensors	Electronics	Total
Basic	$3000	$3000	$6000
Standard	$4000	$3500	$7500
Enhanced	$5200	$7000	$12200

A central computer would also be required to process data from the AWACS sites. These costs of central computer hardware and software have been assumed to be spread over about 30 sites, in deriving costs per site as follows:

Basic	$300
Standard	$550
Enhanced	$600

3. Installation costs

Labor rates have been estimated at $20/hour, 8 hours/day. Six person-days are assumed for installing the basic and standard systems, and eight person-days for the enhanced system. Rental of specialist equipment is costed at $400.

	Per Installation	Five year Optimistic	Pessimistic
Basic	$1360	$1360	$2720
Standard	$1360	$1360	$2720
Enhanced	$1680	$1680	$3360

4. Test and calibration cost

Each calibration and system appraisal is assumed to require eight person-days for the basic and standard systems, and ten person-days for the enhanced system. For standard and enhanced systems, the optimistic scenario assumes an annual calibration and the pessimistic, a calibration at 6-month intervals. These frequencies are doubled in the basic system, which is without self-calibration.

	Per Calibration	Five year Optimistic	Pessimistic
Basic	$1280	$12800	$25600
Standard	$1280	$6400	$12800
Enhanced	$1600	$8000	$16000

5. Operating cost and labor support

For the basic system, 10 person-days/year are assumed for collecting data, with a combined travel and per diem averaging $80/day. For all systems, 12 person-days/year are assumed for WIM/AVC data analysis and reporting. Additional data analysis for the enhanced system is assumed to require 6 person-days/year. Utilities are costed at $800/year for the standard and enhanced systems, and $100 for the basic system.

	Annual	Five Year
Basic	$4500	$22500
Standard	$2800	$14000
Enhanced	$3760	$18800

6. Maintenance cost

Routine and exceptional maintenance are assumed to require 6 person-days/year per site, at hourly and per diem rates as before.

	Annual	Five Year
All systems	$1440	$7200

7. Spare parts cost

	Annual	Five Year
All systems	$500	$2500

8. Staff training cost

Training in the use of the equipment is assumed to require 8 person-days. Optimistic and pessimistic assumptions are made about staff turnover.

	Initial Training	Five year Optimistic	Five year Pessimistic
All systems	$1280	$1280	$2560

Summary of five-year costs

	Optimistic	Pessimistic
Basic	$54940	$70380
Standard	$42290	$51330
Enhanced	$53760	$64720

The basic system, while offering the lowest immediate procurement cost, has the highest costs when evaluated over a five-year life. However, in small jurisdictions where travel to sites is inexpensive, it may prove to be the best system. The standard system has lower life cycle costs because of its self-calibration feature giving reduced test and calibration costs, and its dial-up capabilities giving reduced data retrieval costs. The enhanced system offers further, additional features at a higher overall cost. The additional cost of the enhanced system may be justified if data on tire contact areas and advanced binning capabilities are required.

12.4 DEVELOPMENT OF SPECIFICATIONS

In drafting the procurement specifications, the study team considered three major factors:

1. Testing and analysis program results;
2. Life cycle cost analyses; and

3. Compatibility with various related programs, e.g. HELP, SHRP, and state or federally-mandated truck weight collection programs.

Three recommendations emerge from the analysis of the second generation AWACS weigh-in-motion results, which have considerable significance for WIM performance specifications. These are as follows:

1. Calibration (or checking the self-calibration) should be carried out using random samples of trucks, weighed statically, making comparisons between static and dynamic weights in such a way as to minimize systematic differences for the actual truck population observed at the site.

2. Verification of WIM performance should use standard test vehicles on repeated runs, to examine the capability of the WIM to give consistent results representative of each truck's unique interaction between the pavement and its suspension system.

3. Assessment of the site characteristics and vehicle population characteristics requires comparisons between test vehicle data and random vehicle data. The difference between the scatter of results achieved with test vehicles and the scatter of results observed with random vehicles will indicate the characteristics of the site in terms of pavement approach profile and vehicle population.

The first recommendation assumes that static/dynamic weight variations are equally likely to be positive as negative. Although we cannot easily predict the actual forces which will be exerted on the pavement by any specific vehicle crossing the sensors, we can reasonably assume that the mean weight of a large sample of vehicle axles is known with sufficient accuracy for calibration purposes.

Regarding the second recommendation, test vehicles will show up the capability of the WIM to consistently record actual dynamic forces as individual trucks go by. To ask a WIM system to do more than this is unrealistic. Using test vehicles largely eliminates the uncertainty associated with variations in pavement approach profile, which is outside the control of the WIM manufacturer. This is because the test vehicles 'pitch' in the same way each time they pass the site. It also eliminates the problem of vehicle fleet variations, through which the composition of the random vehicle sample (e.g. proportion of 3S2s) significantly affects the scatter of weights experienced by the WIM system.

The final recommendation acknowledges that site appraisal is as important as WIM system appraisal in utilizing WIM data. To interpret WIM data, we need to understand the characteristics of the site, and their relationship to those of the highway system as a whole. "Good" sites are stretches of highway with little dynamic variation; ie. smooth pavements. "Bad" sites are rough pavements which amplify the dynamic variations in weight experienced by trucks. "Good" sites and "bad" sites are a fact of life: they make up the highway system. We need dynamic weight data for both.

The following specifications suitable for the procurement of equipment from manufacturers are for complete systems including sensors, software and all other components. Three specifications are given corresponding to a different level of system. The basic specification is for a simple low-cost AWACS system, the standard and enhanced specifications are for AWACS systems with additional features. The estimated procurement cost for each level of system was given in the life cycle cost analysis.

12.5 PROCUREMENT SPECIFICATIONS

1.0 GENERAL REQUIREMENTS

1.1 These specifications cover the supply and installation of low-cost weigh-in-motion (WIM) systems. The terms "low-cost WIM", "equipment", and "systems" mean piezo-electric cable WIM systems, including all sensors, electronics and interconnections.

1.2 The operation of systems supplied under this specification shall be compatible with the requirements of the Heavy Vehicle Electronic Licence Plate (HELP) program. The vendor's attention is drawn to the weigh-in-motion-performance specification developed for the HELP program.

1.3 Three (3) sets of operator's manuals for each WIM unit shall be submitted with the equipment.

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

1.5 All software used with the WIM systems must be clearly documented and provided at no additional cost. Software must include source code. A software manual, including documentation, will be provided for each WIM system.

1.6 Any proposed software licensing agreements by the supplier shall be submitted as part of the proposal.

1.7 The operation of the equipment will be tested for a minimum of thirty (30) consecutive days of continuous operation for conformance to specifications.

1.8 If the equipment does not operate according to the specifications during the acceptance testing period, the State shall have the option of returning the

equipment at vendor's cost. Payment for the equipment shall not be made until after the testing has been successfully completed.

1.9 The manufacturer shall provide training to state personnel in operation, maintenance, trouble-shooting, and repairs for the equipment. The bid shall include the vendor's proposed training schedule.

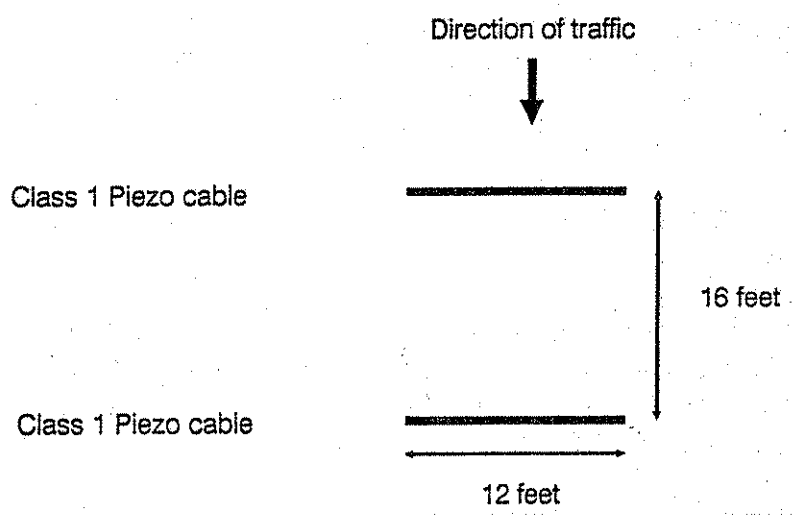
1.10 The vendor shall state how their equipment meets each of the specifications. Any variations from these specifications shall be listed by vendor and approved by the State.

1.11 Vendors are invited to meet with state personnel to discuss needs and to visit sites.

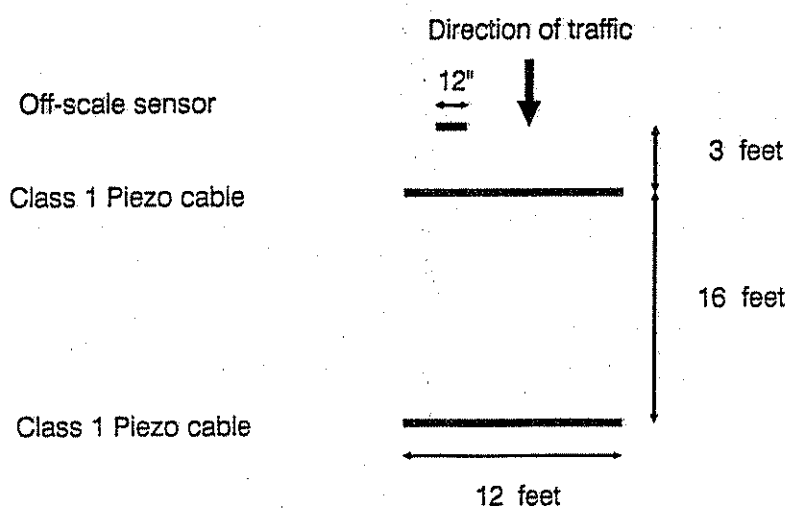
2.0 CONFIGURATION

The proposed system will be one of the following types:

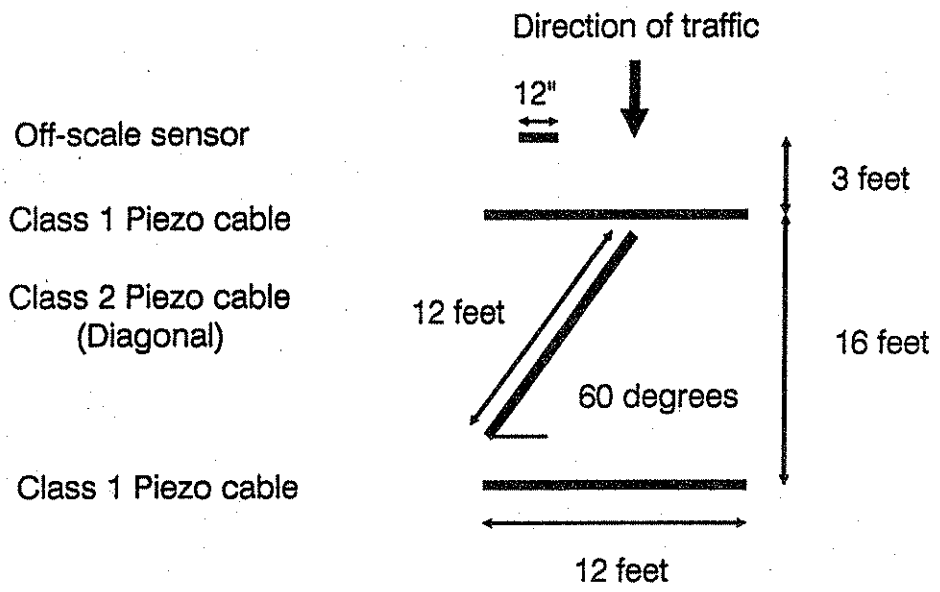
2.1 Basic



2.2 Standard



2.3 Enhanced



Notes: 1. The short sensor must be located in the right wheel track, starting approximately 2 feet 6 inches from the shoulder line.

2 In multi-lane systems the piezo cables are located directly adjacent in the adjoining lanes, with software to avoid double counting of straddling vehicles.

2.4 It should be noted that these configurations are suggestions. Vendors may be using different configurations which will be considered.

3.3 OPERATING ENVIRONMENT

3.1 The low-cost WIM system is required to operate in through traffic lanes of interstate and principal highways covering the full range of traffic volumes and truck percentages to be found in the United States.

3.2 The piezo WIM sensors shall operate within specification in both asphalt and portland cement concrete pavements, constructed on all commonly encountered sub-base materials and soil types.

3.3 The low cost WIM systems shall function within the specified accuracy limits over the temperature range 0 to + 160 degrees Fahrenheit, and up to 95 percent relative humidity. The systems shall additionally be capable of withstanding temperatures in the range -40 to + 160 degrees Fahrenheit without suffering permanent damage or significant deterioration.

4.0 DURABILITY

4.1 The piezo WIM sensors shall achieve an operating life of at least two (2) years in 80% of cases.

4.2 The electronics sub-system shall achieve an operating life of at least four (4) years in 80% of cases.

5.0 IN-PAVEMENT SENSORS

5.1 Piezo cables shall be manufactured by Thermocoax, or equivalent, mounted in accordance with the cables tested in the Iowa/Minnesota demonstration. Provision shall be made for temperature monitoring in at least one sensor per installation. Other mountings will be considered, where vendors can provide independent evidence of compliance with HELP WIM performance specifications.

5.2 Active lengths of cable shall be 11'6" for use in 12' lanes or adjusted as necessary for other lane widths.

5.3 Feeder lengths must be sufficient to reach roadside electronics without joints in the feeders.

5.4 Feeder cables shall be protected by PVC sleeves where they cross joints in or adjacent to the pavement.

5.5 For axle weight purposes, No. 1 grade piezo-electric cables only are acceptable; all others will be refused. Vendors must provide evidence of compliance with additional laboratory test requirements set out in the Iowa/Minnesota demonstration.

5.6 Piezo cable mountings shall be permanently installed, flush with the pavement surface along the entire length of each sensor, using Hermetite epoxy or similar approved materials.

5.7 Installation of piezo-electric cables, electronics, equipment box and conduits will be carried out by the vendor, or an approved sub-contractor having experience of piezo cable installations. All wiring, conduit and electrical equipment shall conform to state specifications and standards, and local building codes. The maximum depth of pavement cut allowed for piezo-electric cables is two (2) inches. Width of cut shall not exceed two (2) inches.

5.8 Installation procedures including traffic control and safety measures shall be approved by the State before any works are commenced. All work shall be carried out in accordance with the approved procedures.

6.0 DATA INPUT AND PROCESSING

6.1 The electronics sub-system for axle weighing and vehicle classification shall be capable of monitoring signals from two piezo sensors per lane, plus one in-pavement thermocouple or other approved temperature sensor per installation, sampling each piezo sensor output at a rate between 1kHz and 2kHz.

6.2 Appropriate charge amplifiers with sealed connectors shall be provided within the electronics sub-system, giving time constants of between 2 and 4 seconds certified by the manufacturer over the relative humidity range 0% to 95%.

6.3 The signal processing algorithm shall be certified to operate in accordance with a flow-chart to be supplied by the manufacturer, which will indicate and quantify how provision is made for automatic zeroing, elimination of pavement bending effects, suppression of noise, detection of wheel passages, digital signal integration, speed compensation and temperature correction. Detection of off-scale vehicles and self-calibration shall also be similarly certified for standard and enhanced systems only.

6.4 The vehicle classifier algorithm shall be certified to classify in accordance with the FHWA Scheme F look-up table appended as Table 12.2. Other look-up tables supplied by the manufacturer which indicate and quantify the ranges of parameters used to specify each vehicle category will also be considered, if these can be shown to meet HELP WIM Performance Specifications.

6.5 When selected, the self-calibration algorithm shall initially change the manually-input calibration factor such that the mean axle weight of the steering axles of at least 150 on-scale 3S2s shall be made equal to a user-programable lead axle target weight. Each subsequent sample of at least 150 on-scale 3S2s shall be similarly utilized to readjust the calibration factor, by a maximum of one percentage point per adjustment in the direction of the newly-calculated factor.

6.6 In binned data modes, self-calibration adjustments shall only be permitted at the end of each recording period, if sufficient vehicles have been accumulated since the previous adjustment. In all modes, however, each adjustment shall be logged in the data record, including time, date, lane number, calculated factor and actually-implemented factor.

6.7 Provision shall be made for input of all system operating parameters on-site using a terminal or keyboard.

6.8 User programmable factors shall include an initial calibration factor, having a nominal value of 1.00, the self-calibration lead axle target weight, the temperature compensation factor, and other parameters required for setting-up the system such as site identification, time and date, sensor configuration, etc.

6.9 Mode of operation and parameters for data processing and storage shall be user-programmable.

6.10 Monitoring of traffic and implementation of the self-calibration facility shall be suspended or resumed upon receipt of appropriate user instructions.

6.11 Diagnostic checks of system operation and performance shall include, as a minimum, checks for low battery power, axle sensor failure, data consistency between sensors, telemetry errors, and condition of module data.

7.0 DATA STORAGE AND OUTPUT

7.1 All data output will be ASCII and RS232-C compatible. External data transmission rates will include 1200/1200 baud. Protocols and handshaking shall be provided for communication to external printers, terminals and IBM-compatible microcomputers. It is desirable that the data output is subject to an xon/xoff type protocol.

7.2 An RS232-C port shall be provided for data output at the WIM site.

7.3 In the continuous mode of operation, individual vehicle data for all vehicles shall be stored in memory or output in real time, including vehicle number, time, lane, speed, class, axle spacings, gross weight, and all individual axle weights (NOT combined into tandems or triples). Axle group weights of tandems and triples shall also be provided in real-time output, but need not be stored in memory.

7.4 In the selection mode, individual vehicle data as above shall be output or stored in memory for all trucks and buses, or for any selected vehicle class.

7.5 For enhanced systems only, in the tire width mode, individual vehicle data for trucks and buses only shall be output in real time including vehicle number, time, lane, speed, class, axle weights, axle spacings, and tire widths and lengths for individual axles.

7.6 For enhanced systems only, in the summary mode, periodic (15 minute to 24 hour) summary data will be output or stored in memory including time period, fault status, calibration factor, number of vehicles in each FHWA vehicle category, number of vehicles in each of twelve user-defined gross weight bins, and number of single

axles, tandem axles, and triple axles in each of three user-defined 12-bin histograms of axle weight.

7.7 For enhanced systems only, in the detail mode, periodic summary data will be output or stored in memory as specified above, but with separate gross weight and single/tandem/triple axle weight histograms for each category of trucks or buses.

7.8 For basic systems only, data storage capacity shall be provided for at least 64k characters. For standard systems, data storage capacity shall be provided for at least 256k characters. For enhanced systems, data storage capacity shall be provided for at least 1 million characters.

8.0 DATA RETRIEVAL SYSTEM

8.1 A data retrieval system with a portable memory module or similar provision for manually collecting data from the site is not a requirement for permanent Heavy-Vehicle Electronic License Plate (HELP) monitoring points, where data will normally be accessed by telemetry from standard or enhanced AWACS units. For other applications of the piezo-electric cable WIM system, however, provision shall be made for portable data retrieval from the site by means of take away memory, portable memory modules, downloading to a dedicated retrieval unit, downloading to a portable microcomputer, or a similar system to be clearly defined and demonstrated by the manufacturer.

8.2 Whatever data retrieval system is utilized, the eventual data output shall be as specified in Section 7 above.

9.0 POWER AND TELEMETRY

9.1 The electronics sub-system shall be designed for low power consumption and continuous operation. It shall be capable of operating on 110-120 VAC, batteries and a solar panel. Where 110-120 VAC commercial power is utilized, battery back-up shall be provided for 48 hours of continuous operation during supply failures, brown-outs or other supply fluctuations.

9.2 Standard and enhanced units 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 by a defined and approved protocol.

9.3 All of the data input parameters listed in 6.6 through 6.8 above shall be capable of being monitored and re-set via the telemetry sub-system provided in standard and enhanced units.

10.0 EQUIPMENT CABINET

10.1 At permanent HELP sites, the WIM equipment will be housed in an unheated, uncooled, and unsealed roadside cabinet containing mains power, telephone connection, and other electronic equipment. The WIM manufacturer shall provide an appropriate case and rack system for the equipment, capable of excluding dust and moisture and preventing accidental damage to components during routine maintenance.

10.2 For other applications of the piezo WIM system, the equipment may be used in a portable mode as roadside traffic monitoring equipment. For this purpose, its case shall have sufficient strength to withstand tampering, vandalism and attempted theft of components. Connections shall be appropriately sealed and inaccessible so as to make unauthorized disconnection difficult.

11.0 DESIGN REQUIREMENTS

11.1 All electric components shall be of solid state design with high noise immunity utilizing low power consumption, 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.

11.2 Wherever possible, the equipment shall contain standard manufactured products, so that prompt and continuing service and delivery of spare parts may be assured.

CLASS	AXLE SPACINGS (feet)															
	1 TO 2		2 TO 3		3 TO 4		4 TO 5		5 TO 6		6 TO 7		7 TO 8		8 TO 9	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
2	6.0	9.8														
3	9.8	12.2														
5	12.2	19.5														
4	19.5	40.0														
1	0.0	6.0														
2	6.0	9.0	8.0	40.0												
3	9.8	13.0	8.0	19.5												
8	13.0	19.5	8.0	19.5												
2	9.0	9.8	8.0	19.5												
8	9.0	19.5	19.5	40.0												
4	19.5	40.0	0.0	40.0												
1	0.0	6.0	0.0	8.0												
6	0.0	40.0	0.0	40.0												
2	6.0	9.8	6.0	40.0	0.0	3.5										
3	9.8	13.0	6.0	40.0	0.0	3.5										
8	13.0	19.5	6.0	40.0	0.0	3.5										
3	9.8	13.0	8.0	20.0	6.0	10.5										
5	13.0	19.5	8.0	20.0	6.0	10.5										
8	6.0	19.5	20.0	40.0	3.5	10.5										
8	6.0	19.5	0.0	8.0	0.0	40.0										
4	19.5	40.0	0.0	40.0	0.0	40.0										
7	0.0	40.0	0.0	40.0	0.0	40.0										
2	6.0	9.8	6.0	40.0	0.0	3.5	0.0	3.5								
3	9.8	13.0	6.0	40.0	0.0	3.5	0.0	3.5								
6	9.8	20.0	0.0	6.0	8.0	20.0	6.0	10.5								
11	6.0	40.0	8.0	40.0	8.0	40.0	8.0	40.0								
7	6.0	40.0	0.0	8.0	0.0	8.0	0.0	8.0								
7	0.0	8.0	0.0	40.0	0.0	8.0	0.0	8.0								
9	6.0	40.0	0.0	8.0	20.0	40.0	3.5	10.5								
9	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0								
12	8.0	19.5	0.0	8.0	8.0	40.0	8.0	40.0	8.0	40.0						
12	8.0	19.5	8.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0						
7	0.0	40.0	0.0	8.0	0.0	8.0	0.0	8.0	0.0	8.0						
7	0.0	8.0	0.0	40.0	0.0	8.0	0.0	8.0	0.0	8.0						
10	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0						
10	8.0	19.5	0.0	8.0	8.0	40.0	0.0	8.0	0.0	8.0	0.0	8.0				
10	8.0	19.5	0.0	8.0	0.0	8.0	8.0	40.0	0.0	8.0	0.0	8.0				
7	0.0	40.0	0.0	40.0	0.0	8.0	0.0	8.0	0.0	8.0	0.0	8.0				
13	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0				
10	8.0	19.5	0.0	8.0	0.0	8.0	8.0	40.0	0.0	8.0	0.0	40.0	0.0	8.0		
13	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0		
13	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0	0.0	40.0

Table 12.2 Look-up table for FHWA classification scheme

13. Conclusions

13.1 BACKGROUND

Preceding chapters have described all of the work undertaken during the development of a low-cost Automatic Weight and Classification System (AWACS) for the States of Iowa and Minnesota, in association with the Federal Highway Administration. This chapter brings together the main conclusions of the demonstration.

The objectives of the demonstration were to establish the performance of a low-cost AWACS under representative traffic volumes, pavement types and climatic conditions. This involved field appraisal at two test sites, one in Iowa and one in Minnesota. Two generations of low-cost AWACS equipment were developed and tested within the project. Comprehensive results of all tests and their outcome are summarized in this chapter.

13.2 INITIAL TASKS

Previous Work

'Vibracoax' piezo-electric cable was patented by Philips in 1971. This cable forms the basis of current low-cost WIM developments. More than ten years of research and development have been carried out in Europe to define preferred techniques for cable installation and signal processing. This project builds directly upon that basis of solid, scientific research.

Vibracoax comprises a copper-sheathed coaxial cable containing a highly-compressed, piezo-electric ceramic dielectric. During manufacture, the cable is poled using a radial electric field at an elevated temperature. The cables generate charge in proportion to changes in radial and longitudinal stress. Problems have arisen in the past with variations in response along cable lengths, which can only be addressed through rigorous testing before and after mounting.

The importance of the mounting design used with the piezo-electric cables cannot be overstated. More than thirty mountings were tested before the current design utilized in this project was selected. This design can be manufactured under license to the UK Transport and Road Research Laboratory (TRRL).

Signal processing requires real-time digital integration of output voltages from charge amplifiers, at a sampling rate of between 1 and 2 kHz. Provision must be made for tracking background drift, elimination of pavement bending effects and compensation for vehicle speed. Appropriate algorithms had been derived for these purposes before the start of this demonstration.

Test Program

A testing and analysis program was agreed to establish preproduction system performance and reliability in PCC and asphalt pavements during the various seasons of one year. The program comprised laboratory tests, random vehicle evaluations, test vehicle appraisals and a long-term assessment. Random vehicle evaluations were the major type of field tests, serving to calibrate the system, assess its weigh-in-motion performance, evaluate its axle spacing measurement accuracy and determine its ability to measure tire widths and lengths. The other appraisals provided supporting evidence to assess system performance under more extreme conditions.

Site Selection

A quantitative scheme was developed to help states select AWACS sites consistently. Engineering factors considered to be of prime importance include pavement rigidity, profile, surface condition and maintenance schedules. Other factors to be considered for economic and administrative reasons include availability of services, equipment housing, and proximity to a static weighscale. The site selection scheme should be further developed in the light of experience with future AWACS sites.

13.3 FIRST GENERATION SYSTEMS

The first generation AWACS systems were procured from GK Instruments in accordance with a specification prepared within the demonstration project. The system was capable of monitoring up to six piezo-electric cables and one inductive loop located in a single traffic lane. It used established sensor designs and signal processing techniques, and operated from mains power or battery backup over a temperature range of -40 degrees F to 160 degrees F, in a relative humidity of up to 95%.

Three modes of operation were provided in the first generation system. In continuous mode, data were output in real time as each vehicle traversed the sensor array. In selection mode, only selected vehicles were logged using a push-button trigger. Finally, in remote

mode, summary data were stored for subsequent retrieval. All data are ASCII and RS232-C compatible.

Laboratory Testing

Laboratory tests examined the uniformity of the cable before and after mounting. Standards are recommended within this project for cable uniformity prior to installation, assessed by a standardized test procedure. Not all cables tested during the program met required standards; one batch was rejected and returned to the manufacturer.

Environmental tests also examined the performance of sensors and electronics under extremes of temperature and humidity. The tests indicated that the first generation AWACS equipment met the provisional specification. Additional tests were performed on the response of the system at low temperatures following the winter's field observations. These tests were used to form the basis for a temperature compensation feature incorporated into the second generation system.

Installation (AWACS1)

The first generation system was initially installed in August/September 1986, though subsequent feature upgrades continued throughout the project. Two different site configurations were utilized initially, one in Iowa and one in Minnesota. Piezo sensor installation requires four persons for one day to cover one to two highway lanes. Rigorous control and experienced supervision of the sensor installation are essential if satisfactory results are to be achieved. Electronics installations can follow normal practices for roadside equipment.

Weigh-in-Motion Accuracy (AWACS1)

Random and test vehicle data collected during September and December 1986 in Iowa and Minnesota were analyzed, identifying systematic and random differences between static and dynamic weights. Systematic differences are given by the mean of the weight difference distribution, and random differences by its standard deviation.

The conclusions of the analyses were as follows:

1. During September 1986, in Iowa, random differences between static and dynamic weight with two full-length piezo sensors were 8.9% for axle weights and 6.3% for gross weights. In December 1986, the random difference was 10.5% for axle weights and 8.1% for gross weights.

2. Expressed in terms of the HELP 'funnel' concept, September 1986 random differences for two full length sensors were 758 lbs below 10,000 lbs, and 7.8%, above this value. In December 1986 the equivalent results were 1018 lbs and 9.4%. Systematic differences were less than 1% above 10,000 lbs.

3. The Minnesota data were less satisfactory, with large percentage errors in weight measurement for certain combinations of axle sensors. Modifications were made at the Minnesota test site, but the sensors continued to perform less well than those in Iowa. During the December tests, random differences were found to be 15.5% on axle weight and 13.1% on gross weight. In terms of the 'funnel' concept, these axle weight differences equate to 1312 lbs below 10,000 lbs, and 14.8% above 10,000 lbs. Systematic differences were less than 1%.

4. The tradeoff between system cost and system performance utilizing one, two or three weight sensors was examined. A system with two weight sensors appeared to represent an optimum, meeting user needs while minimizing costs.

5. Differences in weighing accuracy between weight ranges were found in the Iowa data. These differences indicate that the AWACS equipment showed least random variation, in percentage terms, for weighing heavy axles.

6. Axle spacing measurement accuracy using the first generation AWACS was very high (± 1") and should satisfy all user needs.

7. AWACS speed measurement accuracy was very high (± 0.5 mph), and should also satisfy all user needs.

Vehicle Classification Accuracy (AWACS1)

1. The accuracy of FHWA Scheme F classification using previously-existing flow-charts did not satisfy draft HELP guidelines. Enhanced classification routines were developed which aimed to substantially improve classification accuracies.

2. Classification accuracies achieved using an inductive loop as well as piezo cables were significantly worse than accuracies achieved without an inductive loop. The loop was excluded from the second generation system design.

Tire Length and Width (AWACS1)

1. The first generation AWACS was capable of measuring tire contact lengths with a random error of less than one inch. Tire width measurements had a random error

of less than two inches. This is easily sufficient to distinguish single from double tires.

2. Several refinements to signal processing algorithms were implemented in the second generation system, which aimed to increase the reliability of tire contact measurement, avoiding tires being missed.

13.4 SECOND GENERATION SYSTEMS

The second generation AWACS systems were developed to include additional features such as automated tire length and width measurement, diagnostic checks and self-calibration. They also implemented several system modifications which were determined during the first generation system tests.

The principle of self-calibration is that loads on the steering axles of 3S2s show relatively little variation, regardless of the loading on the truck. Once a sufficient number of 3S2 steering axles have been weighed, the calibration factor is automatically adjusted so that the measured axles fit the expected mean.

Installation (AWACS2)

The Minnesota piezo sensors were removed and reinstalled in such a way as to profile the sensors more closely to the pavement surface. Two of these three sensors subsequently failed, within three months of being moved. No other sensor failures were recorded at any time in the project. The failures resulted from damage to the PVC sheaths of the coaxial feeders during their removal from the pavement. The three sensors were replaced by new equipment which functioned without problems.

The second generation sensor arrays in both states standardized on a modified subset of the original Iowa installation. Two parallel, 12 ft sensors spaced 16 ft apart provide both weight and classification data. An additional short sensor allows for off-scale vehicle detection, and a diagonal sensor for tire width measurement.

The short sensor, located in the right wheeltrack, determines whether vehicles wholly or partially avoid the main axle load sensors. Off-scale vehicles are weighed less reliably because the complete tire contact area does not pass over the active length of the load transducers.

Weigh-in-Motion Accuracy (AWACS2)

The analysis of random and test vehicle data collected in the second generation system appraisal led to the following main conclusions.

1. Based on the Iowa test results, the second generation AWACS system gave overall random differences between static and dynamic weight of 12.3% for axles and axle groups of all weight ranges combined. Second generation random differences between static and dynamic weight were calculated to be 1126 lbs below 10,000 lbs and 11.8% above this value.

2. The second generation AWACS should be capable of satisfying user needs for gross weight accuracies. Iowa test data indicate that these have a random static/dynamic difference of 9.4%.

3. The Minnesota data are less satisfactory, with larger percentage differences in weight measurement. With charge amplification of 15 nC/volt, random differences between static and dynamic weight were found to be 1418 lbs below 10,000 lbs and 16.7% above this value. Overall random differences for all axles and axle groups were 16.5%. These differences may result from characteristics of the approach profile, or could be related to the low pavement rigidity at this site. Further work is needed to assess the AWACS performance at a range of sites on asphalt cement concrete (ACC) pavements.

4. Systematic differences for random samples of vehicles were generally less than 2%, due to the calibration procedure utilized in the tests associated with the need to recalibrate after each equipment upgrade. Longer-term appraisal of calibration factor stability is now required, including an assessment of self-calibration performance.

5. Axle spacing measurement accuracy is very high in all tests ($\pm$ 1.5") and should satisfy all user needs.

6. Test vehicle results indicate that individual test vehicles are generally not representative of the vehicle population. For this reason, calibration of the AWACS using test vehicles is considered inappropriate.

7. Unusually large static/dynamic weight differences associated with certain vehicles appear to be a function of the design particular to that type of vehicle. This has important implications for WIM performance specifications, vehicle design and pavement loadings.

8. Analyses indicate that over the temperature range in which the second generation tests were conducted (70 degrees F to 100 degrees F), there is no appreciable change in calibration or axle weight accuracy corresponding to changes in

temperature. Further tests are required over the coming winter to fully determine system performance at low temperatures.

9. Random differences for offscale vehicles are higher than for those which are onscale. From a sample of 435 trucks in Iowa, 26 were identified as offscale. Analysis indicated that they were approximately 2 feet right or left of the wheel track. From a sample of 527 vehicles in Minnesota, 71 were classed as offscale, using a shorter offscale sensor. The shorter sensor did not create any increase in weighing accuracy over that achieved in Iowa.

Vehicle Classification Accuracy (AWACS2)

The analysis of vehicle classification data collected throughout this project led to the following major conclusions on absolute and compensated accuracies, where absolute accuracies relate to individual vehicles and compensated accuracies to periodic totals.

1. In Iowa, the second generation AWACS achieved absolute and compensated accuracies of 95.2% and 98.9% respectively for all vehicles. The classifier also gave excellent results for trucks and buses, with absolute and compensated accuracies of 94.8% and 97.6% respectively.

2. The second generation system in Minnesota gave absolute and compensated accuracies of classification for all vehicle types combined of 89.4% and 98.9% respectively. Trucks and buses have absolute and compensated accuracies of 90.3% and 94.0% respectively.

3. The overall count accuracy is very high with less than 0.1% of vehicles being missed or double counted in Iowa and less than 0.4% of vehicles being missed or double counted in Minnesota.

4. Results indicate that enhanced classification routines implemented following the tests in September and December 1986 significantly improved compensated accuracies between particular categories of vehicle, particularly between cars and pickups.

5. The enhanced classification logic for trucks and buses gives a statistically significant increase in accuracy for these categories of vehicle.

Tire Length and Width (AWACS2)

The analysis of tire length and width data collected in Iowa in May 1987 and in Minnesota in September 1987 led to the following main conclusions.

1. The second generation AWACS equipment is capable of measuring tire contact lengths with a random error of between one and two inches. Systematic differences in static and dynamic tire length can be reduced to less than half an inch by the use of a simple additive correction.

2. The second generation AWACS equipment is capable of measuring tire widths with a random error of between one and two inches. Again, systematic differences can be reduced to less than a half-inch by the use of a simple additive correction.

3. The results suggest that accuracy of tire contact widths on lead axles is greater than that on other axles. This may be due to the incidence of single and double tires on lead and other axles respectively.

Final Recommendations

Three final recommendations emerge from the analysis of the second generation AWACS weigh-in-motion results, which have considerable significance for WIM performance specifications. These are as follows:

1. Calibration (or checking the self-calibration) should be carried out using random samples of trucks, weighed statically, making comparisons between static and dynamic weights in such a way as to minimize systematic differences for the actual truck population observed at the site.

2. Verification of WIM performance should use standard test vehicles on repeated runs, to examine the capability of the WIM to give consistent results representative of each truck's unique interaction between the pavement and its suspension system.

3. Assessment of the site characteristics and vehicle population characteristics requires comparisons between test vehicle data and random vehicle data. The difference between the scatter of results achieved with test vehicles and the scatter of results observed with random vehicles will indicate the characteristics of the site in terms of pavement approach profile and vehicle population.

13.5 PROCUREMENT

The overall conclusion of the project is that for PCC pavements, low-cost weigh-in-motion giving accuracies comparable to those of conventional WIM equipment is now a proven reality. Procurement specifications are presented in Chapter 12 for complete systems including electronics hardware, software, sensors and all other components. They provide

sufficient detail for manufacturers to follow necessary approaches and reach required standards of performance without restricting the peripheral areas of technical design.

Within this project, preproduction systems have been demonstrated under actual traffic volumes, pavement types and climatic conditions experienced in two states. Two generations of low-cost WIM equipment have been developed and tested. Comprehensive results of all tests are presented in this report.

This project does not answer all the questions on low-cost weigh-in-motion; further work is required and will continue as the systems spread more widely and as operational experience broadens. What has been accomplished is technology transfer of piezo cable WIM from research to manufacturing, and initial implementation through the states. Considerable progress has been made, and much has been learned. The states must now take up the challenge of using the new techniques in their vital continuing truck traffic monitoring and appraisal activities.

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APPENDICES

Appendix A - statistical analyses

A.1 DETERMINING SAMPLE SIZES FOR WIM ACCURACY APPRAISAL

As with any measuring device, the AWACS is subject to both systematic and random errors. Systematic errors can arise for reasons relating to the design, installation or operation of the system, and cause a repeatable bias in all measurements. Random errors, on the other hand, are uncontrollable and unpredictable, and are intrinsic to any measurement. The random errors in any weigh-in-motion system will be a function of highway, environmental and vehicle characteristics. The purpose of calibration is to compensate for systematic errors, reducing them as far as possible.

WIM accuracies are expressed in terms of static to dynamic comparisons, using either absolute or percentage weight differences. Absolute differences in pounds would be appropriate if weighing errors were approximately equal, irrespective of truck or axle weight. Percent differences are more appropriate if the size of the weighing error increases in proportion to the axle being weighed, which is usually the case. If neither of these conditions is true, separate accuracies must be quoted for axles in different weight categories, perhaps using percentages for heavy axles and absolute accuracies for lighter axles.

More formally, to assess the accuracy of the AWACS for weighing, two statistics are measured. These are the Percentage Difference (PD) and the Absolute Difference (AD), defined by:

$$\text{Percentage Difference (PD)} = \frac{\text{WIM weight - static weight}}{\text{static weight}} \times 100\%$$

$$\text{Absolute Difference (AD)} = \text{WIM weight - static weight}$$

These formulas may be applied to both gross weights and individual axle weights. WIM weight is the value obtained after the calibration has been applied to the raw system output.

Of these measures, previous experience indicates that the PD statistic is likely to be the more useful. In statistical terms, the population on which the AWACS WIM function is principally designed to operate is that of the usual mix of trucks that cross the installation site. Based on this population, we can assume that both PD and AD will have an approximately normal distribution after the initial calibration. What is meant then by measuring the system accuracy is to obtain values for the mean and standard deviation of these distributions for both individual axle and gross vehicle weights, at various points in time following the initial system calibration.

It is not practicable to measure these standard deviations directly, since it is impossible to check every vehicle that crosses the site. However, these values can be estimated statistically using a random sample from the vehicle population of interest. This sample is exactly what will have been collected for the initial calibration and these data can be used again here. Subsequent appraisals/calibration checks will repeat this procedure at a later stage.

The sample size required for initial calibration depends upon the calibration accuracy required and the inherent variability of the data. A perfect calibration would eliminate all systematic error in weight measurement for the population of trucks at that site. In practice, we can only eliminate all systematic error for the calibration sample by ensuring that the sample has zero mean error. This will leave a small residual calibration error for the population as a whole.

Previous experience indicates that the standard deviation (SD) of the PD distribution will be of the order of 10%. The standard error of the mean (SEM) is given by

$$\text{SEM} = \frac{\text{SD}}{\sqrt{n}}$$

where n is the number of static/dynamic weight comparisons. Confidence limits of 95% are given by approximately 2 SEM. Therefore, for a calibration accurate to 1%, with 95% confidence, we require

$$n = \left[\frac{10}{0.5}\right]^2 = 400 \text{ observations}$$

As each observation comprises one single or one tandem axle static/dynamic comparison, this is likely to require about 150 trucks. However, at the request of the Federal Highway Administration, a 200-vehicle sample was used to provide a further margin over the statistical requirement.

The mean values for AD and PD from this sample will be an unbiased estimate of the means for the population as a whole, and should both be numerically equal to zero if the calibration has removed all systematic error. Any differences in the actual values from zero can be tested to see if they are statistically significant. A significant difference would imply a change of calibration.

The standard deviation of the sample can be used to obtain an unbiased estimate of the standard deviation of the population, representing the random error component of the system. It is possible to estimate confidence limits on this estimate of the population standard deviation.

According to Spiegel (1961) the standard error of this standard deviation (SED) is given by

$$SED = \frac{SD}{\sqrt{2n}}$$

Therefore, for an initial calibration using 150 trucks, 95% confidence limits on the standard deviation would be about 0.7%. The jackknifing technique of sub-dividing the data sets provides an approximate check on values calculated by this formula.

Using a two-tailed t-test to evaluate significant differences in sample means

This test is used to determine, at any desired level of confidence, whether or not the means of two samples drawn from the same population are significantly different.

Applying this to the WIM calibration, and using the percentage difference (PD) statistic based on the population of randomly selected trucks passing over the equipment, the two samples could be the one for the original calibration, and the second another sample collected to test for significant changes in that calibration.

The null hypothesis is that the two means are equal and any actual numerical difference is due only to that amount of scatter expected when sampling a normal distribution. The t value is defined by:

$$t = \frac{X_1 - X_2}{S_d}$$

where X_1 = sample mean of the calibration sample and X_2 = sample mean of the second sample. S_d is defined by:

$$Sd = \left[\frac{(N_1 - 1)\, S_1^2 + (N_2 - 1)\, S_2^2}{N_1 + N_2 - 2}\right]^{0.5} \left[\frac{1}{N_1} + \frac{1}{N_2}\right]^{0.5}$$

where N_1, N_2 are the sample sizes, and S_1 , S_2 are the sample variances.

We can estimate the second sample size (N_2) needed so that we can be sure of detecting differences in the means of greater than 2% with 95% confidence.

Assuming N_1 (original calibration) = 400 axles and that the standard deviations of the samples S_1, S_2 are both 10%, then

$$Sd = 10\% \left[\frac{1}{400} + \frac{1}{N_2} \right]^{0.5}$$

If we are interested in detecting differences in the means at a 0.05 level of significance, then statistical tables show that the critical values of t are 1.96 in this two-tailed test. That is, if t = 1.96 or t = -1.96, the difference in the means was not due to the random scatter expected when sampling a normal distribution, but due to the population of the two samples being different. In this case this would mean that the calibration had changed, leading to a systematic bias.

Using these values to find the minimum number for N_2, gives

$$t = \frac{2\%}{S_d} = 1.96, \quad \text{or } S_d = \frac{2\%}{1.96}$$

Since we have already estimated

$$S_d = 10\% \left[\frac{1}{400} + \frac{1}{N_2} \right]^{0.5}$$

solving for N_2 yields N_2 = 126 axles. This number of axles corresponds to about 50 trucks.

A.2 WEIGHT RANGE ANALYSIS - ANALYSIS OF VARIANCE

Iowa September data

Single sensors

Test the null hypothesis that there is no significant difference between the sample means, for single sensors.

	1 <10,000lb	2 10-20,000lbs	3 20-30,000lbs	4 >30,000lb	Totals
ΣPD	690.97	106.34	-126.44	-656.10	ΣPD_T = 14.77
ΣPD^2	77832.93	60456.90	15407.72	16505.73	ΣPD^2_T = 170203.28
N	461	425	149	154	N_T = 1189
$\frac{(\Sigma PD)^2}{N}$	1035.67	26.61	107.30	2795.24	G = 3964.82
$\frac{\Sigma PD}{N} = \overline{PD}$	1.50	0.25	-0.85	-4.26	

K = Number of groups = 4

Table A.1 Analysis of variance - single sensors

Estimate of population variance based entirely on scatter between the group means : - S_B^2

$$S_B^2 = \frac{G - \frac{(\Sigma PD_T)^2}{N_T}}{K - 1}$$

$$= \frac{3964.82 - \frac{14.77^2}{1189}}{3}$$

$$= 1321.55$$

<u>Estimate of population variance based entirely on scatter among scores within the groups : $-S_W^2$</u>

$$S_W^2 = \frac{\Sigma PD^2{}_T - G}{N_T - K}$$

$$= \frac{170203.28 - 3964.82}{1189 - 4}$$

$$= 140.29$$

$$\frac{S_B^2}{S_W^2} = \frac{1321.55}{140.29} = 9.42$$

F Value at 5% significance level = 2.61

Therefore at the 5% level reject null hypothesis and conclude that there is a significant difference between the sample means.

<u>Two-sensor combinations</u>

Test the null hypothesis that there is no significant difference between the sample means, for combinations of two sensors.

	1 <10,000lb	2 10-20,000lb	3 20-30,000lb	4 >30,000lb	Totals
ΣPD	552.49	36.40	-83.74	-456.42	48.73
ΣPD^2	34904.56	28552.50	8124.44	6975.14	78556.64
N	392	354	118	110	974
$\frac{(\Sigma PD)^2}{N}$	778.69	3.74	59.43	1893.81	2735.67
$\frac{\Sigma PD}{N} = \overline{PD}$	1.41	0.10	-0.71	-4.15	

Table A.2 Analysis of variance - 2-sensor combinations

$$S_B^2 = \frac{2735.67 - \frac{48.73^2}{974}}{3} = 911.1$$

$$S_W^2 = \frac{78556.64 - 2735.67}{974 - 4} = 78.2$$

$$\frac{S_B^2}{S_W^2} = 11.66$$

F Value at 5% significance level = 2.61

Therefore at the 5% level reject null hypothesis and conclude that there is a significant difference between the sample means.

Three sensor combinations

Test the null hypothesis that there is no significant difference between the

sample means, for combinations of three sensors.

	1 <10,000lb	2 10-20,000lb	3 20-30,000lb	4 >30,000lb	Totals
ΣPD	145.53	-5.71	-23.60	-92.19	24.03
ΣPD^2	5858.44	5882.16	1766.54	1298.31	14805.45
N	109	96	30	24	259
$\frac{(\Sigma PD)^2}{N}$	194.30	0.34	18.56	354.12	567.32
$\frac{\Sigma PD}{N} = \overline{PD}$	1.34	-0.06	-0.79	-3.84	

Table A.3 Analysis of variance - 3-sensor combinations

$$S_B^2 = \frac{567.32 - \frac{24.03^2}{259}}{3} = 188.36$$

$$S_W^2 = \frac{14805 - 567.32}{259 - 4} = 55.83$$

$$\frac{S_B^2}{S_W^2} = 3.37$$

F Value at 5% significance level = 2.65

Therefore, at the 5% level reject the null hypothesis and conclude that there is a significant difference between the sample means.

Iowa December data

Test the null hypothesis that there is no significant difference between the sample means.

	1 <10,000lb	2 10-20,000lbs	3 20-30,000lbs	4 >30,000lb	Totals
ΣPD	-94.65	37.15	124.23	-113.11	ΣPD_T = -46.38
ΣPD^2	16724.70	12015.57	2775.69	2866.40	$\Sigma PD^2{}_T$ = 34382.36
N	111	113	35	41	N_T = 300
$\frac{(\Sigma PD)^2}{N}$	80.71	12.21	440.95	312.05	G = 845.92
$\frac{\Sigma PD}{N} = \overline{PD}$	-0.85	0.33	3.55	-2.76	

K = Number of groups = 4

Table A.4 Analysis of variance

Estimate of population variance based entirely on scatter between the group means : - S_B^2

$$S_B^2 = \frac{G - \frac{(\Sigma PD_T)^2}{N_T}}{K - 1}$$

$$= \frac{845.92 - \frac{46.38^2}{300}}{3}$$

$$= 279.58$$

<u>Estimate of population variance based entirely on scatter among scores within the groups :</u> $-S_W^2$

$$S_W^2 = \frac{\Sigma PD^2{}_T - G}{N_T - K}$$

$$= \frac{34382.36 - 845.92}{300 - 4}$$

$$= 113.30$$

$$\frac{S_B^2}{S_W^2} = \frac{279.58}{113.30} = 2.47$$

F Value at 5% significance level = 2.636

Therefore at the 5% level uphold the null hypothesis and conclude that there is no significant difference between the sample means.

Minnesota December data

Test the null hypothesis that there is no significant difference between the sample means.

	1 <10,000lb	2 10-20,000lbs	3 20-30,000lbs	4 >30,000lb	Totals
ΣPD	98.66	29.30	26.91	181.81	ΣPD_T = -26.94
ΣPD^2	17018.56	18318.47	5577.11	6328.14	$\Sigma PD^2{}_T$ = 47242.28
N	66	81	16	33	N_T = 196
$\frac{(\Sigma PD)^2}{N}$	147.48	10.60	45.26	1001.66	G = 1205.00
$\frac{\Sigma PD}{N} = \overline{PD}$	1.49	0.36	1.68	-5.51	

K = Number of groups = 4

Table A.5 Analysis of variance

Estimate of population variance based entirely on scatter between the group means : - S_B^2

$$S_B^2 = \frac{G - \frac{(\Sigma PD_T)^2}{N_T}}{K - 1}$$

$$= \frac{1205.00 - \frac{26.94^2}{196}}{3}$$

$$= 400.43$$

Estimate of population variance based entirely on scatter among scores within the groups : $-S_W^2$

$$S_W^2 = \frac{\Sigma PD^2{}_T - G}{N_T - K}$$

$$= \frac{47242.28 - 1205.00}{196 - 4}$$

$$= 239.78$$

$$\frac{S_B^2}{S_W^2} = \frac{400.43}{239.78} = 1.67$$

F Value at 5% significance level = 2.653

Therefore at the 5% level uphold the null hypothesis and conclude that there is no significant difference between the sample means.

A.3 F AND t-TEST ANALYSES

The abbreviations used in the following tables are as follows:

N1 = sample size for sample 1
N2 = sample size for sample 2
V1 = degrees of freedom for sample 1, given by (N1 -1)
V2 = degrees of freedom for sample 2, given by (N2 -1)
M1 = systematic difference (mean) of sample 1
M1 = systematic difference (mean) of sample 1
S1 = random difference (standard deviation) of sample 1
S2 = random difference (standard deviation) of sample 2
F = F-distribution value
$F_{5\%}$ = F-value contained in statistical tables for the 5% significance level
$F_{1\%}$ = F-value contained in statistical tables for the 1% significance level
t = t-distribution value
** = significant at 5%
* = significant at 1%

	Ranges x1,000 lbs	V1	V2	S1	S2	F	$F_{5\%}$ 1 tail	$F_{1\%}$ 1 tail
Single Sensor	10/20	461	425	12.9	11.9	1.18*	1.16	1.24
	10/30	461	149	12.9	10.0	1.66**	1.25	1.37
	10/30+	461	154	12.9	9.3	1.92**	1.25	1.37
	20/30	425	149	11.9	10.0	1.42**	1.26	1.38
	20/30+	425	154	11.9	9.3	1.64**	1.26	1.38
	30/30+	149	154	10.0	9.3	1.15	1.32	1.47
Two Sensors	10/20	392	354	9.3	9.0	1.07	1.18	1.27
	10/30	392	148	9.3	8.2	1.29*	1.28	1.41
	10/30+	392	110	9.3	6.8	1.87**	1.30	1.46
	20/30	354	148	9.0	8.2	1.20	1.27	1.40
	20/30+	354	110	9.0	6.8	1.75**	1.28	1.41
	30/30+	148	110	8.2	6.8	1.45*	1.35	1.53
Three Sensors	10/20	96	109	7.8	7.3	1.14	1.38	1.57
	10/30	30	109	7.6	7.3	1.08	1.56	1.87
	10/30+	109	24	7.3	6.3	1.34	1.80	2.33
	20/30	96	30	7.8	7.6	1.05	1.69	2.13
	20/30+	96	24	7.8	6.3	1.53	1.80	2.33
	30/30+	30	24	7.6	6.3	1.46	1.94	2.58

Table A.6 Weight range comparison for Iowa data (September 1986)

Ranges x1000lbs	V1	V2	S1	S2	F	$F_{5\%}$ 1 tail	$F_{1\%}$ 1 tail
10/20	111	113	12.3	10.3	1.43*	1.38	1.56
10/30	111	35	12.3	8.2	2.25**	1.63	2.02
10/30+	111	41	12.3	7.9	2.42**	1.58	1.92
20/30	113	35	10.3	8.2	1.58	1.65	2.06
20/30+	113	41	10.3	7.9	1.70*	1.58	1.92
30/30+	35	41	8.2	7.9	1.08	1.71	2.14

Table A.7 Weight range comparison for Iowa data (December 1986)

Ranges x1000lbs	V1	V2	S1	S2	F	$F_{5\%}$ 1 tail	$F_{1\%}$ 1 tail
10/20	66	81	16.0	15.0	1.14	1.48	1.67
10/30	16	66	18.6	16.0	1.35	1.80	2.30
10/30+	66	33	16.0	12.7	1.59	1.70	2.13
20/30	16	81	18.6	15.0	1.54	1.77	2.24
20/30+	81	33	15.0	12.7	1.40	1.67	2.08
30/30+	16	33	18.6	12.7	2.15*	1.96	2.60

Table A.8 Weight range comparison for Minnesota data (December 1986)

Data Type	Date	V1	V2	S1	S2	F	F 5% 1 tail	F 1% 1 tail
Gross Weights	Sept 86/Dec 86	99	158	8.10	6.30	1.65**	1.34	1.51
	Dec 86/May 87	408	99	9.36	8.10	1.34*	1.30	1.46
	Sept 86/May 87	408	158	9.36	6.30	2.21**	1.25	1.37
Weights < 10,000 lbs	Sept 86/Dec 86	110	172	12.30	9.70	1.61**	1.33	1.50
	Dec 86/May 87	414	110	14.74	12.30	1.43*	1.30	1.46
	Sept 86/May 87	414	172	14.74	9.70	2.31**	1.24	1.35
All axles 10,000	Sept 86/Dec 86	188	279	10.10	7.79	1.68**	1.25	1.37
	Dec 86/May 87	782	188	11.82	10.10	1.37**	1.22	1.33
	Sept 86/May 87	782	279	11.82	7.79	2.30**	1.18	1.29
10,000 to 20,000 lbs	Sept 86/Dec 86	112	159	10.30	8.90	1.43*	1.33	1.49
	Dec 86/May 87	518	112	12.60	10.30	1.50**	1.29	1.44
	Sept 86/May 87	518	159	12.60	8.90	2.00**	1.25	1.37
20,000 to 30,000 lbs	Sept 86/Dec 86	34	58	8.20	7.40	1.23	1.63	2.00
	Dec 86/May 87	99	34	8.57	8.20	1.09	1.64	2.04
	Sept 86/May 87	99	58	8.57	7.40	1.34	1.49	1.75
30,000 lbs and above	Sept 86/Dec 86	40	61	7.90	5.30	2.22**	1.59	1.93
	Dec 86/May 87	40	163	7.90	7.26	1.18	1.46	1.71
	Sept 86/May 87	163	61	7.26	5.30	1.88**	1.46	1.71

Table A.9 Iowa accuracy changes by data collection period

N1	N2	M1	M2	t	Biased
57	1198	9.13	0	3.29	Yes

Table A.10 Iowa comparison of 3-axle vehicles +2-axle 'pups' with random vehicles (May 87)

Data Type	Amplification nC/V	V1	V2	S1	S2	F	F 5% 2 tail	F 1% 2 tail
Axles < 10,000 lbs	15/20	19	53	1526 lbs	1418 lbs	1.16	2.30	3.04
	15/25	43	53	1845 lbs	1418 lbs	1.69	1.79	2.16
	20/25	43	19	1845 lbs	1526 lbs	1.46	2.03	2.53
Axles 10,000 lbs	15/20	185	48	16.73%	14.42 lbs	1.35	1.56	1.80
	15/25	185	108	16.73%	16.38 lbs	1.04	1.35	1.58
	20/25	108	48	16.38%	14.42 lbs	1.29	1.59	1.84

Table A.11 Effect of different charge amplification settings at Minnesota (September 1987).

Tests to Evaluate the Compliance of the Iowa Weight Range Analyses (May 1987) with HELP Specifications.

1. Is a random difference of 12.6% for the 10,000 - 20,000 lbs weight range significantly above 12%?

'F' test N1 = 519 N2 = ∞ S1 = 12.60 S2 = 12.00

F calculated = 1.10 $F_{5\%}$ = 1.11 $F_{1\%}$ = 1.15

Therefore this is not significant at 5% level.

2. Are the systematic differences of 5.9% and 7.8% significantly above 5%?

The standard error of mean is $\frac{\sigma}{\sqrt{n}} = 1.65 \times \frac{5.9}{\sqrt{100}}$

95% confidence limit is given by $1.65 \frac{\sigma}{\sqrt{n}} = 1.65 \times \frac{7.8}{\sqrt{164}}$ for a 1 tailed test

Therefore the 95% 1-tailed confidence limits on 5.9% is 4.9%, which is below the HELP threshold of 5%; ie. 5.9% is not significantly above 5%. The 95% confidence limit on 7.8% is 6.8%, which is above the HELP threshold of 5%; ie. 7.8% is significantly outside HELP performance specifications.

	V1	V2	S1	S2	F	F 5% 1 tail*	F 1% 1 tail
0-10/10-20	414	518	14.74	12.60	1.37**	1.16	1.24
0-10/20-30	414	99	14.74	8.57	2.96**	1.30	1.46
0-10/30+	414	163	14.74	7.26	4.12**	1.25	1.37
10-20/20-30	518	99	12.60	8.57	2.16**	1.30	1.46
10-20/30+	518	163	12.60	7.26	3.01**	1.25	1.37
20-30/30+	99	163	8.57	7.26	1.39*	1.34	1.51

Table A.12 Weight range comparison for Iowa data (May 1987)

Weight Range	M1	M2	t	Biased
0-10/10-20	3.5	0.8	2.99	Yes
0-10/10-20	3.5	-5.9	8.37	Yes
0-10/30+	3.5	-7.8	12.29	Yes
10-20/20-30	0.8	-5.9	6.53	Yes
10-20/30+	0.8	-7.8	10.82	Yes
20-30/30+	-5.9	-7.8	1.84	No

Table A.13 Iowa weight range t-tests (May 1987)

Sample	Number of axles/ axle groups combinations	Mean of percentage differences (%)	Variance of percentage differences	t	Biased
random	1198	0.00	173.44	-	-
2-axle	32	-15.40	18.30	6.603	Yes
3-axle	32	-10.05	23.16	4.309	Yes
6-axle	30	-4.31	30.23	1.790	No

Table A.14 Iowa t-test analysis between test vehicles at 55 mph (May 1987)

Sample	Number of axles/ axle group combinations	Mean of percentage differences (%)	Variance of percentage differences	t	Biased
random	238	0.00	273.2	-	-
2-axle	34	-10.45	121.0	3.69	Yes
3-axle	34	-16.35	96.0	5.77	Yes

Table A.15 Minnesota t-test analysis between test vehicles at 55 mph (September 1987)

Appendix B - vehicle classification

B.1 PARTITIONING THE DATA

The first step in the statistical analysis of the vehicle classification results was to partition the data into groups of about 15 minute duration, corresponding to approximately 100 vehicles. This disaggregated approach was employed for several reasons. Firstly, having several samples leads to a distribution of the accuracy measurements, to which it may be possible to fit a mathematical model. Secondly, this approach makes it possible to test if there are any significant changes in accuracy with sample size. Finally, the method enables statistically significant changes to be identified following changes to the classification logic.

Partitioning the AMES 2 to 5 data in this way gave rise to 32 samples of mean size 103 vehicles, each of which contained about 20 trucks and buses. The analysis of these samples gave the following results:

Mean sample size	Absolute accuracy		Compensated accuracy	
	Mean	Std Dev	Mean	Std Dev
103	86.85%	4.24%	89.75%	7.15%

Table B.1 Accuracy of 100-vehicle samples for all vehicle categories

Using the means and standard deviations given above, the expected frequencies in 5% bands were calculated, based on a normal distribution model. A Chi-squared value was calculated to test the goodness of fit of the normal distribution. The results for the absolute accuracies were $\chi^2 = 0.139$ (df = 1), and for the compensated accuracies, $\chi^2 = 9.87$ (df = 2). The former result shows that the fit is very good, while the latter indicates that the hypothesis that the compensated accuracy figures are normally distributed can be rejected at the 0.01 level of significance.

The reason why the normal distribution is a good fit in one case, and a poor fit in the other, is clear from Figure B.1. In the absolute accuracy case, the upper tail of the distribution has fallen to a small value at 100%. However, in the compensated case, the normal distribution's upper tail extends a long way past 100%, and the data it is trying to fit are skewed. Clearly accuracies greater than 100% are not possible, and so the fit in the latter case is poor.

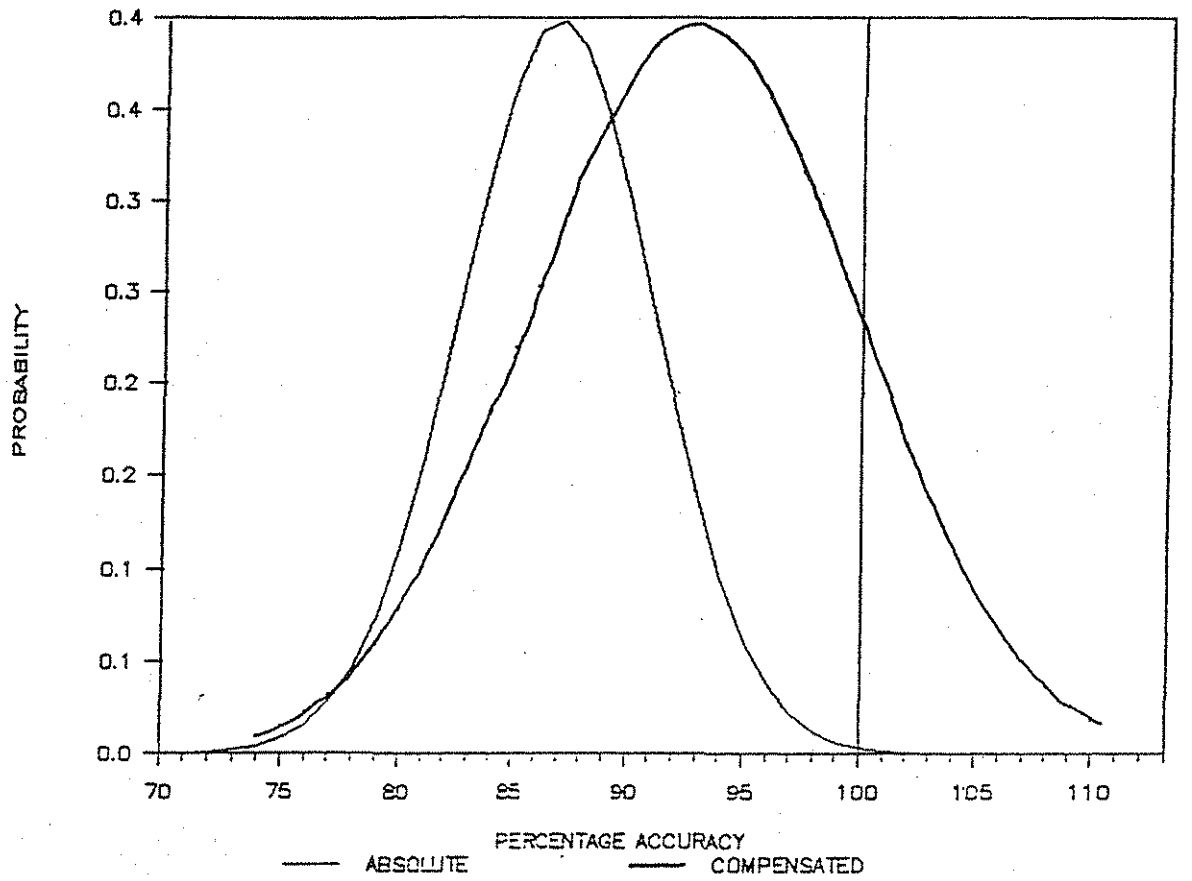

Figure B.1 Normal Distribution Model

A distribution that is suitably skewed and falls off to zero at 100% should give a much better fit than the normal distribution in the compensated accuracy case. It was decided to invent a probability function to fit this requirement and test it against the measured data. The distribution function invented was

$$p(x) = Ae^{kx}(100x-x^2) \qquad (1)$$

This function is largely empirical, though the term $100x-x^2$ was chosen to force the distribution to be zero at $x=0\%$ and $x=100\%$.

Using p(x), the constant A must be found such that:

$$\int_0^{100} p(x)dx = 1 \qquad (2)$$

The mean of the distribution, $\bar{x}$, is then given by:

$$\bar{x} = \int_0^{100} xp(x)dx \qquad (3)$$

Fitting the p(x) distribution to results for the compensated accuracies was carried out by solving equation (3) for the mean, in order to find the value of k. The expected frequencies were then calculated. Again, the accuracy of this model was assessed by calculating a Chi-squared value. *In this case it found that the compensated results were modeled well* by the p(x) distribution.

Using this distribution, the 95% confidence limits, l & u, may be calculated from

$$l = \int_0^{100} p(x)dx = 0.025 \;\&\quad u = \int_0^{100} p(x)dx = 0.975$$

In this case $l = 71.9\%$ and $u = 98.3\%$, for a value of $\bar{x} = 89.7\%$. As expected, these limits are not symmetrically placed about the mean as would be the case for normally distributed data. The p(x) distribution is illustrated in Figure B.2.

In the next stage of the analysis, pairs of the 100 vehicle samples were combined to give samples of approximate size of 200 vehicles, or about 30 minutes of data. Here, it was found that the absolute accuracy and the compensated accuracy data could both be described well by the normal distribution. This result was expected since for both cases, the normal distribution model produced only a very small tail past the 100% limit.

From these findings, *it is possible to postulate a rule to predict which of the two distributions* would be likely to give the better fit to the results. In general, the mean, x, of the sample lies in the range 85% to 95%. If many measures of a particular accuracy were taken, then the spread of values that would be obtained around this mean could not include any value greater than the highest possible accuracy of 100%. For the normal distribution model to be a good fit, therefore, it must predict accuracies greater than 100% with only a small

probability. For this to be true, it would be reasonable that $x + 2\sigma < 100\%$, where σ is the standard deviation.

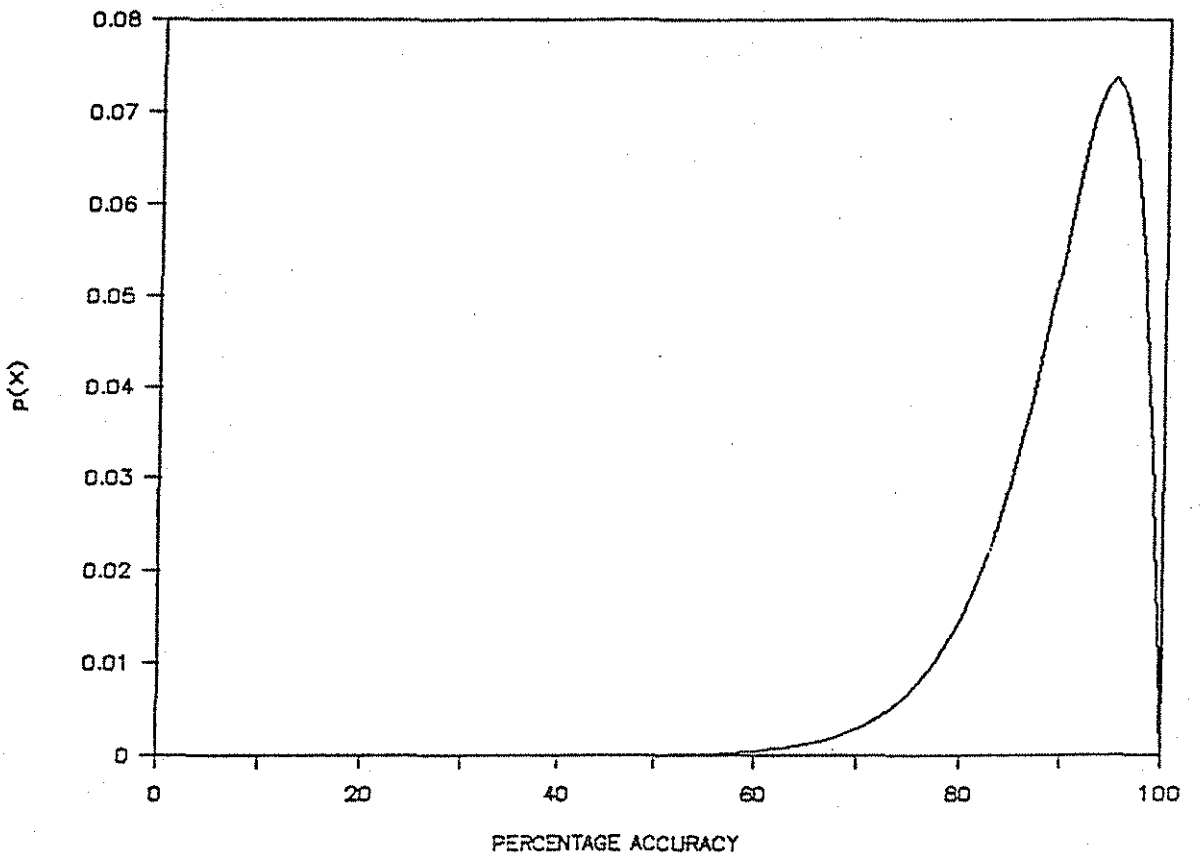

Figure B.2 Probability Distribution p(x)

In accordance with this appraisal, it was postulated that the normal distribution will fit the results when $x + 2\sigma < 100\%$. If this is not true, then the p(x) distribution model should give the better fit. This rule was found to apply for the all-vehicle category data already obtained. It was also found to work for the truck and bus data alone. This finding, that the normal distribution will fit the accuracy data when $x + 2\sigma < 100\%$, is important since the standard results of this distribution are easy to calculate and apply.

Having found that the normal distribution may be applied in certain circumstances, attention was now turned to the effects of sample size. If both the standard deviation and the distribution of the accuracy data were known, then comparisons between the data collected using the different look-up tables could be made. The next section therefore examines how the standard deviation of the accuracy data varies with sample size.

Variation of $\bar{x}$ and σ with Sample Size

The table below shows how the mean $\bar{x}$, and the standard deviation σ, of the accuracies varied as the data were partitioned into samples of increasing size. Figures 8.2 and 8.3 illustrate the same data in graphical form.

Mean sample size	Absolute accuracy		Compensated accuracy		Mean sample size	Absolute accuracy		Compensated accuracy	
	$\bar{x}$ (%)	σ (%)	$\bar{x}$ (%)	σ (%)		$\bar{x}$ (%)	σ (%)	$\bar{x}$ (%)	σ (%)
103	86.8	4.24	89.7	7.15	19	92.3	6.19	89.2	8.99
207	86.8	3.38	90.6	4.14	38	91.9	4.24	89.6	5.69
414	86.9	1.85	91.0	2.29	77	91.9	2.07	91.3	1.72
827	86.9	1.43	91.0	1.04	153	92.2	1.20	91.7	0.13
1654	86.8	1.12	91.2	0.18	307	92.3	0.33	92.2	0.82
3308	86.9	----	91.4	----	613	92.5	----	92.8	----

Table B.2 Variation of $\bar{x}$ and σ with sample size

These figures show that in general, the absolute accuracy remains constant with sample size, while the compensated accuracy has a tendency to increase. Increasing compensated accuracy with sample size is to be expected, since with larger samples, the likelihood of compensating errors is greater.

To test whether the changes in mean accuracy were significant, an analysis of variance was performed on the data for each case. The data in the last line of Table B.2 could not be included since σ cannot be calculated from a single sample. The analysis of these data showed that the changes in the absolute accuracy were not significant. It also indicated that the increase in the compensated accuracy did not amount to a significant change at the 0.01 level either, although a trend is apparent in the data. It is possible that if larger samples, such as those on the last line of the table, could be included, then a significant increase in compensated accuracy might be detected. This possibility was re-examined after σ had been estimated for the large samples.

Attention was now turned to the variation of σ. A knowledge of σ is important for several reasons. If σ were known, and the accuracy could be shown to be normally distributed, then comparisons between data collected at different times or in different ways could usefully be made. If a relationship between σ and sample size could be established, then it would be possible to estimate the standard deviation of the accuracy of a single sample. This result would be useful to make comparisons between the AMES1, AMES2-5 and GK data, which are essentially single samples whose standard deviation is unknown.

The relationship would also be important since it would allow estimates to be made of the likely sample size needed to measure the accuracy to within any particular limits. This could be carried out before any expensive data collection and analysis is undertaken.

The binomial probability distribution was used as a starting point to indicate how the standard deviation σ should vary with the sample size N. Given a large sample, then it can be postulated that the probability, p, of any particular vehicle being classified correctly is about equal to the overall absolute accuracy. If this is the case, then the standard deviation of the number of vehicles being classified correctly is Np(1-p), and the standard deviation of the overall accuracy is thus σ = Np(1-p)*100%/N. Table B.3 indicates the values predicted by this formula compared with those from the AMES 2 to 5 absolute accuracy data.

N	$\frac{Np(1-p)*100\%}{N}$	Measured Std. Dev
103	3.42%	4.24%
207	2.35%	3.38%
414	1.66%	1.85%
827	1.17%	1.43%
1654	0.83%	1.12%

Table B.3 Measured values of σ, and those predicted by the Binomial distribution

Although there is some correlation between the calculated and measured values, the formula does not predict the absolute values of the standard deviation very well. One reason for this could be that the original assumption, that one value of p applies to all vehicle categories, is incorrect.

Since this simple theory did not predict the standard deviation σ accurately in numerical terms, an empirical relation $\sigma = AN^{-m}$ was used to try to fit the data in Table B.2. The results obtained are shown in Table B.4.

The results show a close agreement, indicated by the correlation coefficient r. This empirical formula for the standard deviation σ was now applied to the AMES2-AMES5 data. Since the standard deviations fit the rule that $x + 2\sigma < 100\%$, it was assumed that the sample accuracies are normally distributed, so that 95% confidence limits on the final results could be calculated. Table B.5 indicates these confidence limits.

	All vehicles		Commercial vehicles	
Value	Absolute accuracy	Compensated accuracy	Absolute accuracy	Compensated accuracy
m A	0.51 44.6	1.3 3226	1.0 154	1.2 323
r	0.98	0.98	0.98	0.97

Note: r = Product-Moment correlation coefficient

Table B.4 Calculation of r values

Data set	Sample size	Absolute accuracy	Confidence limits 95%	Compensated accuracy	Confidence limits 95%
All vehicles					
AMES2	847	89.0%	± 2.8%	93.4%	±1.0%
AMES3	985	87.3%	± 2.6%	90.8%	±0.8%
AMES4	351	86.0%	± 4.4%	88.6%	±3.1%
AMES5	1125	85.1%	± 2.4%	90.4%	± 0.7%
AMES2-5	3308	86.9%	± 1.4%	91.4%	± 0.2%
Commercial vehicles					
AMES2	188	93.6%	± 1.6%	93.1%	±1.2%
AMES3	155	92.9%	± 1.9%	90.3%	±1.5%
AMES4	70	91.4%	± 4.3%	88.6%	±3.9%
AMES5	200	92.0%	± 1.5%	92.5%	±1.1%
AMES2-5	613	92.5%	± 0.5%	92.8%	±0.3%

Table B.5 95% Confidence limits on results

It is possible to look again at the question of the variation in accuracy with sample size in the light of Table B.5. Comparison between the full sample data (based on 3308 vehicles) and the data given in Table B.2 for the smallest samples (mean size 103 vehicles) shows that absolute accuracies, both for all vehicles and for trucks and buses, are not significantly

different. It is possible to conclude that for the data available, absolute accuracy did not vary significantly with sample size.

When comparisons are made for the compensated accuracy cases, then the larger sample accuracies appear to be significantly greater at the 95% confidence level. An increase in compensated accuracy is expected with larger samples as the chances of canceling or compensating errors increases. This result suggests that, for compensated accuracy at least, comparison between different data sets must be based on samples of similar size.

B.2 CLASSIFICATION ACCURACY MATRICES (AWACS 1)

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	*	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	2	1							1								1	5	
2		1082	113															1195	
3		56	130		7			2										195	
4																		0	
5					8													8	
6			1			4		1										6	
7																		0	
8			2					5								1		8	
9									53							1		54	
10	6											1						1	
11											5							5	
12																		0	
13																		0	
*	8	12	3														4	27	1584
Not counted		1																	
Joined		4				1													
Split		1																	
Manual class totals	10	1157	249	0	15	5	0	8	54	0	5	1	0	0					
Manual grand total									1584										

AMES1 CLASSIFICATION ACCURACY MATRIX

14th Sept 1986 11:20-11:35,12:12-15:00

Absolute overall accuracy (%) 85.78

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	*	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	2																6	8	
2		468	41															509	
3		27	108		4													139	
4				1	1	1												3	
5			2		14												1	17	
6						26											6	32	
7																		0	
8			1					10								1		12	
9									121									121	
10										1								1	
11											3							3	
12																		0	
13																		0	
*	3		2														5	10	855
Not counted																			
Joined		2																	
Split			2					2	5										
Manual class totals	5	497	158	1	19	27	2	12	126	1	3	0	0	0					
Manual grand total							847												

AMES2 CLASSIFICATION ACCURACY MATRIX

18th Sept 1986 10:02-12:13

Absolute overall accuracy (%) 89.82

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	*	Spurious	Joined	Split	AVCS class totals	AV gr total
1		1															1	2	
2		684	68															672	
3		38	108		7													145	
4				4	1													5	
5				1	17													18	
6				1		14											1	16	
7																		0	
8								10								2		12	
9									97									97	
10																		0	
11											6							6	
12																		0	
13										1								1	
*	1	5	1														7	14	[illegible]
Not counted																			
Joined		4																	
Split		1	1						2										
Manual class totals	1	645	178	6	25	14	0	10	95	1	6	0	0	0					
Manual grand total							735												

AMESS CLASSIFICATION ACCURACY MATRIX

18th Sept 1986 14:49-17:00

Absolute overall accuracy (%) 87.31

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	*	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1																		0	
2		203	29															232	
3		13	35		3													51	
4																		0	
5				1	5													6	
6						1											2	3	
7																		0	
8								2										2	
9									53		1							54	
10																		0	
11											3							3	
12																		0	
13																		0	
*																	2	2	353
Not counted																			
Joined																			
Split								2											
Manual class totals	0	216	64	1	8	1	0	4	53	0	4	0	0	0					
Manual grand total								35											

AMES4 CLASSIFICATION ACCURACY MATRIX

18th Sept 1986 17:13-17:23,18:28-19:11

Absolute overall accuracy (%) 86.84

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	*	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	1																	1	
2		645	91		1													737	
3		44	127		9			1										181	
4					4													4	
5			2		29													31	
6						13												13	
7		1						1										2	
8			3					21										24	
9									116									116	
10																		8	
11											5							5	
12																		0	
13																		0	
*		7															4	11	1125
Not counted		2																	
Joined																			
Split		2																	
Manual class totals	1	781	223	0	43	13	0	23	116	0	5	0	0	0					
Manual grand total									1125										

AMES5 CLASSIFICATION ACCURACY MATRIX

19th Sept 1986 8:27-11:14

Absolute overall accuracy (%) 85.07

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	*	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	3	1															7	11	
2		1928	229		1													2158	
3		114	378		23			1										516	
4				5	6	1												12	
5			4	2	65												1	72	
6				1		54											9	64	
7		1						1										2	
8			4					43								3		50	
9									387		1							388	
10										1								1	
11											17							17	
12																		0	
13										1								1	
*	4	12	3														18	37	3321
Not counted		2																	
Joined		6																	
Split		3	3					4	7										
Manual class totals	7	2859	621	8	95	55	0	49	394	2	18	0	0	0					
Manual grand total								3388											

AMEES2-AMES5 CLASSIFICATION ACCURACY MATRIX

Absolute overall accuracy (%) 86.85

COMPARISON OF CLASSIFICATION ACCURACIES WITH AND WITHOUT LOOP

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1																		0	
2		893	96		4													993	
3		59	186		30			10										285	
4				2	1	1												4	
5					13													13	
6		2				21			2									25	1545
7							1											1	
8		1	1					21	1									24	
9									185									185	
10										5								5	
11											10							10	
12																		0	
13																		0	
N																			
Not counted	12	4	1			1			10	2									
Joined																			
Split																			
Manual class totals	12	959	284	2	48	23	1	31	198	7	10	0	0						
Manual grand total						1575													

Date ID .....

Absolute overall accuracy ..84.89 %

Compensated overall accuracy ..93.14 %

AMES-IOWA 135

COMBINED RESULTS
WITHOUT LOOP

October 21, 1986

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1																	22	220	
2		1396	161		3										3		4	1567	
3		90	235		39			9	1								1	375	
4				3	2	1		1	1									8	
5		2	2	1	22				1									28	2259
6		1	1	1		16			1								25	45	
7							1											1	
8		2	7					30	6									45	
9									148									148	
10										1								1	
11			1					1	3		13							18	
12												1						1	
13																		0	
N																			
Not counted	11	17	3		1				6										
Joined																			
Split			1						25										
Manual class totals	11	1508	411	5	67	17	1	41	192	1	13	1	0						
Manual grand total								2268											

Data ID .....

Absolute overall accuracy .82.28. %

Compensated overall accuracy .89.90. %

AMES-IOWA I35

ALL RESULTS FOR
CLASSIFICATION WITH LOOP

September 29, 1986
and October 17, 1986

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS gran tota
1																		0	
2		968	107															1075	
3		72	170		12													254	
4				1	2	4		1	2									10	
5			2		24													26	1575
6		1				16												17	
7		1	16					4	2									23	
8			1					18										19	
9									141									141	
10												1						1	
11											6	1						7	
12										2								2	
13																		0	
N																		0	
Not counted		14			2	1		4	43	1	4								
Joined																			
Split																			
Manual class totals	0	1056	296	1	40	21	0	27	188	3	10	2	0	0					
Manual grand total							1644												

AMES IOWA

Absolute overall accuracy 81.32

Compensated overall accuracy 89.62

December, 1986

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1																		0	
2		839	25		1													865	
3		132	299		17													448	
4				2	4		1											7	
5			8		46													54	
6						21												21	
7			4															4	
8								7	1									8	1448
9									20									20	
10										17								17	
11											3							3	
12																		0	
13										1								1	
N																		0	
Not counted		58	1							6	1								
Joined																			
Split																			
Manual class totals	0	1029	337	2	68	21	1	7	21	24	4	0	0	0					
Manual grand total							1514												

ELK RIVER MINNESOTA

Absolute overall accuracy 82.8%

Compensated overall accuracy 79.7%

December, 1986

AMES2-AMES5 - CLASSIFICATION ACCURACY

Class	Count error	Gain error (%)	Loss error (%)	Absolute accuracy (%)	Compensated accuracy (%)	Ratio AVCS to manual
1	4	114	57	42.9	42.9	N/A
2	91	11	7	93.2	95.6	1.04
3	105	22	39	68.9	83.1	.83
4	4	88	38	62.5	50.0	N/A
5	23	7	32	65.4	75.8	.76
6	9	18	2	98.2	83.6	1.16
7	2	N/A	N/A	N/A	N/A	N/A
8	1	14	12	87.8	98.0	1.02
9	6	0	2	98.2	98.5	.98
10	1	0	50	50.0	50.0	N/A
11	1	0	6	94.4	94.4	.94
12	0	N/A	N/A	N/A	N/A	N/A
13	1	N/A	N/A	N/A	N/A	N/A
*	37	N/A	N/A	N/A	N/A	N/A
OVERALL	13			86.9	91.4	1.00

B.3 CLASSIFICATION ACCURACY MATRICES (AWACS 2)

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	2																	2	
2	2	567	52															621	
3		32	206		8			3										249	
4					1													1	
5			5		27			1										33	970
6						5												5	
7							1											1	
8			1				1	4										6	
9							1		12									13	
10							1			35								36	
11											-							-	
12												-						-	
13													-					-	
N						1				2								3	
Not counted																			
Joined																			
Split																			
Manual class totals	4	599	264	-	36	6	4	8	12	37	-	-	-						
Manual grand total							970												

Data ID .....ELK RIVER.....

Absolute overall accuracy ..... 88.6 %

Compensated overall accuracy ..... 99.7 %

AUGUST 31, 1987

2 Axle class 'o' vehicles assumed to be class 2

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	0																	0	
2		941	94															1035	
3		46	350		10			3										409	
4				8	2	1												11	1706
5			4	1	81													86	
6						66												66	
7							1											1	
8			1				1	12										14	
9									26									26	
10										44								44	
11											2							2	
12												0						0	
13													1					1	
N	2		2		1	2	2			2								11	
Not counted	5																		
Joined		1																	
Split								1											
Manual class totals	7	988	451	9	94	69	4	16	26	46	2	0	1						
Manual grand total								1713											

Data ID .....ELK RIVER.....

Absolute overall accuracy .....89.4 %

Compensated overall accuracy .....98.9 %

SEPTEMBER 3, 1987

2 Axle class 'o' vehicles assumed to be class 2

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	0																	0	
2		908	90															998	
3		46	350		10			3										409	
4				8	2	1												11	
5			4	1	81													86	1706
6						66												66	
7							1											1	
8			1				1	12										14	
9									26									26	
10										44								44	
11											2							2	
12												-						0	
13													1					1	
N	2	33	6		1	2	2			2								48	
Not counted	5																		
Joined		1																	
Split								1											
Manual class totals	7	988	451	9	94	69	4	16	26	46	2		1						
Manual grand total								1713											

Data ID ELK RIVER

Absolute overall accuracy 87.5 %

Compensated overall accuracy 96.8 %

SEPTEMBER 3, 1987

Charge amplification 20n c/v

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	8																	8	
2		1953	46												2		1	2002	
3		54	502	1	11			2	1								1	572	
4			1	1	3													5	
5			8	2	90			5										105	
6						40												40	3158
7							1	2								1		4	
8			4					43								1		48	
9			1						355									356	
10										3								3	
11											13					1		14	
12																			
13																1		1	
N																			
Not counted	1																		
Joined	2	4					1	1											
Split							1												
Manual class totals	11	2011	562	4	104	40	1	54	357	3	13								
Manual grand total								3160											

Data ID .....AMES.....

Absolute overall accuracy 95.22%

Compensated overall accuracy 98.86%

MAY 26 + JUNE 11
1987

Class	1	2	3	4	5	6	7	8	9	10	11	12	13	N	Spurious	Joined	Split	AVCS class totals	AVCS grand total
1	2																	2	
2		562	51															613	
3		32	206		8			3										249	
4					1													1	970
5			5		27			1										33	
6						5												5	
7							1											1	
8			1				1	4										6	
9							1		12									13	
10							1			35								36	
11											-							-	
12												-						-	
13													-					-	
N	2	5	1			1				2								11	
Not counted																			
Joined																			
Split																			
Manual class totals	4	599	264	-	36	6	4	8	12	37	-	-	-						
Manual grand total								970											

Data ID .....ELK RIVER.....

Absolute overall accuracy .....88.0 %

Compensated overall accuracy .....98.9 %

AUGUST 31, 1987

Charge amplification
15n c/v

Appendix C - HELP WIM performance specification

This draft specification for WIM has been prepared by Texas Transportation Institute, under contract to the heavy vehicle electronic license plate (HELP) program.

1.0 GENERAL PROVISIONS

1.1 The H.E.L.P. Program

The Heavy Vehicle Electronic License Plate (H.E.L.P.) program has been designed to "develop and implement a national automatic heavy vehicle license plate system capable of collecting truck weight and classification data as well as identifying and tracking individual vehicles".

1.2 Function of WIM within H.E.L.P. Program

An important element of the H.E.L.P. program is the procurement of truck weigh-in-motion (WIM) equipment that will be integrated with other subsystems to produce the truck monitoring installation at each site. This H.E.L.P. WIM Performance Specification has been produced through a detailed study of the performance characteristics of all highway speed WIM systems available on the U.S. market at the time the evaluation procedures began.

1.3 Types of H.E.L.P WIM Sites

The H.E.L.P. sites will be deployed according to four types which include automatic vehicle identification (AVI), automatic vehicle classification (AVC), and WIM technology in varying configurations. These are:

Type 1: Automatic Port-of-Entry; AVI, AVC, High Precision WIM
Type 2: Fixed Site; AVI, AVC, Low Cost WIM
Type 3: Fixed Site; AVI and AVC only
Type 4: Portable Site; AVI, AVC, and WIM

1.4 General Provisions

The WIM system shall be able to accommodate vehicles that have up to nine axles.

The WIM system shall function properly when the ambient temperature is between -20 and 122 F.

2.0 ACCURACY REQUIREMENTS

2.1 General Information

Accuracy is the most important performance characteristic of WIM systems. The ability of WIM systems to accurately estimate static truck weights, as well as determine vehicle speeds and axle spacings, and identify vehicle types will be assessed through calibration and acceptance tests and compared to performance criteria provided in this specification.

2.1.1 Explanation of Accuracy Concepts

The evaluation of the accuracy of WIM systems includes consideration of both the systematic and random components of errors in measurement produced by each system. This will be accomplished by acquiring paired dynamic and static measurements for each vehicle included in the test sample. A measure of the mean overall difference between these measurements will be used to estimate the systematic error of each system. The random error will be evaluated by examining the variability of the differences between the paired measurements.

2.1.2 Method of Calculating and Expressing Accuracy

Two types of differences will be computed from the paired observations. The first is the percent difference, defined as follows:

$$PD = \frac{\text{WIM Measurement - Static Measurement}}{\text{Static Measurement}} \times 100\ \% \qquad (1)$$

The measurement used in Equation 1 will be either a weight (axle, tandem, or gross), a speed, an axle spacing, or a classification count. The second type of difference is the absolute difference, defined as follows:

$$AD = \text{WIM Measurement - Static Measurement}$$

The measurement used in Equation 2 will be either a weight (axle, tandem, or gross), a speed, an axle spacing, or a classification count. Both the percentage and the absolute measures are included in the specification because each is more appropriate under certain conditions as defined in the following sections.

2.1.3 Method for Evaluating Accuracy of System

The accuracy of each system will be evaluated by comparing the results of the calculations described above for data collected in accordance with the procedures defined under 2.1.3.1, and 2.1.3.3 with the performance requirements given in 2.3 through 2.5, inclusive.

2.1.3.1 Recommended Calibration Procedure

The initial calibration of the WIM equipment is intended to remove as much of the systematic error as possible from the measurements. This goal is achieved through the use of a sample of vehicles; the equipment settings are then adjusted to reduce the systematic error to zero. Determination of the calibration factor(s) will be made using the percentage difference (PD) between the dynamic and static measurements for each sampled vehicle using Equation 1. The mean overall percentage difference will be calculated for the calibration sample and used as a measure of the systematic error. The initial device calibration will be achieved by setting this error to zero following the manufacturer's recommended procedure. A minimum of 150 trucks will be included in this calibration. These vehicles must be selected at random from the traffic stream.

The data gathered at this initial test will also be used to determine the random error of the WIM system. The standard deviations of the percentage and absolute differences will be calculated and used as measures of the random error. The specific variables to be evaluated and maximum acceptable values are given in 2.2 through 2.5.

2.1.3.2 Recommended Acceptance Test Procedure

The WIM system will be accepted only if an acceptance test, conducted thirty days following the initial calibration, is passed. Since the data from the initial calibration will be available, the number of trucks weighed in the second test will be reduced to 75. These vehicles must be selected at random from the traffic stream.

The systematic error will be determined from the sample for both percentage and absolute differences and compared statistically to the maximum values shown in 2.2 through 2.5. The systematic error estimates are the means of the sample percentage and absolute differences. The random errors will be determined from the sample for both percentage and absolute differences and compared statistically to the maximum acceptable values shown in 2.2 through 2.5. The random errors are the standard deviations of the sample percentage and absolute differences.

2.1.3.3 Recommended Periodic Verification Procedure

After the WIM system has been accepted, it will be necessary to carry out a periodic verification procedure to ensure that the equipment is operating within acceptable tolerances. This will be done by comparing the mean weight of the steering axle of a randomly selected sample of 100 three-axle tractor/two-axle trailer (3S2) trucks to the mean weight of the steering axle for the sample acquired at the time of initial calibration. The

device will then be adjusted to yield the same mean values as previously found. The equipment shall have provisions for making this calibration in the field.

2.1.4 Explanation of Different Levels of Accuracy for Each Type of H.E.L.P. WIM System and by Operational Speed of Traffic.

In this specification, the accuracy levels expected from a WIM system depend on the type of WIM site for which it is intended and the operational speed of the traffic at the location at which the equipment is installed. The accuracy requirements given in 2.2 through 2.5 reflect these differences. The values provided reflect both the accuracy needs of the function of the type of H.E.L.P. site and the capabilities of the available equipment as determined from laboratory and field tests.

2.2 Weighing Accuracy Requirements

Since the WIM systems are principally intended as weighing devices, the weighing accuracies are most important. The requirements for gross vehicle and single axle weights are provided in the 2.2.1, 2.2.2, and 2.2.3. The values shown are the maximum allowable for both systematic and random error by H.E.L.P. system type for speeds less than and greater than 40 miles per hour. Percent difference and absolute difference values are shown. The WIM system must satisfy either the percent difference or absolute difference specification. H.E.L.P. Type 3 sites do not include WIM equipment.

2.2.1 Gross Vehicle Weight

2.1.1.1 Speeds Greater Than 20 mph and Less Than 40 mph.

H.E.L.P System Type	Percent Difference	Absolute Difference
1: Automatic Port-of-Entry		
Systematic Error	4%	400#
Random Error	4%	400#
2: Fixed Site		
Systematic Error	5%	500#
Random Error	12%	1200#
4: Portable Site		
Systematic Error	5%	500#
Random Error	12%	1200#

2.2.1.2 Speeds Greater Than 40 mph

H.E.L.P System Type	Percent Difference	Absolute Difference
1: Automatic Port-of-Entry		
Systematic Error	4%	400#
Random Error	8%	800#
2: Fixed Site		
Systematic Error	5%	500#
Random Error	12%	1200#
4: Portable Site		
Systematic Error	5%	500#
Random Error	12%	1200#

2.2.2 Single Axle Weight

2.2.2.1 Speeds Greater Than 20 mph and Less Than 40 mph.

H.E.L.P System Type	Percent Difference	Absolute Difference
1: Automatic Port-of-Entry		
Systematic Error	4%	400#
Random Error	4%	400#
2: Fixed Site		
Systematic Error	5%	500#
Random Error	12%	1200#
4: Portable Site		
Systematic Error	5%	500#
Random Error	12%	1200#

2.2.2.2 Speeds Greater Than 40 mph.

H.E.L.P System Type	Percent Difference	Absolute Difference
1: Automatic Port-of-Entry		
Systematic Error	5%	500#
Random Error	10%	1000#
2: Fixed Site		
Systematic Error	5%	500#
Random Error	12%	1200#
4: Portable Site		
Systematic Error	5%	500#
Random Error	12%	1200#

2.2.3 Tandem Axle Weight

2.2.2.1 Speeds Greater Than 20 mph and Less Than 40 mph.

H.E.L.P System Type	Percent Difference	Absolute Difference
1: Automatic Port-of-Entry		
Systematic Error	4%	400#
Random Error	4%	400#
2: Fixed Site		
Systematic Error	5%	500#
Random Error	12%	1200#
4: Portable Site		
Systematic Error	5%	500#
Random Error	12%	1200#

2.2.2.2 Speeds Greater Than 40 mph.

H.E.L.P System Type	Percent Difference	Absolute Difference
1: Automatic Port-of-Entry		
Systematic Error	5%	500#
Random Error	10%	1000#
2: Fixed Site		
Systematic Error	5%	500#
Random Error	12%	1200#
4: Portable Site		
Systematic Error	5%	500#
Random Error	12%	1200#

2.3 Vehicle Classification Accuracy Requirements

2.3.1 FHWA Scheme F

The vehicle types defined in the Federal Highway Administration's Scheme F have been adopted for use in the H.E.L.P. program. These are as follows.

1. Motorcycles (Optional)
2. Passenger Cars
3. Other Two-Axle, Four-Tire Single Unit Vehicles
4. Buses
5. Two-Axle, Six-Tire, Single Unit Trucks
6. Three-Axle Single Unit Trucks
7. Four or More Axle Single Unit Trucks

8. Four or Less Axle Single Trailer Trucks
9. Five-Axle Single Trailer Trucks
10. Six or More Axle Single Trailer Trucks
11. Five or Less Axle Multi-Trailer Trucks
12. Six-Axle Multi-Trailer Trucks
13. Seven or More Axle Multi-Trailer Trucks.

2.3.2 Overall Vehicle Type Classification Accuracy

The WIM system must accurately classify at least 90% of all vehicles passing the test location during the test period.

2.3.3 Individual Vehicle Type Classification Accuracy

The WIM system must correctly classify at least 90% of each vehicle type that occurs at least 30 times during the test period.

2.4 Speed Measurement Accuracy Requirements

Speed measurements must be taken for all trucks selected for the initial calibration and acceptance test sample. In all cases, a systematic error of no more than 1 mph (absolute) or 2% (percentage) is required. A random error of no more than 2.5 mph or 5% is also required.

3.0 RELIABILITY REQUIREMENTS

3.1 Explanation of Reliability

Reliability is the ability of a system to perform its required function under stated conditions for a given period of time. The vendor of the WIM system must provide documentation for the following reliability measures. Minimum acceptable levels are shown.

	SENSOR	ELECTRONICS
Median Time Between Failures	1 year	2 years
Median Time Between Maintenance Actions	6 months	6 months
Median Time Between Corrective Actions	6 months	6 months
Percent Down Time	5%	5%
Median Time to Repair	15 days	15 days
Median Cost to Repair	---	---

3.2 Definitions of Reliability Measures

Median Time Between Failures (MTBF) is the median value of the length of time between consecutive failures and is usually calculated as the ratio of the cumulative observed time to the number of failures under stated conditions. MTBF is often used for situations in which the equipment is operated continuously until it fails. Median Time Between Actions (MTBMA) is similar to MTBF except that it includes preventive maintenance and periodic calibration as well as failures in its computation. Median Time Between Corrective Actions (MTBCA) assumes no maintenance or calibration is done, but the equipment may not be operated continuously. Percentage Down Time is that portion of the normally scheduled work time that the device is not available because it cannot function as intended. Median Time to Repair (MTTR) measures the average time required to complete a repair of a system from the hour of failure. Median Cost to Repair (MCTR) is the average cost of a repair to a system.

4.0 DURABILITY REQUIREMENTS

Durability is the characteristic of a system that indicates its resistance to "wearing out". In the context of WIM systems, it is the weight sensors in the road that are most critical in terms of durability. The WIM system vendor must provide documentation to be used to produce the following durability measures. Minimum acceptable values are shown.

Average Weight Sensor Life: 40,000 hours/1.5 million equivalent single axle loads (as calculated using procedures recommended by the American Association of State Highway and Transportation Officials).

Average Electronics Subsystem Life: 5 years.

5.0 LIFE CYCLE COST INFORMATION REQUIREMENTS

The vendor shall supply the following information that can be used to develop life cycle cost estimates.

1. Procurement Cost
2. Annual Maintenance Cost
3. Annual Operation Cost
4. Initial and Annual Cost of Necessary Spare Parts
5. Training Cost
6. Maintenance, Test, and Calibration Equipment Cost
7. Labor Support Cost

6.0 WIM SYSTEM OUTPUT FORMAT REQUIREMENTS

The data for each individual truck shall be saved such that the following minimum information is produced by the system.

1. Vehicle Sequence Number
2. Site Number
3. Lane
3. Time of Day
4. Date
5. Wheelbase (feet)
6. Speed (mph)
7. Weight Violations
8. Gross Vehicle Weight
9. Classification
10. Individual Axle Weights
11. Axle Spacings

7.0 WIM SYSTEM CAPACITY REQUIREMENTS

The system shall be able to store the data for up to 30,000 truck records. The data shall be protected from loss due to loss of power.