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PORT OF ENTRY WEIGH-IN-MOTION FEASIBILITY STUDY

Final Report

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16. Abstract

This research effort analyzes the feasibility of using slow speed Weigh-in-Motion (SWIM) equipment for enforcement applications in Arizona. The technical performance of one SWIM System was assessed at the Ehrenberg Port of Entry on the Arizona/California state line.

The effects of variation in platform smoothness and profile on scale accuracy were assessed. Legal and institutional issues were also addressed and recommendations for implementation and further research were presented.

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TABLE OF CONTENTS

6. RECOMMENDATIONS

1. Introduction

1.1 INTRODUCTION

This final report describes work undertaken by Castle Rock Consultants (CRC), to study the feasibility of using slow-speed weigh-in-motion (SWIM) equipment for enforcement applications. The work was carried out for Arizona Department of Transportation (ADOT) and Arizona Transportation Research Center (ATRC). In the project, the technical performance of one particular SWIM system was assessed at the Ehrenberg Port of Entry on the Arizona/California state line. Legal and institutional issues were also addressed and these are outlined in the report. Recommendations on implementation and further work have been developed and are presented at the end of the report.

At present, enforcement scales in the United States are almost invariably static. Typically, vehicles stop with each axle on the scale, pulling forward several times to complete a weighing operation. Each time the vehicle is moved, redistribution of its load takes place within the suspension system, reducing the accuracy of the final result. Although the scales themselves may be highly accurate, their method of utilization introduces errors such that a margin has to be allowed before any citation is issued.

An alternative approach provides very long, segmental scales, with segment lengths matched to the axle spacings of typical trucking rigs. Installations of this type may cost up to $1 million per site, including hardware and installation. Maintenance and calibration costs are significant, while segmental configurations may rapidly be superseded by changing truck dimensions.

Some European countries, particularly the United Kingdom, adopt a different approach to enforcement weighing. Vehicles pass over a high accuracy, slow-speed WIM scale at a constant, minimum speed in bottom gear, allowing an increase in throughput of vehicles of around three times relative to static installations. With appropriate equipment and smooth approach aprons, accuracies similar to that of static weighing can be achieved.

Although an effective system of truck weighing based on high accuracy SWIM equipment is already known to be technically feasible, recommendations on a preferred technical system's specification must be accompanied by consideration of what new laws, if any, would be required for the implementation of the new technologies.

This feasibility study was therefore initiated to particularly examine the US legal and institutional position with regard to the adoption of SWIM equipment for enforcement weighing. Detailed testing of a SWIM system, supplied by CMI Dynamics Inc, was undertaken at the Ehrenberg Port of Entry on I-10. This was carried out to provide the necessary data to verify the accuracy and consistency of SWIM systems under representative US operating conditions.

1.2 PROBLEM STATEMENT

Substantial sums of money are invested in the construction and maintenance of highway infrastructures. Overloaded vehicles contribute significantly to the deterioration of highway pavements, and it is consequently necessary to protect this investment by enforcement of vehicle weight limit laws, to ensure pavement and bridge structures do not fail prematurely. Most jurisdictions provide protection against severe pavement deterioration by enacting legislation which limits permissible axle loads. The enforcement of these axle weight limits does however cause problems of its own.

Research completed in 1960 by the American Association of State Highway Officials (AASHO, now AASHTO) on the effect of vehicle loading on different pavement designs, showed that axle loads could be expressed as equivalent factors based on a defined standard axle. This allows mixed traffic to be represented in the form of equivalent axle loads. Each passage of any given load can be considered as causing the same reduction in the durability of a pavement as an equivalent number of passages of a standard axle load.

The effect of this relationship is that damage caused to the pavement varies with some power of the axle load. As the axle load increases, the equivalent number of standard axles grows rapidly, so that vehicles exceeding the weight limits cause a disproportionate amount of damage. This is one of the main reasons for enforcing weight limit laws, to help ensure that the pavements are only subjected to the loadings for which they have been designed.

Since the time of the AASHO Road Test, it has become accepted that the distribution of axle loads applied to the road pavement is a primary cause of surface deterioration and loss of serviceability. Essentially, pavement damage is proportional to some power of the magnitude of the axle load, and the number of axles passes over the pavement surface. Vehicle weight limit laws are therefore a necessary device for reducing this damaging effect of heavy trucks.

Safety is another aspect which warrants the implementation of a truck weight enforcement program as overloaded vehicles are less maneuverable and can cause a hazard to other road users. Extreme cases of overloading can result in axle and brake failures, or even cargo falling from trucks and creating a danger to following vehicles.

The heavy vehicle electronic license plate program (HELP) is a multi-state research and development effort which addresses many broader issues relating to this project. HELP is investigating the potential benefits of combining automatic vehicle identification (AVI) technology with weigh-in-motion (WIM) and automatic vehicle classification (AVC). Arizona played a key role in instigating the HELP program and has taken the lead throughout its research and development phases.

From the trucking industry's stance, an enforcement program can be of considerable benefit, as those vehicles which operate within the legal limits will not be subjected to unfair competition from carriers who overload their vehicles. Savings can also be made in running costs if the vehicle's engine operates within its normal power output range.

Having identified the need for truck weight law enforcement, there remains the problem of ensuring that legislation is enforced, as efficiently as possible. Economic viability is established when the savings that are realized by improving safety, reducing pavement deterioration and enhancing service life are sufficient to offset the additional hauling and administrative costs which result from enforcement of the law.

Any reduction in the cost of law enforcement, either to the state or to vehicle operators, will help to maximize the benefits that accrue from the legislation. The port of entry (POE) plays an important role in enforcement of state weight legislation, particularly in Arizona. PoEs can however be costly to operate and can cause long delays to truckers waiting in line to be checked at the static weigh scale. During peak periods there is the very real danger of trucks backing up onto the freeway, causing hazards to other road users. Automation of the port of entry could show real benefits, cutting costs to the State and industry alike.

1.3 OBJECTIVES

This feasibility study addresses both technical issues and legal considerations relating to high accuracy in-motion weighing for screening and enforcement. Its overall aim is one of achieving automated operation of ports of entry, the benefits of which could be substantial.

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

1. To evaluate the feasibility of slow speed weigh-in-motion devices for the enforcement of truck weight and bridge formulas.

2. To identify which state and federal standards are applicable and whether new laws will be required to allow weigh-in-motion to be used in preference to static weigh scales.

3. To plan and coordinate a state testing program for the accuracy evaluation of SWIM equipment at the Ehrenberg Port of Entry, including the analysis of data and the development of recommendations.

4. To consider an implementation program and make recommendations on the nature and direction of future work.

5. To prepare a final report, detailing the technical, legal and institutional appraisals and summarizing recommendations on the use of the system for truck weight enforcement in Arizona.

The system resulting from this project could have far-reaching effects on the cost and scale of weight limit enforcement. The use of slow-speed weigh-in-motion offers many benefits over the conventional means of static weighing. Some of these are:

- Automated weighing offers improved weigh station efficiency, potentially benefitting both the state and the trucking industry;
- Truck throughput may be greatly increased;
- Waiting lines and back-ups can be reduced or eliminated, thereby improving both safety and economy;
- Manpower requirements are potentially reduced;
- Trucking industry relationships with states may be improved through more efficient operation of PoEs;
- SWIM equipment promises to be cost effective to install and operate;
- Monitoring and control of oversize and overweight vehicles may be significantly improved;
- Load/frequency data could become more reliable, through widespread use of WIM consistent with the objectives of the HELP program; and
- Long term forecasts of trends in truck characteristics such as size, weight and axle configuration can be based on more reliable information.

1.4 STUDY APPROACH

In order to achieve the various objectives of the project, a series of tasks was undertaken. These tasks are summarized in this section and expanded in later chapters of this report.

Task A - Consultations with MVD

Task A, described in the remaining section of Chapter 1, involved consultations with enforcement and highway agencies, particularly Arizona Motor Vehicle Division representatives, to assess the extent of the truck overweight problem and Arizona's current truck weighing policies at ports of entry and elsewhere. The consultations explored the requirements of the enforcement agencies, together with possible solutions based on the technology available and existing regulatory and legislative frameworks within Arizona. Previous studies of the topic, particularly the operating experience and detailed appraisals of the UK Department of Transport and its research laboratory, TRRL, were reviewed during the task.

Task B - Technical Review

Within Task B, a literature and product search was conducted, including a review of current and new devices or approaches to WIM and automatic vehicle classification (AVC). The assessment of specific systems, devices and components involved consideration of their accuracy, cost, reliability and other merits. Alternative approaches were selected that are technically sound and cost effective, considering the feasibility of using such systems for overweight screening and enforcement weighing, including bridge formula compliance analysis. The review is presented in Chapter 2 of this report.

Task C - Legal Review

Utilizing an Arizona licensed attorney, relevant US and overseas statutes were researched covering the enforcement of truck size and weight limits and bridge formulas. This included existing Arizona and federal laws and National Bureau of Standards' requirements relating to static and dynamic weighing. Chapter 3 also considered the needs of management and administration at state and federal levels, as well as the needs of commercial confidence and security against crime.

Task D - System Evaluation

Within Task D, a test program was developed to evaluate the accuracy of the slow-speed weigh-in-motion installed at the Ehrenberg Port of Entry. The test program, presented in Chapter 4, compared the performance of the SWIM equipment to that of the existing static scale system.

CRC coordinated and monitored state efforts in obtaining comparative data on weighing system performance. The study team also undertook full statistical analysis of the data. The data were used to develop recommendations as to whether the SWIM equipment should be used for truck weight enforcement, taking into account the cost-effectiveness of the system and its institutional/legal acceptability. Full results and analyses of data are presented in Chapter 5.

Task E - Recommendations

Based on the findings of the previous tasks, recommendations were developed on the accuracy, applicability and cost-effectiveness of the slow speed WIM system. These considered whether the system can be legally used by the State of Arizona for enforcement weighing, and how the technology could be implemented by examining a number of different strategies. The recommendations are presented in the final chapter of this report.

1.5 CONSULTATIONS

This final section of the first chapter outlines consultations which were held with enforcement and highway agencies to assess the extent of the truck overweight problem and the context of current truck weighing policies. The major consultations, held with the Motor Vehicle and Transportation Planning divisions of the Arizona Department of Transportation, were important in familiarizing the CRC team with the specific requirements of Arizona's enforcement program and the constraints on strategies which can be adopted. This information, supplemented by the team's knowledge of the operational characteristics of alternative weighing systems, formed the basis of the testing and evaluation program undertaken at the Ehrenberg Port of Entry.

The outcome of discussions with Arizona agencies responsible for weight enforcement operations is contained in the subsection below. The next subsection covers broader consultations with highway agencies who may also potentially benefit from the introduction of SWIM equipment. The final subsection of the chapter provides information obtained from UK agencies, who have been successfully utilizing SWIM systems for enforcement for many years.

Enforcement Agencies

Detailed consultations were held with State of Arizona personnel responsible for truck weight enforcement, to determine the overall aims and detailed objectives of using weigh-in-motion techniques at automated ports of entry and elsewhere. These concentrated on the potential contribution of high precision weigh-in-motion techniques in the enforcement of vehicle and axle load limits, and in monitoring the enforcement of these limits. State policies on the issue of oversize and overweight vehicle permits were considered, as was the frequency of issuance and cost of operation.

Arizona currently spends several million dollars each year on maintaining and operating its ports of entry. While these facilities are very necessary, this is a high price to pay. What is more, this price conceals the still higher costs incurred through delays and inconvenience to the trucking industry.

The general view of the agencies was that the current methods of weight limit enforcement are slow and expensive. Potentially, they may therefore be less cost effective than more recently developed alternates. The static scales used to weigh the vehicles are very expensive to purchase and install; moreover, through high maintenance costs they have shown themselves not to be particularly durable. Individual axle loads are rarely considered, citations often being based on gross vehicle weights alone. Consequently bridge formula violations are not usually checked.

Slow speed weigh-in-motion technologies backed by the necessary legal statues and regulations were felt to offer a potentially cost-effective solution to the enforcement of vehicle weight limits. Automated ports of entry using weigh-in-motion and automatic vehicle classification technology could reduce dollar costs to the state and cut delays to most carriers. There is a perceived need for SWIM equipment in a form and configuration responsive to the needs of PoE operation, from which citations can be issued which would withstand challenges within courts of law. In the longer term, automatic vehicle identification could further increase the efficiency of essential border checking procedures. This application is currently being considered within the framework of the Heavy Vehicle Electronic License Plate (HELP) program.

Highway Agencies

In addition to the consultations with enforcement agency representatives, agencies were also asked to consider the potential of providing data from the enforcement program for other purposes. Those responsible for transportation planning or vehicle taxation may benefit from better vehicle weight data and it could prove cost-effective to incorporate certain features into the enforcement strategy to meet their particular needs. For example, the heavy vehicle electronic license (HELP) system would have the capability of gathering data for many different agencies, or end users, including truck weight enforcement personnel. To assess the significance of WIM to users other than the enforcement agencies, discussions were held with the Transportation Planning Division of Arizona DOT.

As well as providing better truck data for enforcement, it is likely that an improved truck weighing system with WIM and AVC technologies would create some further positive spin-offs. One benefit could be continuous classified traffic count data for trucks, providing a basis for traffic forecasting and appraisal by vehicle category on a statistically valid basis. These advantages may prove to be considerable in their own right. It is likely that the use of weigh-in-motion techniques in conjunction with AVI could also greatly simplify the operation and monitoring of the oversize/overweight permit system, with consequent savings to the State and to the trucking industry.

Factors which will influence the types of strategy used would be the level of sophistication of the technology selected, the budgets available for both installation and operation, the number and distribution of sites, and the operational techniques employed. These factors must be set against the objectives of the truck weight enforcement program, the resources available and the extent of the overweight problem. Unfortunately, accurate determination of the extent of the overweight problem is difficult to achieve given current opinions on the extent of successful evasion.

UK Experience

As a final part of this task, consultations were also held with officials involved in truck weight enforcement using SWIM in the United Kingdom. SWIM equipment was first installed in the UK in 1974 at cross channel ports and brought into enforcement use in 1978 when legislation was enacted. Since that time it has been the preferred method of enforcement and 72 SWIM systems are in operation in the United Kingdom. The SWIM systems are used by enforcement officers to ensure both the gross weights and axle weights of trucks are within legal limits.

Codes of practice have been prepared covering all aspects of enforcement using SWIM scales including weighing procedures, scale verification and construction. Trucks are weighed only once provided they satisfy the speed requirements of the code. Difficult legal problems arise if trucks are re-weighed because the reweighing of the vehicle would normally give a different result, due to the dynamic effects of tires, suspension and pavement surface. English law cannot cope with statistical evidence such as averaging of differing results.

The UK legislation, however, does take account of the fact that an axle weight is not traceable to National Standards, although gross weights are. Axle loads within a vehicle configuration can and do change due to weight distribution shifts caused by starting/stopping and braking. This has also been noted by The Standards and Tolerances Committee of the National Conference on Weights and Measures. Because of the effect, an operating instrument tolerance of ± 330 lbs (150 kg) per axle is allowed in the UK, with a six-month verification tolerance of ± 220 lbs (100 kgs).

Verbal warnings are issued if weight limits are exceeded by only a small amount (around 5%); above this, limit citations are issued. Shifted goods is not a valid defence and a trucker found to be overweight may only challenge the validity of the weighing equipment and the procedure adopted. This consequently means that the construction of the scales is particularly important and that the scale is verified at six month intervals.

The scale verification procedure involves three test vehicles with differing axle configurations and loads. Nine runs are made with each test vehicle crossing the scale. For each vehicle, the sum of the recorded axle weights has to agree with the total vehicle weight, established via an independent single-draft weighscale, to within a tolerance of ± 220 lbs (100 kg) per axle multiplied by the number of axles of the vehicle.

The construction requirements for SWIM installations are particularly stringent. The platform has to be set into a length of precision-laid concrete. This concrete has to be constructed to be flat and level to within a tolerance of ± 3mm (1/8") for a distance of 8 m (24 feet) either side of the platform. Operating experience in the UK, where vehicles are required to cross the scale at a constant speed not exceeding 2.5 mph, suggests that these standards are essential for weights which will stand up in a court of law.

The extensive experience gained from utilizing SWIM systems on a regular basis in the United Kingdom indicates that the technical performance of these systems is sufficient for enforcement weighing, given the UK legislation.

2. Technical review

2.1 INTRODUCTION

Within this task, CRC undertook literature and product searches relating to high accuracy, slow speed weigh-in-motion for overweight screening and enforcement weighing to confirm the system best suited to the requirements of this study.

Several systems for weighing vehicles in motion are currently obtainable from manufacturers in the USA and Europe. In determining the available WIM technologies, the research team investigated a wide range of equipment and techniques. In addition to investigations into the performance of current commercially available, proven systems, the study team also considered the status of ongoing research into the development of low-cost, permanent weigh-in-motion systems and evaluated the potential of these relatively new devices for use in meeting the objectives of this study. A brief summary of the options identified is outlined in the section below. Details of the preferred system are presented in the subsequent section.

2.2 ALTERNATIVE TECHNOLOGIES

The technologies available for permanent weigh-in-motion sites can be divided into six main headings. These are:

1. Bending plate systems;
2. Strain gauge load cells;
3. Hydraulic load cells;
4. Bridge systems;
5. Piezo systems; and
6. Capacitive systems.

An outline of the various technologies is given in the following paragraphs, together with examples of manufacturers who supply systems using the technology in question.

Bending Plate Systems

With this sensor technology, a high-strength steel plate with strain gauges bonded to the underside is used to determine the axle loads. The strain induced in the plate as an axle crosses is proportional to the axle load.

A system utilizing this approach is marketed by PAT Corporation in the United States. Originally developed by the Deutsche Bundesanstalt (BAST), the system comprises two plates 4ft or 6ft by feed 8 inches by 5/8 inch thick, supported along the longer edges. Strain gauges are located on the underside of the plate in two milled slots. A lightweight frame supports the two plates so that both wheel tracks are covered.

The system is fully automatic and can be powered from batteries. A minimum system for two lanes of axle weight monitoring costs about $25,000 with more complex versions working out at up to $250,000 per site. Portable versions of the equipment are also available at lower cost.

Strain Gauge Load Cells

Several firms offer WIM systems that use bearing plates resting on strain-gauged load cells. One of the most widely used for slow-speed operation is the Weighwrite ADS-4 system, manufactured and marketed in the United States by CMI Dynamics, Inc. The system is used in several countries, particularly the United Kingdom, for enforcement operations.

It consists of a steel platform, 10ft by 2ft 6 inches, in a pit 9 inches deep. The plate is supported on electrical resistance strain gauge load cells at each corner, standing on a foundation frame. Vehicles pass over the platform at a constant speed not exceeding 2.5 mph. High accuracies (± 100 lbs) can be obtained from this system, providing a smooth concrete platform is constructed adjacent to the scale.

Another strain gauge load cell system is sold by the Radian Corporation and consists of a relatively shallow, light weight sensor assembly that is installed in a steel frame, permanently placed in the road surface. The weighing surface of each sensor assembly is 4ft 6 inches wide by 1ft 8 inches in the direction of travel and is segmented into six triangular loadplates. One of these sensor assemblies is normally placed in each wheel path.

Streeter Richardson also markets a system that is based on bearing plates with load cells. The 5150 system uses one rectangular bearing platform for each sensor assembly. Load cells are located at each corner and at the center of each lateral edge of the 12 ft wide transducer. Several versions are available, SS, SE and XT, each of which can be operated at a different speed range.

Hydraulic Load Cells

CMI Dynamics markets a WIM system which uses hydraulic load cell technology. It is the most massive on the U.S. market and was originally developed by the University of Saskatchewan. The weight sensor consists of a single oil-fitted piston which acts as a load cell. The trucks cross a single steel platform, 5ft 4 inches wide by 21 inches long by 9 inches deep, and the load is transmitted to the load cell by lever arms. The system cost is understood to be around $150,000.

Bridge Systems

In the Bridge System, the active weight sensing device is a strain transducer which is clamped or permanently fixed to the longitudinal support beams of a highway bridge. Temporary or permanent axle sensors are placed on the pavement surface of the approach to the bridge to assist in the classification of vehicle types and to acquire speed data. Reasonable accuracies have been achieved for gross vehicle weights, although individual axle weight accuracies are significantly less accurate. A commercial bridge weighing system is available in the US from Bridge Weighing Systems, Inc. The nature of this technology is such that is unsuitable for enforcement applications.

Piezo Systems

Piezo-electric transducers operate by the generation of charge when subjected to stress. They have been quite widely used for permanent axle detection and now offer the possibility of low-cost WIM detection. Accuracy levels for commercially available systems, though suitable for screening purposes, are below the level required for the enforcement of weight limits. Several piezo systems are now available from manufacturers such as GK Instruments, Streeter Richardson and CMI (Weighwrite) at costs varying between $6,000 - $25,000. Because the piezo effect is dynamic, the technology can not effectively be used for static or slow-speed weighing.

Capacitive Weighmats

Portable capacitive weighmat systems are now offered by Streeter Richardson, Golden River Corporation, and PAT. The weight sensor used by each of these vendors is a capacitive weighmat, 6 ft wide by 20 inches long by 3/8 inches thick. It consists of three sheets of steel maintained in approximately parallel position by a rubber dielectric. The instrumentation treats the weighmat as a variable three-plate capacitor within a tuned circuit. Compression of the sensor by a wheel load causes a change in the oscillation frequency of the tuned circuit. This frequency shift is interpreted by microprocessor-based circuitry in the WIM electronics. Again, this technology is not suited to static or slow-speed applications because of creep in the rubber dielectric.

2.3 PREFERRED SYSTEM

Following the literature and product search of weigh-in-motion systems, the study team identified the Weighwrite ADS-4 system as the most promising for meeting the project objectives. This selection was based on knowledge of the performance and capabilities of currently available systems, and on the findings of other researchers, notably those of the UK Transport and Road Research Laboratory. The system is unique in that it is already certified for SWIM enforcement in several countries overseas, subject to certain standards. A limited amount of experience has been obtained with this system in US, through one installation in Michigan and another in North Carolina.

The scale and attendant electronics were developed in 1970 by Weighwrite Ltd in the UK. The current electronics system is the fourth generation and uses more modern components and techniques. It is used by the UK Department of Transport for enforcement, and also commonly used in truck terminals. Upward of 500 units have been produced and are in service in many parts of the world.

The scale and associated electronics are designed for both portable use and permanent installation. The scale is 10 feet wide by 2 1/2 feet in the travel direction. Capacity is 30,000 lbs per axle with an overload range up to 44,000 lbs.

As with all weigh-in-motion systems, the accuracy of the system is dependent on the smoothness of the approach to the scale. Experience in the UK has indicated that the approach and exit ramps to this system must be flat and level within 1/8 inch. Periodic verification is necessary to ensure this high tolerance is maintained. A shallow, well drained pit is required, measuring 10 ft by 2 ft 6 inches by 9.5 inches deep.

As the vehicle approaches the scale, the operator initiates the weighing session by pushing a button on the instrument console. Several things then happen simultaneously.

1. The system prints the time, date and then the ticket heading.

2. It identifies and prints a sequential ticket number. This can be reset on a shift basis or any other selected time base.

3. While this is taking place, the system automatically performs a self diagnostic check of zero and calibration parameters. It then prints these parameters. If

for any reason the parameters are incorrect, the system will print a warning message to the operator.

As the vehicle progresses across the scale, each individual axle weight is printed automatically.

Once the last axle of the vehicle has crossed the scale, the operator terminates the weighing session by depressing the "totalize" pushbutton, the gross vehicle weight is printed. If the operator does not terminate the session in this manner, the system will automatically terminate and print total weight after a 30 second time delay.

Constancy of speed is important as the vehicle passes over the scale. Braking or accelerating while the wheels are on the platform can cause errors to occur. An operational speed of 2.5 mph has been chosen, this being average low gear idle speed for most heavy vehicles. Should the vehicle or any axle cross the platform too quickly, the weight ticket is invalidated and the operator informed.

Several additional programs are available which provide increased automation and, in some cases, record keeping capabilities. One such program automatically totalizes and prints tandem axle weights in addition to the individual axle weights. A second program, enforcement mode, allows the operator to initiate the weighing session by entering the vehicle classification by keyboard selection. Individual axle and group weights are recorded as the vehicle crosses the scale and gross weight is automatically totalized and printed once the last axle has been weighed. This program also has the capability to summarize the weighing operation on a shift basis or on demand.

Custom programs are also available, and these can be designed to meet specific or unusual needs. Other optional items include a scoreboard indicator which can be used in conjunction with the standard LCD display. This is mounted such that it is visible to the driver. A changeable message sign can also be used to assist the operator in traffic control. Instructional messages include:

STOP
FORWARD
BACK UP
PARK
LEAVE

Messages can be operator controlled by pushbutton. It is also possible to activate any existing traffic signals and use directional arrows.

Having confirmed the use of the Weighwrite ADS-4, it was agreed that this system be installed at the Ehrenberg Port of Entry on I-10, on the Arizona/California state line. The system was installed adjacent to a static, three-plate platform to enable a detailed assessment of its operating performance to be determined.

3. Legal review

3.1 INTRODUCTION

The legal aspects of using slow-speed weigh-in-motion for citation purposes have been considered in detail so that recommendations can be made concerning revisions that may be necessary in government rules, regulations or statutes, in order to issue citations which will withstand court challenge. The existing statutes of law and regulation in the State of Arizona and applicable within the State as a result of federal mandate have been reviewed, together with the laws and regulations governing the use of SWIM scales for enforcement purposes in the United Kingdom. This review has been undertaken by Bob Schlosser, an Arizona licensed attorney, under subcontract to Castle Rock Consultants.

3.2 REVIEW OF EXISTING STATUTES

The first source of inquiry was Title 28 of the Arizona Revised Statutes. This Title allows the government, per statute, to impose sanctions upon those who violate weight limitations on the highway. The statutes, which have been successfully used with existing scales for the past several years, contain next to no detail concerning the accuracy of the scale, nor are there any legislative mandates in this Title that even describe the nature of the scale, the scale's certification, or presumptions of scale accuracy. Title 28, in summary, states that it is a violation for a vehicle, that has not been issued any form of special permit, to exceed the specified weight limitations set out in Title 28.

In two sections of Title 28 (A.R.S. Section 28-1010(A) and A.R.S. Section 28-1031(I)) reference is made to a "stationary scale". This term "stationary" as used in these statutes suggest that the statutes are referring to scales that are at a set location as opposed to portable, rather than scales that weigh an object that is stationary as opposed to being in motion.

Title 41 of the Arizona Revised Statutes as it pertains to weights and measures in the State of Arizona was also reviewed. Although there are a variety of references in the weights and measures portion of the Arizona State Code to scales utilized by governments for the enforcement of weight limitations on public highways, there is nothing specific in Arizona's weights and measures statutes concerning either the type or certification of scales utilized for weight enforcement violation on the public highways.

A.R.S. Section 41-2064 adopts the standards of the Federal Handbook 44 for specifications, tolerances, and other technical requirements for commercial weighing and measuring devices. Technically, the government scales utilized to weigh overweight vehicles for enforcement purposes do not fall within the definition of "commercial weighing and measuring devices" as found in Title 41. Notwithstanding, by history and custom, in the State of Arizona scales utilized in weight enforcement on public highways are certified periodically by the Arizona Department of Weights and Measures. The portable overweight scales at the port of entry locations are certified without any express schedule of frequency. Generally certification is made whenever state certifying people are in the geographical area certifying other scales. If possible, these scales are certified at least once a year.

In reviewing the State of Arizona's administrative rules and regulations, it was found that Handbook 44 is also adopted as the source document to guide Arizona Department of Weights and Measures in the certification of scales. But once again, the scales described are arguably limited to what is termed "commercial weighing", which per statutory definition seems not to be applicable to government scales utilized for overweight enforcement. It is interesting to note that in these rules and regulations (R4-31-104) there is a general reference allowing the Division of Weights and Measures of the Arizona State Government to enter into agreements to inspect the weighing and measuring instruments of federal, state and local government agencies that are utilized by those agencies in the enforcement of any statutory provisions.

Also, by express provision (R4-31-207), these same rules and regulations dealing with the installation of vehicle scales and the specifications required allow a deviation from Handbook 44.

Other than Handbook 44 the only other source of federal material of any significance is found in the Code of Federal Regulations, parts 657 and 658 dealing with the certification of size and weight enforcement.

It is interesting to note that section 657 makes reference to the state's participation in weight enforcement on highways within the Federal Highway System, and authorizes a variety of procedures for weighing vehicles. Included therein are references to weigh in motion equipment. It appears that this particular regulation would not need to be amended for the use of SWIM scales.

U.S. Federal Statutes that have any application to this review are found in Title 23 of the United States Code, at sections 127 and 307. Section 127 basically states that a state which does not impose certain specified weight limitations shall not receive certain federal funds. Section 307 authorizes the Federal Secretary charged with the administration of Title 23 to engage in research on a variety of subjects dealing with the highways and their use, to include weight enforcement.

The last source material meriting discussion is National Bureau of Standards Handbook 44. Although there is not a clear legal requirement that makes Handbook 44 applicable to the utilization by the State of Arizona of its scales for weight enforcement, per custom it does appear to be the existing "bible" on which all parties rely. Although this publication is amended periodically it appears that at the current time the utilization of weigh-in-motion scales for vehicle weighing is not officially a part of Handbook 44. Officially adopted standards in Handbook 44 deal with the utilization of vehicle scales and their method of use and the tolerances permitted in order for them to be considered in good working order for the purposes of certification.

In reviewing the specifications given in Handbook 44 certain items are of particular interest:

a. It does appear that for the purposes of "monorail scales" there is a specific reference to weighing-in-motion scales suggesting that weighing-in-motion scales for monorails have been officially sanctioned by the National Handbook 44.

b. There are also specifications concerning the approaches to vehicle scales and this regulation should be carefully reviewed by state engineering personnel as it pertains to the installation of the SWIM scale units.

One other point that is of significance is that there is a report from the National Bureau of Standards concerning potential revisions of Handbook 44. Contained in that report is the finding of the Handbook 44 Committee that there appears to be many benefits to be achieved by the use of weigh-in-motion scales for vehicle overweight enforcement. The Committee is reluctant at the time of its most recent report to officially adopt SWIM standards for National Handbook 44 until provided with appropriate data and research. These data would need to satisfy the Committee that they have sufficient and appropriate materials to determine that weigh-in-motion scales are, in fact, reliable, so that they would have the ability through the data to enact appropriate certifications that they would feel comfortable with.

3.3 SWIM ENFORCEMENT IN THE UNITED KINGDOM

In the United Kingdom, SWIM scales are routinely utilized by the enforcement agencies to issues citations for axle loads and gross vehicle weights which exceed the mandated limits. Since the introduction of the scales in 1976, the UK Department of Transport has been very successful in withstanding legal challenge to their usage.

A review of the UK Road Traffic Act and the Department of Transport Code of Practice for Dynamic Axle Weighers indicates detailed certification procedures must be followed in order for SWIM to be used for enforcement. These procedures cover the installation of the system, the calibration and certification requirements and the operating procedures to be followed. Routine verification of the system at six month intervals is essential.

3.4 OPERATION OF WEIGH-IN-MOTION SCALES

One area which merits discussion and about which there appears to be no guidelines within the US is the actual operation of the scale to be installed. At the current time there does not appear to be any specific checklist in printed form that is utilized by the operator of the scale who is designated with the responsibility to actually weigh the vehicle and then if appropriate issue the citation. For illustration, a police officer who is administering a blood alcohol test to a suspected driving under the influence vehicle operator has a specific checklist that he or she goes through in the actual administration of the test by the utilization of the machine. The certification of the accuracy of the machine is usually left to a police chemist, but the officer administering the test must follow the checklist (which is, in fact, in printed direction form) for the actual administration of the test.

3.5 SUMMARY OF FINDINGS AND RECOMMENDATIONS

An enterprising defense attorney could convince a judicial officer in a traffic proceeding that the use of the term "stationary" is limiting the type of scale to one which weighs objects that are not in motion. For that reason, it is suggested that A.R.S. Sections 28-1010(A) and 28-1031(I) be amended to clarify that the use of the word "stationary" means a scale at a set location and does not preclude enforcement people from using a weigh-in-motion scale for the enforcement of overweight violations.

There appears to be no specific statue or regulation within the State of Arizona which necessarily prescribes the requirement, frequency of, or procedure for the certification of scales which are utilized by enforcement people in weighing vehicles for the purposes of enforcing overweight statutes. The existing procedures appear to be solely by custom. Recommendations in this category are optional. It could be stated that "if it ain't broke don't fix it".

Alternatively, if by adoption of other regulations or rules the State becomes specific in other areas concerning the installation and/or certification of SWIM scales or their operation, this issue should also be addressed either through legislative amendment or through utilizing appropriate, legislative authority to enact rules and regulations. Legislative authority to allow the Division of Weights and Measures to enact administrative regulations covering these issues would be more appropriate, for in the event of technical advancement, revising of regulations is a far simpler procedure than getting a bill through the legislature. Legislation which clearly gives the Division of Weights and Measures authority to enact regulations in this area is suggested. Furthermore, the Division of Weights and Measures should also be given the authority to deviate from the Handbook 44, presuming that a deviation from Handbook 44 in this fashion would not cause the state to be considered in violation of any Federal law nor would it subject the State of Arizona to the loss of any Federal revenue.

Arizona Administrative Regulation 4-31-207 causes concern. Currently, regulation R4-31-207 per its express language, allows the state to deviate from Handbook 44, and as a general legal principle administrative regulations cannot go beyond or be contrary to statutory authority. The concern is that Arizona's weights and measures statutes, generally speaking, adopt Handbook 44. If it were construed that statutory authority made Handbook 44 applicable to State Enforcement Scales, then this regulation should be considered void.

In the definition of commercial weighing devices, state vehicle scales for enforcement purposes do not seem to be included. Notwithstanding, by custom the weights and measures department has relied on Handbook 44. Consequently, there is some real confusion as to whether or not Handbook 44 is appropriate to this area, per statute, and it is suggested that the statutes be revised to expressly deal with this issue. Either Handbook 44 should be made applicable, or make Handbook 44 applicable if the Division of Weights of Measures feels it is appropriate but allow the Division of Weights and Measures to deviate therefrom expressly by statute. Another problem with this regulation is that if it does not specify standards which are applicable in the actual construction of SWIM scale units, then it most certainly must be revised so that the units are not in violation of state regulation. It is recommended that this regulation be deleted or suitably amended or specific statutory authority should be enacted which allows the state by regulation to deviate from Handbook 44.

Handbook 44 also has a section dealing with the approaches to vehicle scales. These handbook standards appear to have been prepared without reference to SWIM units. Notwithstanding, these specifications should be clearly reviewed by state engineering personnel for the purposes of determining whether or not they are compatible with R4-31-207 and whether or not they are compatible with the proposed construction of the SWIM scales. If not, to the extent that Handbook 44 is legally binding, or by custom and usage is binding upon state enforcement authorities, this regulation must either be amended, or additional regulations must be enacted that apply specifically to SWIM units to allow the State to construct SWIM units to the correct specification.

Research has not disclosed any specific written procedures for the operation of vehicle weigh scales in the form of a checklist to be utilized by an enforcement officer when weighing vehicles for the purposes of issuing overweight citations. An operator's checklist does not however appear to be relevant in this case. There are only two ways that the scale can malfunction. One is if the driver drives the vehicle across the scale too fast. If so, this will be indicated on the scale, so that the weight will not be utilized and the vehicle will have to be driven across the scale again. The other method of malfunction by the operator would be if the driver did not operate the vehicle such that all of the wheels of the vehicle crossed the scale. Any malfunction in that regard would work to the driver's benefit as opposed to the enforcement authorities and should therefore be of no concern if citations are to be issued.

There are no regulations on the proper method of certifying a SWIM scale unit that are applicable in this case. It is suggested that operational procedures be adopted, be it either through Handbook 44 coupled with a proper tie-in to the application of Handbook 44 standards for certification to these scales, or by the legislature creating an exception to the application of Handbook 44 to these scales and at the same time expressly giving the Division of Weights and Measures authority to adopt their own rules and regulations for the purposes of certification of these scales. As we enter a new area of weighing which is not commonly accepted as the current area is, defense attorneys will once again be creative in attempting to challenge not only the accuracy or the ability of the operator to operate the scale but challenge the lack of any official sanctioning as to how the scale was certified, notwithstanding the reading procured by the operator or the operator's ability to follow standard procedures.

There are several questions that may be asked regarding the utilization of SWIM scales for enforcement purposes, the answers to which serve to summarize the findings of this legal review.

- Firstly, if nothing was done to alter the statutes and regulations, could the state issue valid tickets under the current existing statutes and regulations with the SWIM scales?

It is not absolutely necessary to amend either statues or regulations for the use of SWIM scales for enforcement purposes. One possible exception would be the Arizona Administrative Rule and Regulation R4-31-207(D) concerning the installation of scales. There is no reference to either the type of scale necessary, or any requirements for certification found in Title 28 of the Arizona Revised Statutes. Also, Title 28 makes reference to "public" scale and "weighmaster". These are scales that would require certification pursuant to Title 41 of the Arizona Revised Statutes. However, an enforcement officer's utilization of the "public" scale or "weighmaster" is discretionary, and if an enforcement officer doesn't have to use them, then this does not present an insurmountable problem. Also, these two statutes in making references to the alternative uses of "public" scale and public "weighmaster" deal primarily with enforcement people who make their initial check of weights with a portable scale.

Title 41 of the Arizona Revised Statutes adopts Handbook 44. A.R.S. Section 41-2064(8) exempts government scales from licensing. If it is assumed that no licensing is required and there is no independent requirement for certification, it is safe to assume no certification is required. Also, lack of "licensing" presumes that there is no mandatory duty to certify or inspect without any express authority to the contrary, and there is none.

Arizona Regulations R4-31-104 allows the weights and measures division to inspect the weighing devices of the state, but does not require and/or establish any particular standards. Once again, it is a discretionary provision with no mandatory duty imposed. This same regulation also applies Handbook 44 to "commercial weighing devices", but the government enforcement scales do not meet the definition of "commercial weighing devices" as found in A.R.S. Section 41-2051.

Arizona Regulation R4-31-207(D) must be complied with as far as specifications on vehicle scales installation. Assuming SWIM scale installation is in accord with this regulation, no modification would be necessary. If it is not, this regulation might be amended by revision; an exception to this regulation for SWIM scales could be added; or a separate regulation for SWIM scales could be provided. There appears to be nothing in the Federal authorities which prevent the use of SWIM scales for state weight enforcement and the Federal authorities seem to encourage the same.

One problem envisioned however is that in the prosecution of an overweight ticket the state, as in all criminal form of certification of accuracy, even though only by custom and usage as it currently exists, an enterprising defense attorney could easily convince many trial courts that certification is a necessary element of the state's case. A system of certification of SWIM scales should therefore be adopted, even if there is no formal requirement, similar to the current system utilized for certifying the port of entry scales.

* Secondly, could the State of Arizona create a SWIM handbook and utilize the same as a standard for SWIM scales and certification thereof and, in essence, do nothing more in the way of statutory or rule and regulation revision?

Simply, the answer to that question would be yes. A.R.S. Section 41-2065(A) (4) allows the Department of Weights and Measures to make rules and regulations to carry its official duties and functions. A.R.S. Section 28-108 provides for rule making authority by the Department of Transportation and authority for administrative agencies to adopt rules and regulations is also found in A.R.S. Section 41-1001 et seq. These authorities would allow the administrative agencies affected to adopt regulations which authorize, implement, and provide to the installation and certification of SWIM scales for weight enforcement. The only limitation is that by rule and regulation, the administrative agencies cannot go beyond the scope of the jurisdiction granted to them by the legislature as expressly found in the Arizona Revised Statues. No such limitation can be found which would prevent the state agencies from adopting sufficient standards to authorize the installation, certification and utilization of SWIM scales for enforcement purposes.

* Finally, by utilizing SWIM scales which have not been officially certified for truck weight enforcement by Handbook 44, would the state somehow be in derogation of Handbook 44, and are there any federal funding laws or regulations which would be jeopardizing the state's right to federal funds by utilizing the SWIM scales if they are not certified by Handbook 44 for truck weight enforcement at the current time?

The answer to that question would be no. Pursuant to federal law and/or rule or regulation, a committee adopts Handbook 44 standards. That committee is currently on record as being in favor of the usage of weigh-in-motion scales for enforcement purposes and are currently soliciting data on weigh-in-motion scales usage, for once they have sufficient data which supports the reliability of said scales, it is suggested that they intend on adopting the same. 23 U.S.C. Section 307 encourages the federal government to cooperate with state agencies on projects such as this. 23 C.F.R. Section 657 expressly approves weigh-in-motion scales as an approved method of overweight enforcement.

The following chapters of this report describe tests carried out on one such scale with the purpose of deriving the type of data required by the Handbook 44 committee. The test data would also provide a basis for the State of Arizona to create and adopt its own SWIM handbook, if desired. The final aim of the test data is to provide material which could be cited in the event of challenge to a prosecution for driving an overweight vehicle brought under any new SWIM procedures which might be adopted.

4. Test program

4.1 INTRODUCTION

Following the confirmation of the Weighwrite ADS-4 SWIM system for detailed evaluation, and the outcome of the legal review, the study team developed a test program to determine the operating performance of the system. The tests were designed to provide a thorough evaluation of all aspects of the system, as well as operational procedures and installation requirements. Details of the tests performed on the Weighwrite system, installed adjacent to the weighscale at the eastbound Ehrenberg port of entry on I-10, are described below with results presented in the next chapter. These tests were performed by state personnel in cooperation with CRC team members between January and June 1988, in three separate test periods.

The test program was developed following several meetings with agencies in the UK responsible for using SWIM technology for the enforcement of axle weights. The UK Transport and Road Research Laboratory (TRRL) has undertaken a detailed appraisal of the Weighwrite SWIM system, the results of which were considered in the development of the test plan, to avoid unnecessary duplication of effort and to ensure that the Arizona tests cover all important aspects of system performance. Account was taken of the UK operating experience and legislation, and of the current US documentation on enforcement weighing contained in the US Bureau of Standards Handbook 44.

The program of testing was divided into four sections to examine various aspects of the system's performance. Although the overall accuracy of the slow-speed weighing system is the prime consideration, the factors which affect its performance also need to be quantified. Dynamic to static comparisons of axle weights of random vehicles formed the basis of the system accuracy appraisal. The influence of other factors on the accuracy was examined using specially selected test vehicles and other survey techniques.

In the testing of the SWIM technology, the following testing and analysis categories were considered for evaluation:

1. <u>Site Tests</u>

    * Installation assessment
    * Static calibration

- Temperature response

2. Random Vehicle Tests

   - Accuracy evaluation
   - Repeatability

3. Test Vehicle Tests

   - Speed evaluation
   - Suspension effect
   - Profile effect

4. Long Term Tests

   - Reliability
   - Durability

Statistical parameters and procedures were identified in the test plan to evaluate the performance of the system, with consideration given to the basic principles of repeatability and sample size. Repeatability, or repetition of the experiment, is important because it provides the basis for determining the significance of observed differences. The required sample size is a function of the data variability, the degree of confidence required and the standard error which is acceptable.

Specific details of the tests carried out under each test heading are given in the sections below.

4.2 SITE TESTS

Installation Assessment

Prior to carrying out the system evaluation, the newly constructed pavement in front of and behind the weighing platform was surveyed to determine the levelness of the installation and surrounding pavement. In the UK, the Department of Transport Code of Practice allows the concrete slab to vary in level by only ± 3 mm (1/8").

To ensure the SWIM results are meaningful, it was recommended that a precise and comprehensive leveling survey be performed covering the pavement 115 feet either side of the scale. Experiments in the UK have indicated that the pavement level immediately adjacent to the scale is most critical, due to positioning of tandem and triple axles during weighing. For this reason, more levels are required close to the weighscale.

The study team proposed that the concrete pavement be divided by a series of grids, with levels taken at each nodal point. One foot grids were recommended for 12 feet either side of the scale, with two-foot grids over the next 24 feet of concrete and three-foot grids over the remaining 60 feet. Because of the high tolerances needed, CRC advised that a high precision automatic level and staff be used when obtaining these levels.

Additionally, it was recommended that a series of permanent leveling points be set up around the outside of the apron and a closed traverse carried out to establish the heights of these points. Subsequently, the leveling instrument can be set up off the pavement and those points on the proposed grid which lie within an arc between 30 feet and 100 feet from the instrument can be leveled, moving the level to cover all grid points.

The leveling survey was undertaken by the Photogrammetry and Mapping Services Section of the Arizona Department of Transportation, using a WILD N3 level and inver meter rods. Levels were taken over 27 feet either side of the SWIM scale, at one-foot increments in the direction of travel. Laterally, the levels were determined at positions 0 feet, 2 feet, 8 feet and 10 feet, relative to the ten-feet wide scale.

Static Calibration

Initial calibration of the system was undertaken by the company responsible for the equipment installation. The Weighwrite system is calibrated in the factory before dispatch and this was used in the initial calibration. An internal system testing feature was also utilized in the calibration process, to verify the response of the electronics.

Once the system had been set up and was fully operational, the object of this part of the testing was to monitor any change in the system calibration over time and at different temperatures. By using static weights traceable to the Bureau of Standards, the system output was monitored so that any temperature effect could be identified.

The calibration checks were performed by Arizona Weights and Measures Division, using certified weights. The weights were loaded onto the weighing platform in 3 kip intervals, with a reading taken after the application of each weight. The linearity of the measurements was examined up to 18 kips. The same process was followed as the weights were removed. A check was made to see whether the system output returned to zero following removal of all the weights. Results from these static load tests were examined for linearity and consistency.

4.3 RANDOM VEHICLE TESTS

The most important test that was carried out during the system appraisal involved the use of random vehicles, selected from the truck traffic passing through the port of entry at the time of the tests. By utilizing random vehicles, the systematic and random error components of SWIM measurements were measured on a representative selection of trucks. Dynamic to static comparisons were used to directly measure the system's performance.

The study team collected the static axle and gross vehicle weights from the port of entry, three-section weighing platform during each random vehicle appraisal. This platform was certified by Arizona Weights and Measures Division immediately prior to each of the three test sessions. The certification process revealed that two of the three platforms were out of specification on all three occasions, and so only one section of the platform could be utilized during the tests. The static weights obtained were compared with SWIM results, acquired using the slow-speed scale in accordance with manufacturer's recommendations.

The accuracy of the system was assessed by direct comparison of static weights, measured at the certified weighscale, with the measurements produced by the SWIM system. Where possible the accuracy was determined for individual axle weights, axle group weights and gross vehicle weights. Systematic errors in the measurements indicate whether the system had been correctly calibrated for dynamic weighing and whether on-site calibration is necessary.

As with any measuring device, the SWIM system 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 pavement, 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 errors in pounds would be appropriate if weighing errors were approximately equal, irrespective of truck or axle weight. Percent errors may be more appropriate if the size of the weighing error increases in proportion to the axle being weighed. If neither of these conditions is true, separate accuracies must be quoted for axles in different weight categories.

More formally, to assess the accuracy of the SWIM system for weighing, two statistics have been calculated. These are the percentage error and the absolute error, defined by:

$$\text{Percentage Error} = \frac{\text{SWIM weight - static weight}}{\text{static weight}} \times 100\%$$

$$\text{Absolute Error} = \text{SWIM weight - static weight}$$

For large populations of trucks, we can assume that both distributions will be approximately normal. What is meant by determining the system accuracy is obtaining values for the mean and standard deviations of these distributions for both axle and gross vehicle weights.

It is not practical to measure these standard deviations directly, since this would involve weighing every vehicle crossing the site. However, these values can be estimated statistically using a random sample from the vehicle population of interest. This procedure can be repeated to detect any significant changes in the calibration and/or spread of individual readings with time.

The sample size required for the accuracy assessment depends on the variability of the data and the accuracy levels to be detected. UK operating experience suggests that most results lie within ± 330 lbs (150 kg). This suggests that the standard deviation of the distribution for individual axles is around 165 lbs (75 kg). For a typical axle weighing 16500 lbs (7500 kg), this corresponds to a standard deviation of 1%. If we wish to determine the accuracy within ± 0.1%, with 95% confidence, the required sample size is given as follows:

$$\frac{2\sigma}{\sqrt{n}} = 0.1\%$$

$$n = \left(\frac{2}{0.1}\right)^2 = 400 \text{ observations}$$

As each observation typically comprises one single, one tandem or one triple axle static/dynamic comparison, this is likely to require about 150 trucks.

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 identified during repeat testing 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. The standard deviation is also used to estimate the standard error of the mean in checking the accuracy of the calibration.

In all of the three test sessions, the project team collected weight data for approximately 150 randomly selected trucks. These trucks were first statically weighed and then directed round the return loop to be weighed on the Weighwrite scale at slow-speed (Figure 4.1). Drivers were requested to stop prior to the scale and told to engage bottom gear and idle over the scale at a constant 2.5 mph. One of the project team walked along side the truck to assist the driver in maintaining the correct speed.

4.4 TEST VEHICLE TESTS

Suspension Type

Tests undertaken by the UK Transport and Road Research Laboratory have shown that the magnitude of the difference between the static and SWIM weight is influenced, to some extent, by the vehicle suspension type. Therefore, CRC recommended that test vehicles with different suspensions be made available to allow this variable to be investigated at the Ehrenberg installation. By making repeated runs with specific types of vehicle, random scatter can be eliminated and systematic differences between suspension types can be identified.

Suspension characteristics vary considerably between vehicles according to their design and the way in which they have been maintained. However, a distinction can be made according to the operating principles. Essentially, they can be divided into either mechanical or air suspensions. Tandem and triple axles often have linked suspensions and their dynamic behavior is particularly important.

The CRC team suggested that six test vehicles with different suspension characteristics should be examined during the course of the tests. In the event, only three of the six proposed vehicle types were readily available within Arizona Department of Transportation. The three vehicles were a two-axle with mechanical suspension, a three-axle also with mechanical suspension and a six-axle semi-trailer (3S3), again with mechanical suspension.

Each vehicle was driven repeatedly across the weighscale at a steady speed (less than 2.5 mph). The SWIM outputs were then analyzed to detect any significant differences between the suspensions and axle groupings.

Some further data on the effect of suspension type were also obtained from the random trucks by noting the particular suspension. In this way a limited amount of data on air suspensions was acquired.

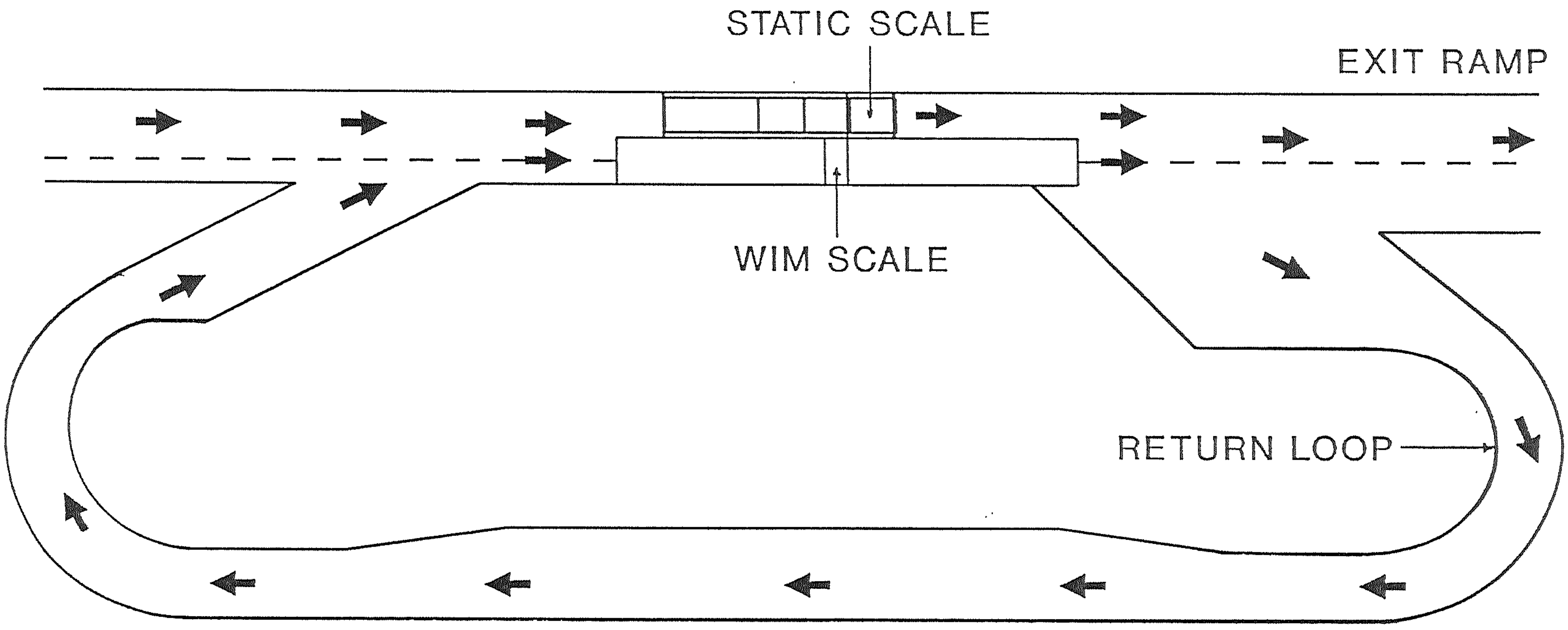

FIGURE 4.1 EHRENBERG POE - SCALE LAYOUT

Speed Evaluation

The UK Code of Practice on SWIM stipulates that the vehicle must be driven across the weighbeam at a steady speed not exceeding 2.5 miles per hour. This approach was followed during the random vehicle evaluations, in order to comply with manufacturers' recommendations.

An increase in speed could increase the vehicle weighing rate and improve driver compliance but is likely to reduce the system accuracy. A series of tests was therefore proposed to quantify the effect of speed with the test vehicles, selected from the previous trials.

Four vehicle speeds were proposed 0 mph, 2.5 mph, 5 mph and 10 mph. This was found to be impractical as the limitations of the current SWIM system are such that above 4 mph no measurements are produced. It was possible, however, to analyze the results obtained during the random vehicle testing to see whether the accuracy is affected when vehicles cross the scale at a speed above 2.5 mph but below the maximum speed of 4 mph. These vehicles were identified as "overspeed" by the SWIM system during the first two sessions. A modification to the system prior to the final test session increased the operational speed to 4 mph.

Profile Effects

During installation of the scale, considerable care was taken to ensure that the platform levels were satisfactory and in accordance with the manufacturer's guidelines. This test involved deliberately altering the levels to observe the impact on the SWIM measurements. Again, test vehicles were used for this test to allow repeated measurements with specific vehicles.

The tests involved raising the height of the scale approach and exit by varying degrees and monitoring the SWIM measurements for the test vehicles. Packing material, in the form of plywood sheets, was placed on the concrete approach and exit to increase its height relative to the scale (Figures 4.2 and 4.3). The levels were raised by the following amounts: 1/16", 1/8", 1/4", and 3/8". An identical procedure was also used to raise the height of the weighscale relative to the apron.

For each height increase, at least five runs were made with the test vehicles. The vehicle speeds were kept constant at 2.5 mph while the vehicles crossed the scale.

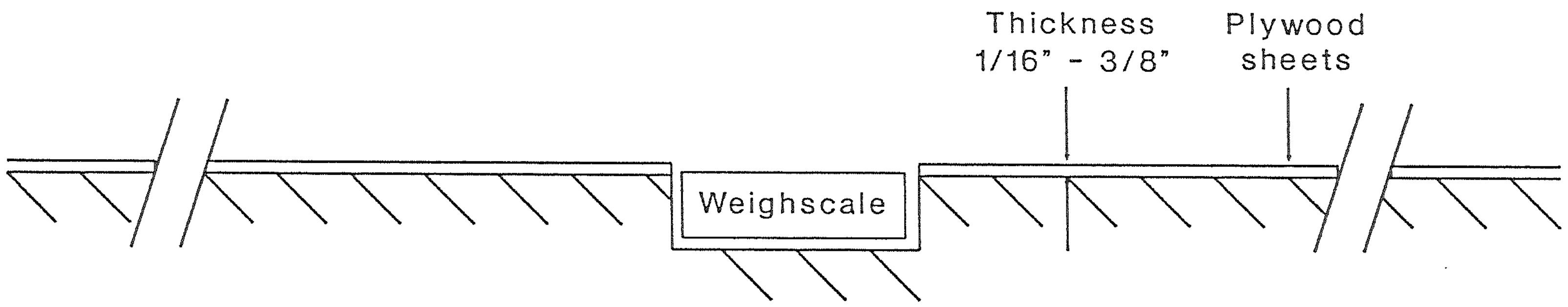

FIGURE 4.2 RAISED PROFILES ON WEIGHSCALE APPROACH AND EXIT

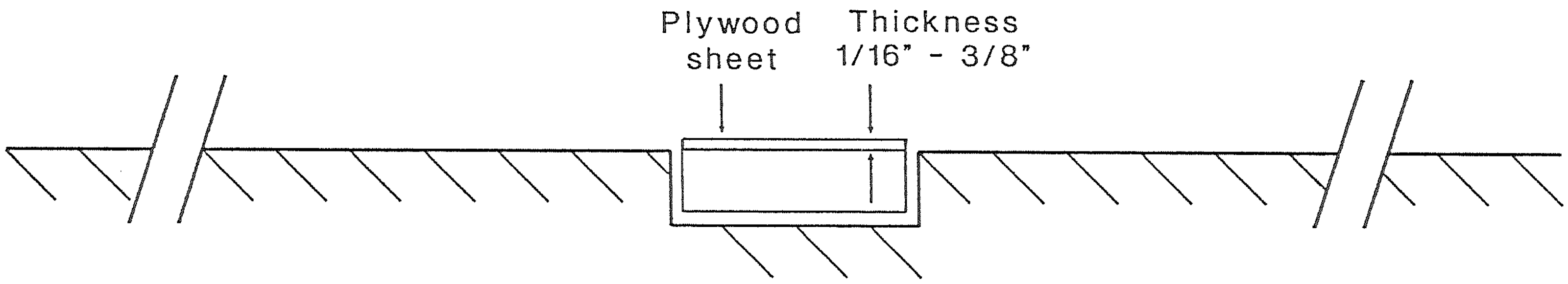

FIGURE 4.3 RAISED PROFILE ON WEIGHSCALE

4.5 LONG TERM TESTS

System Reliability

The reliability of the system is an important operational aspect. Reliability is the ability of a system to perform a required function under stated conditions for a stated period of time. Reliability measures for the weighing platform and electronics could include:

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 and are discussed in more detail under this section.

Insufficient data to produce a realistic indication of the system reliability are available from the field test program alone. To assess these parameters, therefore, it would be necessary to utilize reliability data from recent test programs on the Weighwrite system in conjunction with data produced by this project.

System Durability

The durability of the Weighwrite system is another operational aspect which must be assessed. The two principal measures of durability are the mean electronics subsystem life and the mean weighing platform life, which can be assessed in hours, vehicles, or total equivalent single axle loading (ESAL).

Past experience indicates that neither of these measures can be fully assessed during a five month period. As with system reliability, this is due to the long-term nature of the durability characteristic. Results of previous field and laboratory trials elsewhere are needed to fully assess this performance characteristic, together with extended monitoring after the end of this contract.

4.6 SUMMARY

The test program outlined in this chapter was recommended by the study team as being suitable to fully appraise the technical performance of the SWIM system installed at Ehrenberg. Following approval of the test program the study team prepared field sheets for recording the test data by ADOT personnel. Results of the tests are contained in the next chapter.

5. Test results

5.1 INTRODUCTION

This chapter contains the results of the tests and subsequent analyses carried out on the Weighwrite ADS-4 SWIM system at the Ehrenberg Port of Entry between January and June 1988. The tests were conducted in accordance with the approved test program, outlined in the previous chapter. Results are presented under the respective headings of the test program, with details of system modifications implemented after the second test session contained in the section on long term tests. An additional section has been included within the chapter to specifically describe the effects of temperature on the results.

5.2 SITE TESTS

Installation Assessment

As indicated in Section 4.2, Arizona DOT carried out a leveling survey of the approach and exit concrete slabs to the SWIM scale. Results of this survey show that both slabs were constructed with a cross-fall for drainage. The levels have been plotted and are shown graphically in Figure 5.1.

Excluding the level variation due to the cross-fall, Figure 5.1 reveals that in a few places the concrete apron does not conform to the recommended tolerance of ± 1/8 inch. For example, at the zero line the tolerance is nearer to ± 3/16 inch. The resulting scale performance should be interpreted with these facts in mind.

Static Calibration

Results of the static calibration performed by Arizona Weights and Measures Division indicated that the system calibration had not been correctly established following installation. The system appeared to be consistently underweighing by approximately 160lbs during the first session and by a similar amount in the subsequent sessions. UK

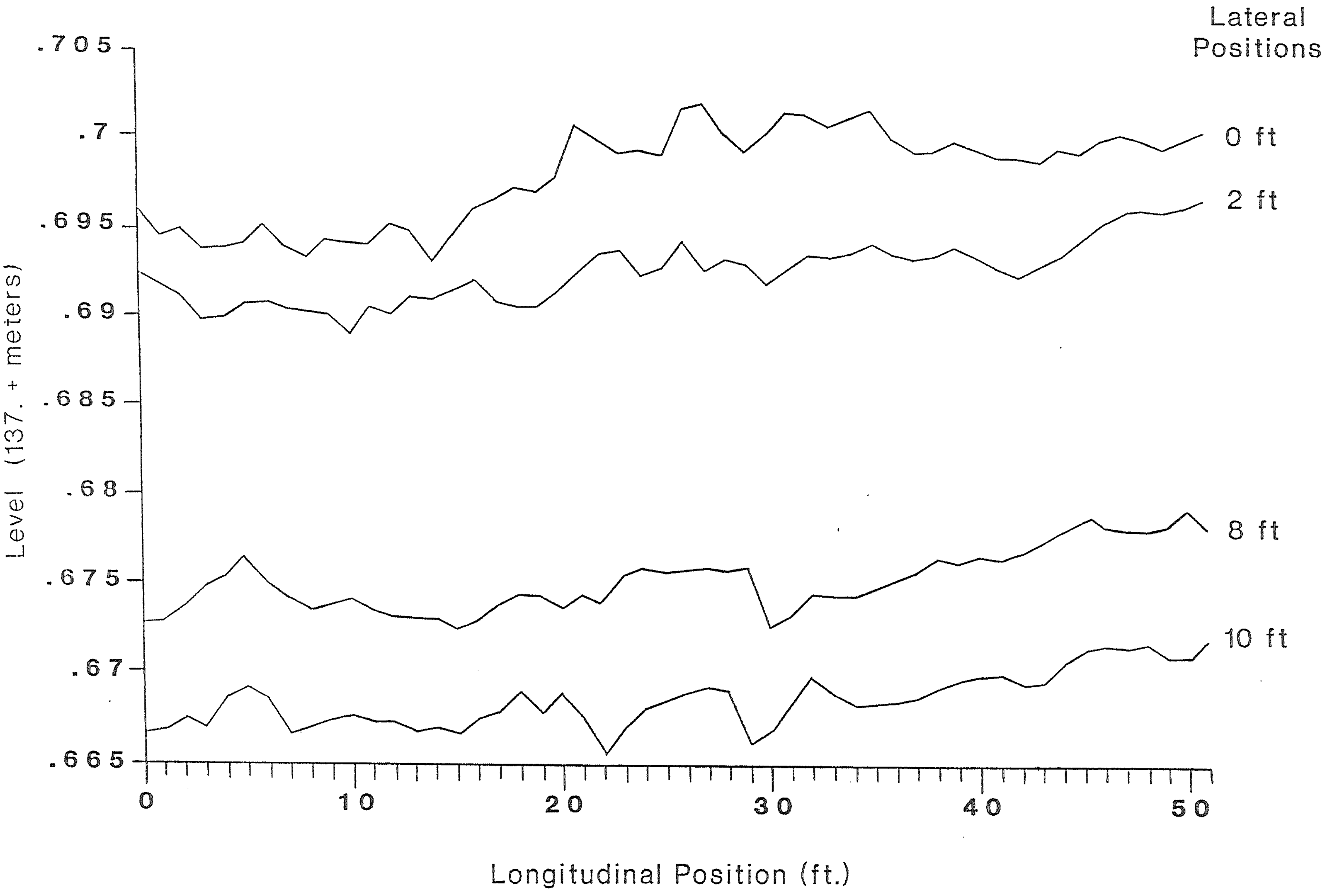

FIGURE 5.1 ASSESSMENT OF SWIM SCALE LEVELS

practice is to ensure that the outcome of this test is such that the two weights are within ± 22 lbs (10 kgs) at new and subsequently ± 44 lbs (20 kgs) for maintenance.

No changes to the calibration were attempted during the first two sessions, although steps were taken in the third test session following the results of the static calibration. Instructions provided by the manufacturer were followed when efforts were made to adjust the calibration. However, problems in the suggested procedure were encountered by the field team and the calibration change was not carried out as desired.

During the first series of tests, the system was monitored at temperatures of 52 degrees F and 65 degrees F. Twelve weeks later, during the second testing series, the static calibration was repeated at a temperature of 72 degrees F. A further eleven weeks later, during the third series of tests, the system was monitored at temperatures of 80 degrees F and 100 degrees F. The results of these analyses are shown in graphical form in Figures 5.2 through 5.6.

For each temperature, the corresponding systematic and random errors have been calculated and are shown in Table 5.1 below. Additionally, the results have been sub-divided into two weight bands to identify any differences with weight. These latter results are tabulated in Table 5.2.

TABLE 5.1 STATIC CALIBRATION

Test Session	Temperature (°F)	Systematic Error lbs (%)	Random Error lbs (%)
January	52	-106 (-1.17)	33 (0.44)
	65	-182 (-2.86)	58 (1.39)
March	72	-157 (-1.97)	21 (1.11)
June	80	-175 (-2.45)	40 (1.75)
	100	-188 (-2.02)	63 (1.39)
Mean values		-162 (-2.09)	43 (1.21)

The results indicate that there has been no appreciable change in the system calibration over a period of twenty three weeks, and that the system calibration appears unaffected by changes in temperature. In general, there are small random errors but appreciable systematic errors leading to the applied loads being underweighed by typically 162 lbs (2%). The dotted line on the graph represents the correct calibration.

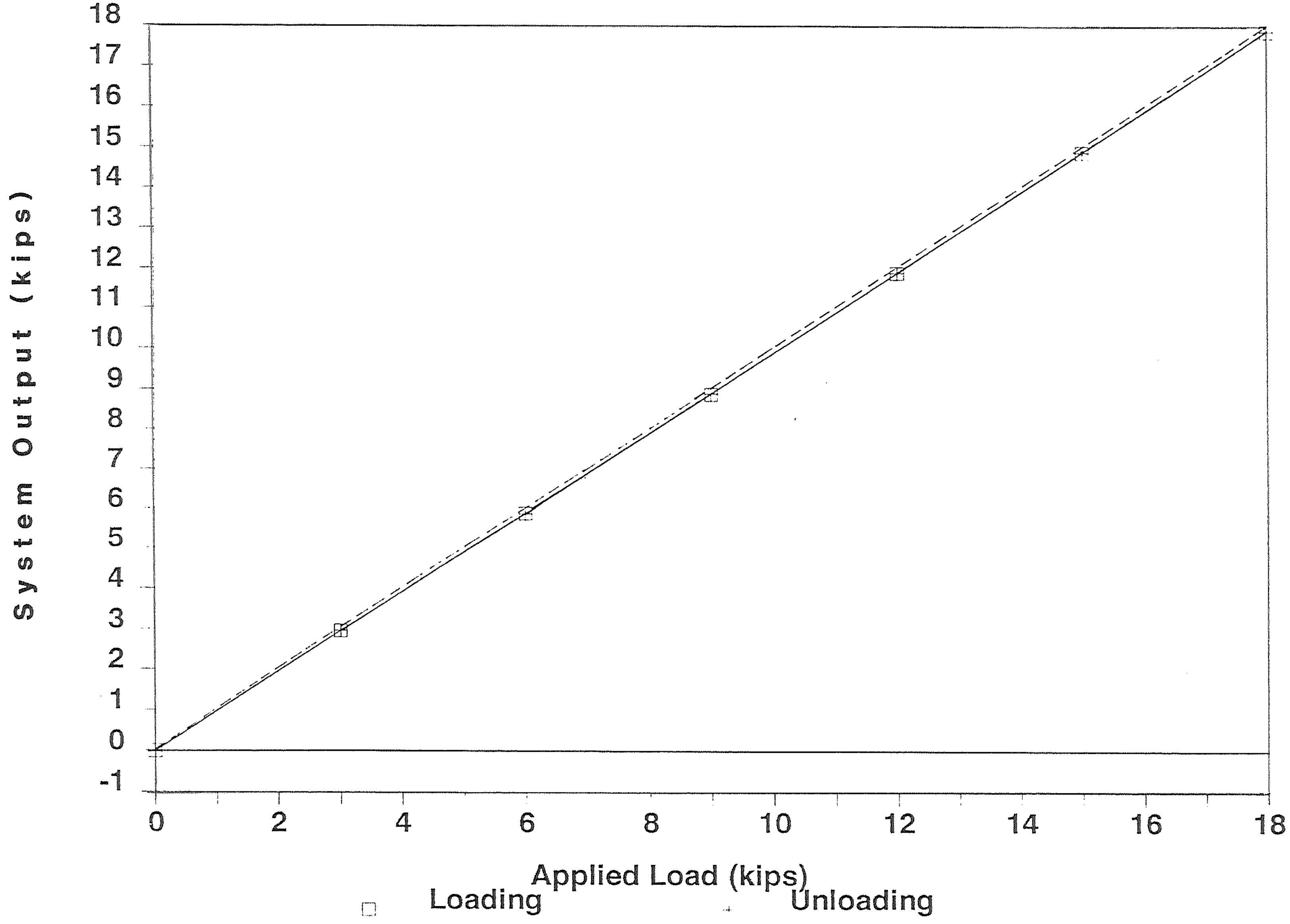

FIGURE 5.2 STATIC CALIBRATION - 1ST TEST, 52°F

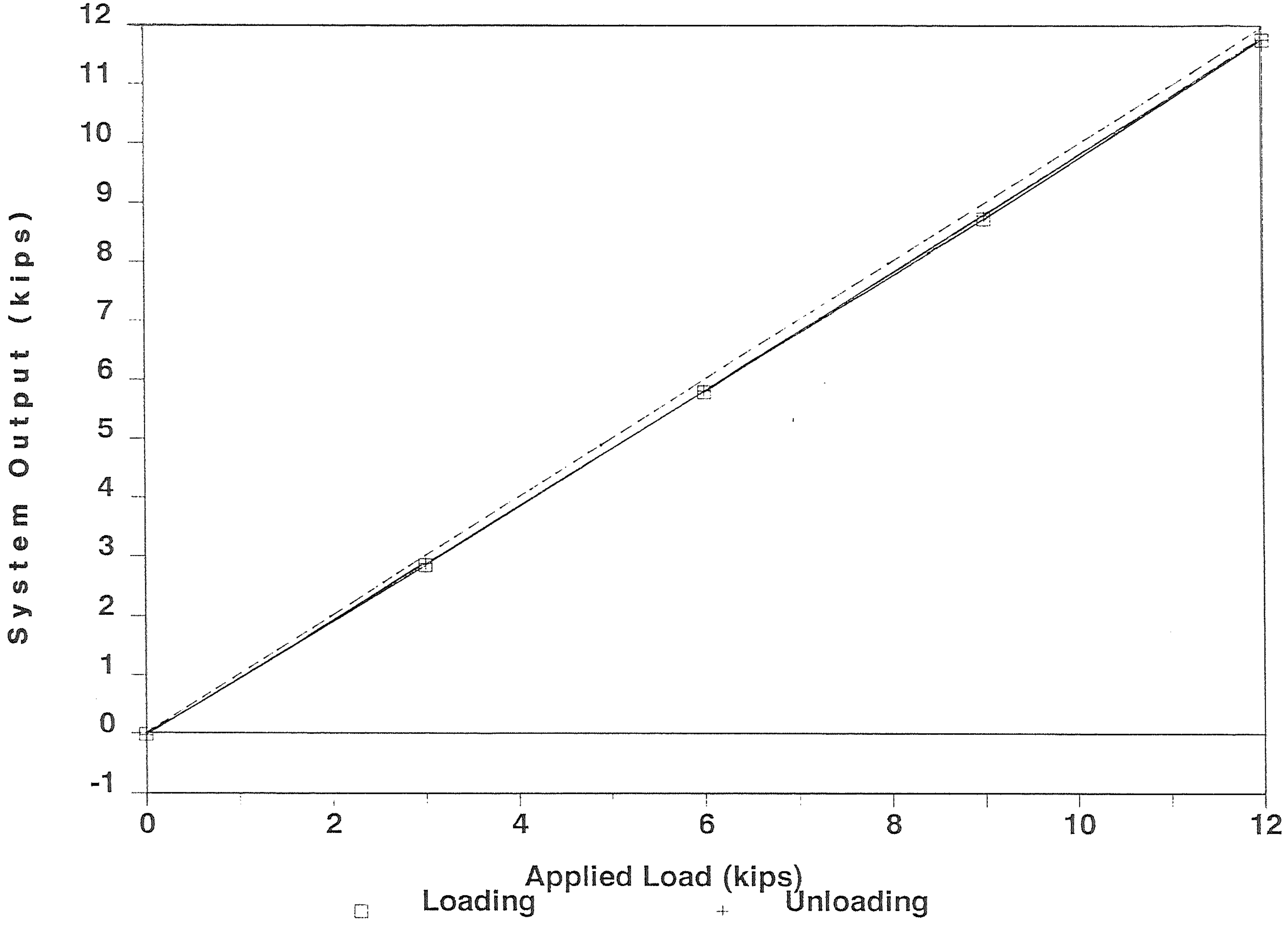

FIGURE 5.3 STATIC CALIBRATION - 1ST TEST, 65°F

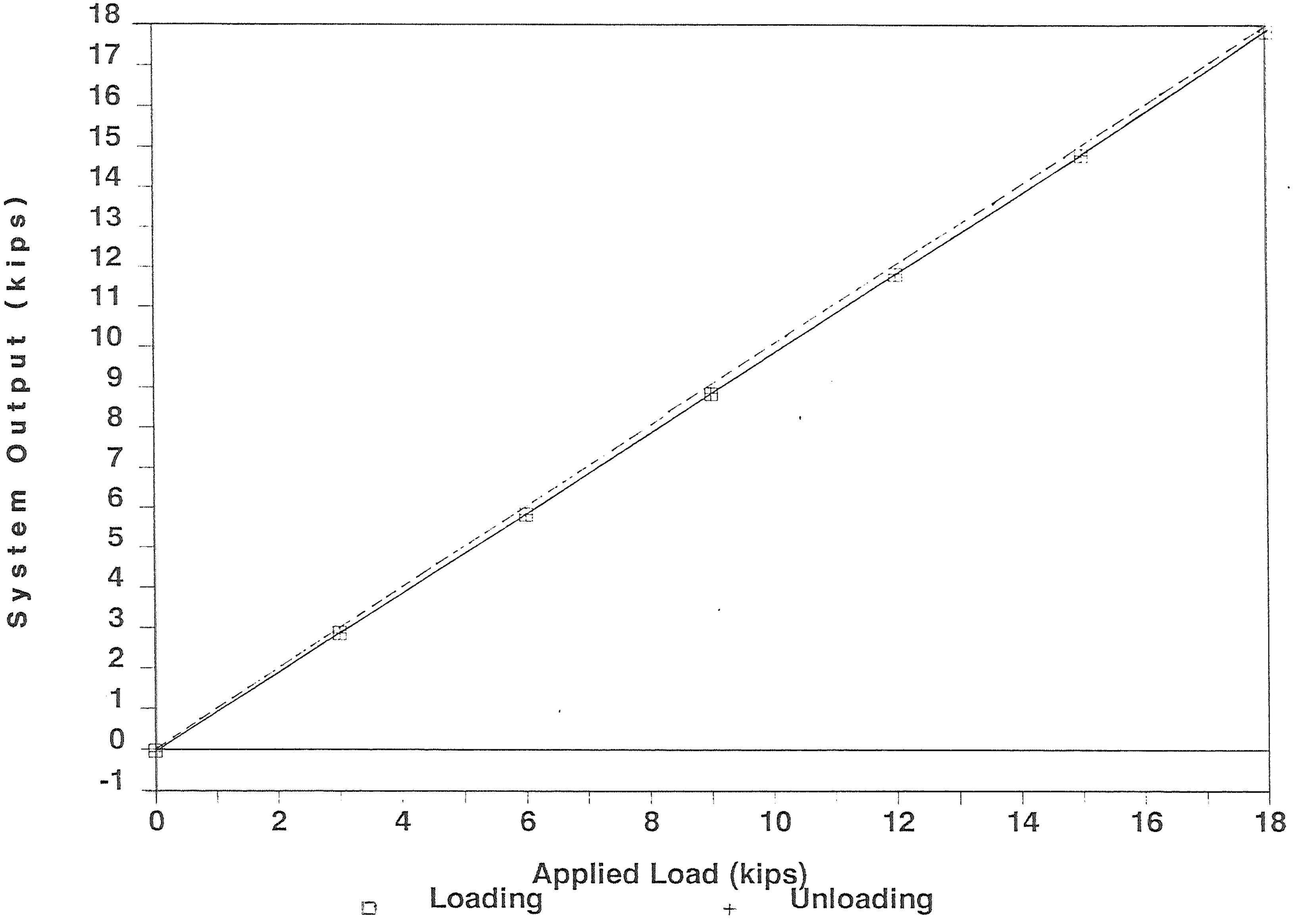

FIGURE 5.4 STATIC CALIBRATION - 2ND TEST, 72°F

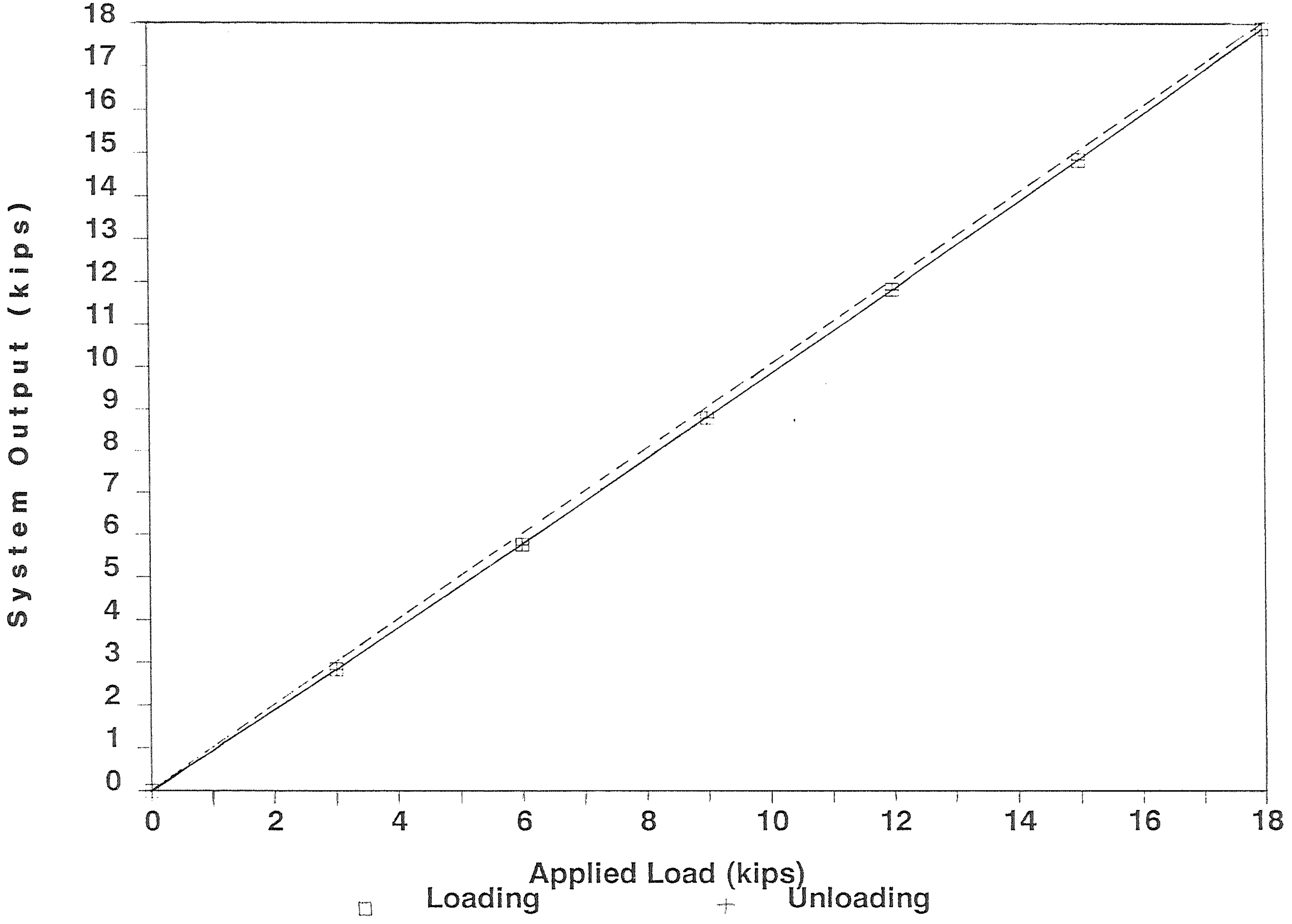

FIGURE 5.5 STATIC CALIBRATION - 3RD TEST, 80°F

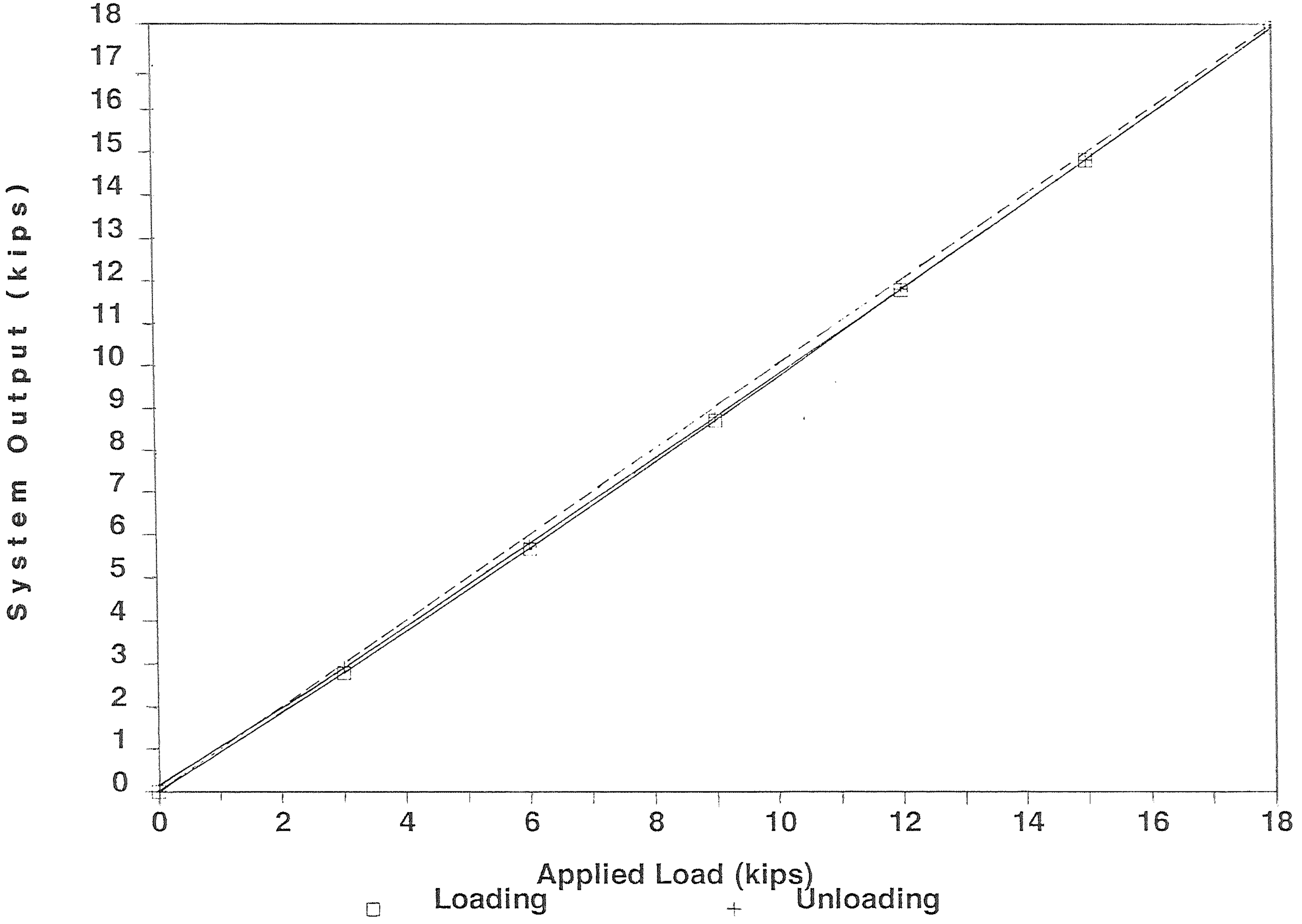

FIGURE 5.6 STATIC CALIBRATION - 3RD TEST, 100°F

The weight band analysis reveals that in absolute terms the systematic error does not change between weight bands, although there is a decrease in random error with increasing weight.

Regression analyses have also been undertaken for the test results obtained at the five different temperatures. The results of these analyses are presented in Table 5.3 below.

TABLE 5.2 STATIC CALIBRATION - WEIGHT ANALYSIS

Temp.	0 - 10,000 lbs		10,000 - 20,000 lbs	
(°F)	Systematic Error lbs (%)	Random Error lbs (%)	Systematic Error lbs (%)	Random Error lbs (%)
52	-90 (-1.52)	38 (0.37)	-122 (-0.82)	16 (0.11)
65	-161 (-3.13)	42 (1.51)	-145 (-2.05)	57 (0.48)
72	-143 (-2.78)	20 (1.05)	-170 (-1.17)	11 (0.24)
80	-200 (-3.85)	36 (1.40)	-150 (-1.06)	28 (0.37)
100	-213 (-2.89)	82 (1.52)	-163 (-1.15)	23 (0.37)
Mean	-161 (-2.83)	44 (1.17)	-170 (-1.25)	27 (0.31)

TABLE 5.3 REGRESSION ANALYSES

Sample	R Squared	X Coefficient	Constant (lbs)
1st session 52 °F	0.99999	0.994	- 35
1st session 65 °F	0.99995	0.982	- 54
2nd session 72 °F	0.99998	0.994	- 89
3rd session 80 °F	0.99985	0.995	- 113
3rd session 100 °F	0.99964	0.992	- 85

The value of R squared indicates the accuracy with which the points follow a straight line; a value of one being the result of all points being exactly in line. It can be seen that, in all cases, R squared is close to one, indicating a very good correlation.

The value of the X coefficient can be used as a measure of comparison between the actual and theoretical straight lines. Ideally the system output (Y) should be equal to the applied load (X), as shown by the dotted line on each of the graphs. In practice, however, the relationship is of the form

$$Y = (X \text{ coefficient} \times X) + \text{constant.}$$

The X coefficient can therefore be used to measure how close the gradient of the line produced by the regression analysis is in comparison with the desired gradient of one. The results show a good approximation to a unit gradient in all cases. The gradient appears independent of ambient temperature. The final "constant" term gives the intercept of the regression line with the y-axis. The values tend to become increasingly negative as the test progress, suggesting some small change in calibration.

5.3 RANDOM VEHICLE TESTS

Three samples of random vehicles were taken during the testing program, one at the start of the program in January, the second in March and the third in June. Each sample has been individually analyzed and changes between samples have been checked statistically. A change in calibration will lead to different sample means, tested for using a two-sample t-test, and changes in the spread of individual readings will lead to different sample variances, tested for using the F-test.

Differences in errors between various weight ranges may be significant, so three different weight ranges were assessed in the analysis. Each of the data sets were sub-divided into axle readings for each weight range, given a suitable spread of weights.

January Data

During the first test session, 132 vehicles with a total of 397 axle groups were weighed. Of these, 22 vehicles (64 axles) were overspeed. The results are presented below in tabular form (Table 5.4) for all vehicles, overspeed vehicles and correct speed vehicles, showing systematic and random errors represented by the mean and standard deviation respectively. The statistics are shown as percentage weight error, with corresponding absolute errors in pounds shown in parentheses.

TABLE 5.4 MEASUREMENT ACCURACY - JANUARY DATA

Sample	Systematic Error		Random Error	
	Axle	Gross	Axle	Gross
All vehicles	-1.7% (-264)	-1.5% (-784)	1.4% (211)	0.6% (339)
Overspeed	-1.8% (-248)	-1.5% (-686)	1.4% (198)	0.6% (324)
Correct speed	-1.7% (-267)	-1.5% (-804)	1.4% (214)	0.6% (339)

The results show close agreement of systematic and random error between overspeed vehicles and those traveling within the specified limit. Those vehicles registered as overspeed were typically traveling at less than 4 mph. This suggested that the UK overspeed limit of 2.5 mph might be relaxed without loss of accuracy.

Statistical analyses of the systematic errors are shown in Appendix A.1. These show that there is a significant difference between the systematic error and the expected value of zero for gross weights, but not for individual axle group weights. The significance of this finding is that the system calibration needs to be improved.

Table 5.5 below shows the results of analyzing the data in three different weight ranges. All random vehicle results were used, and the data divided into 3 ranges; 0 - 10,000 lbs, 10 - 20,000 lbs and over 20,000 lbs. Results in the lightest weight band have been expressed as absolute errors in pounds. Percentage errors have been shown for the heavier weight bands, with the corresponding absolute error indicated in brackets.

TABLE 5.5 WEIGHT RANGE ANALYSIS - JANUARY DATA

Range	Sample Size	Systematic Error	Random Error
0 - 10,000 lbs	79	-199 lbs	138 lbs
10 - 20,000 lbs	156	- 1.9% (-236 lbs)	1.5% (174 lbs)
> 20,000 lbs	162	- 1.2% (-325 lbs)	1.0% (256 lbs)

Statistical analyses shown in Appendix A.1 suggest significant differences between the random error for those axle groups weighing more than 20,000 lbs, when compared with those in the 0 - 10,000 lbs or 10 - 20,000 lbs range. The system is generally more accurate in percentage terms when weighing heavy axles, though absolute errors are greater.

March Data

Following analysis of the January data, it became clear that the results for those vehicles registered as overspeed but not traveling above 4 mph were not significantly different from those traveling at the correct speed. Consequently, it was decided to retain overspeed vehicles within the sample for analysis. For vehicles traveling at above 4 mph, no measurements were obtained. The results of the test session are reproduced in Tables 5.6 and 5.7. As before, the tables show both percentage errors and absolute errors in terms of pounds.

TABLE 5.6 MEASUREMENT ACCURACY - MARCH DATA

Sample	Sample Size	Systematic Error % (lbs)	Random Error % (lbs)
Axle weights	458	- 2.2 (-343)	1.7 (255)
Gross weights	145	- 1.9 (-1083)	0.7 (381)

TABLE 5.7 WEIGHT RANGE ANALYSIS - MARCH DATA

Sample	Sample Size	Systematic Error	Random Error
0 - 10,000 lbs	90	-282 lbs	155 lbs
10 - 20,000 lbs	168	- 2.6% (-328 lbs)	1.8% (208 lbs)
20,000 lbs	200	- 1.4% (-380 lbs)	1.1% (309 lbs)

Statistical analyses were repeated for this data set, and are shown in Appendix A.2. Analysis of the entire data set indicates that the systematic difference for the gross weights is significantly different from zero, whereas the systematic difference for individual axle/axle groups is not. This again confirms that an improvement to the system calibration would be desirable.

Considering the data set in the three weight ranges, there are significant differences between the random errors for axles weighing more than 20,000 lbs compared with the lighter weight ranges. Again, for axles over 20,000 lbs, percentage errors are smaller, with larger absolute errors.

June Data

The results of the June random testing session are summarized in Tables 5.8 and 5.9 below.

TABLE 5.8 MEASUREMENT ACCURACY - JUNE DATA

Sample	Sample Size	Systematic Error % (lbs)	Random Error % (lbs)
Axle weights	433	- 2.4 (-419)	1.5 (233)
Gross weights	148	- 2.3 (-1232)	1.0 (363)

TABLE 5.9 WEIGHT RANGE ANALYSIS - JUNE DATA

Sample	Sample Size	Systematic Error	Random Error
0 - 10,000 lbs	82	-306 lbs	161 lbs
10 - 20,000 lbs	153	- 2.5% (-333 lbs)	1.4% (193 lbs)
20,000 lbs	198	- 1.8% (-532 lbs)	0.9% (234 lbs)

Statistical analyses for the June data are shown in Appendix A.3. As for the January and March data, the systematic errors in gross weights are significantly different from zero. Significant differences are also again observed between random errors of axle groups weighing above and below 20,000 lbs. For this data set, moreover, the difference between axle groups in the range 0 - 10,000 lbs and those in the range 10 - 20,000 lbs is also significant.

Trend Analysis

Comparison of the three data sets and their respective results allows any trends or patterns that exist to be established. One such trend that is noticeable is the system's consistent underweighing of both axle and gross weights. This suggests that the system has not been correctly calibrated; an assumption backed up by the static calibration tests.

Secondly, the systematic and random errors for gross weights are consistently lower than those for individual axle/axle group weights, as summarized in Table 5.10. This is probably due to the errors introduced in weighing individual axles statically, particularly compensated axles.

Although gross weights have lower systematic errors than axle/axle group weights, when tested statistically these are of sufficient magnitude to be significantly different from zero (i.e. a proven systematic bias), whereas those of individual axle/axle group weights are not (Appendix A.4). This is because the gross vehicle weights have low random errors, allowing greater certainty that the systematic errors represents a bias in the system. A larger sample would have allowed the same conclusion to be drawn for individual axle/axle group weights.

TABLE 5.10 COMPARISON OF SYSTEMATIC AND RANDOM DIFFERENCES FOR AXLE AND GROSS WEIGHTS

Sample	Systematic Error % (lbs)		Random Error % (lbs)	
	Axle	Gross	Axle	Gross
Jan	-1.7 (-264)	-1.5 (-784)	1.4 (211)	0.6 (339)
March	-2.2 (-343)	-1.9 (-1083)	1.7 (255)	0.7 (381)
June	-2.4 (-419)	-2.3 (-1232)	1.5 (233)	1.0 (363)

Table 5.10 also shows the changes in systematic and random errors for both individual axle/axle group weight and gross vehicle weights throughout the evaluation period. These variations have been evaluated in Appendix A.4.

Changes in the systematic errors, which have risen consistently throughout the test program, are revealed to be significant for axle weights and gross weights between all three sessions at varying levels of significance. Between January and March, the change in axle weight systematic errors is significant at the 1% level whereas between March and June it is significant only at the 5% level. For gross weights, all changes are significant at the 1% level.

These consistent and significant variations in axle groups and gross vehicles systematic errors are indicative of a change in calibration over the duration of the test program. The magnitude of the change did not show up in the static test calibration. The effect may, therefore, be attributable to a change in the scale height relative to the height of the concrete platform caused by temperature. Level surveys of the scale and platform over an extended temperature range would confirm whether this was the cause of the change in systematic error.

With random errors, the situation is rather more complicated. No consistent trends emerge in terms of either increases or reductions in weighing accuracy between samples. The small changes which occurred are probably attributable to changes in operating conditions and environment.

Frequency Analysis

By assuming that each data set is normally distributed, it is possible to calculate the proportion of vehicles/axles which lie within specified limits of accuracy. The approach used in this calculation is detailed in Appendix A.5. Since the mean systematic error is related to the calibration of the system, and can be reduced to approximately zero by the use of a simple corrective factor, the accuracy of the system can be considered as related primarily to the random error. Consequently, the accuracy of the system may be assessed by calculating the proportion of vehicles or axle/axle groups which lie within a certain range of the mean, independent of the actual value of the mean. The results of the analysis are presented in Tables 5.11 and 5.12.

TABLE 5.11 FREQUENCY ANALYSIS - INDIVIDUAL AXLES/AXLE GROUPS

Sample	Proportion Within P% of mean				
	P = 2%	P = 3%	P = 4%	P = 5%	P = 6%
January	84.6	96.8	99.6	100	100
March	77.2	92.9	98.4	99.7	100
June	82.8	96.0	99.4	100	100

TABLE 5.12 FREQUENCY ANALYSIS - GROSS WEIGHTS

Sample	Proportion Within P% of mean	
	P = 2%	P = 3%
January	100	100
March	99.7	100
June	95.9	100

TABLE 5.13 PERCENTAGE LIMITS FOR 95% CONFIDENCE

Similarly, Table 5.13 shows the percentage limits (P) about the mean in which 95% of the sample lie. The method of calculation is again shown in Appendix A.5.

Sample	P limits for 95% confidence lbs (%)	
	Axles	Gross
January	414 (2.74)	664 (1.18)
March	500 (3.25)	747 (1.31)
June	456 (2.86)	711 (1.92)

5.4 TEST VEHICLE TESTS

Suspension Type

January Data

During the January test session, SWIM outputs from the three different types of test vehicle were monitored. The test vehicles were a two-axle truck, a three-axle truck consisting of a single axle and a tandem axle, and a six-axle semi truck with a single axle, a tandem axle and a triple axle. All three vehicles possessed mechanical suspensions. The results of the analysis of the test vehicle data for January are presented in Tables 5.14, 5.15 and 5.16.

TABLE 5.14 MEASUREMENT ACCURACY - 2-AXLE TEST VEHICLE

Sample	Sample Size	Systematic Error lbs (%)	Random Error lbs (%)
Axle weights	48	-119 (-0.9)	65 (0.6)
Gross weights	24	-281 (-1.0)	63 (0.2)

TABLE 5.15 MEASUREMENT ACCURACY - 3-AXLE TEST VEHICLE

Sample	Sample Size	Systematic Error lbs (%)	Random Error lbs (%)
Axle weights	50	-218 (-1.1)	98 (0.3)
Gross weights	25	-434 (-1.0)	87 (0.2)

TABLE 5.16 MEASUREMENT ACCURACY - 6-AXLE TEST VEHICLE

Sample	Sample Size	Systematic Error lbs (%)	Random Error lbs (%)
Axle weights	15	-189 (-1.5)	61 (0.5)
Gross weights	5	-568 (-1.4)	122 (0.3)

From these results, data can be tabulated for single axles, tandem axles and triple axles, as shown in Tables 5.17 and 5.18. The two-axle test vehicle consisted of single axles only, and its results are therefore not retabulated.

TABLE 5.17 MEASUREMENT ACCURACY BY AXLE TYPE (3-AXLE TEST VEHICLE)

Sample	Sample Size	Systematic Error lbs (%)	Random Error lbs (%)
Single	25	-138 (-1.1)	35 (0.3)
Tandem	25	-298 (-1.0)	73 (0.3)

TABLE 5.18 MEASUREMENT ACCURACY BY AXLE TYPE (6-AXLE TEST VEHICLE)

Sample	Sample Size	Systematic Error lbs (%)	Random Error lbs (%)
Single	5	-172 (-1.7)	36 (0.4)
Tandem	5	-216 (-1.4)	51 (0.3)
Triple	5	-180 (-1.2)	92 (0.6)

Examining the results on a vehicle-by-vehicle basis, systematic errors for both axle group weights and gross vehicle weights tend to increase with vehicle weight. No clear pattern can be established for the random errors, and values are low in all cases. This indicates high repeatability, within the ± 330 lbs (150 kgs) operating tolerance per axle allowed in the UK Code of Practice.

March Data

During the March session, vehicles with air suspension were identified within the sample of random vehicles analyzed previously. The sample set has consequently been split into two subsets; those vehicles having air suspension and those having mechanical suspension. Analysis of the SWIM outputs for both groups is shown in Table 5.19.

TABLE 5.19 COMPARISON OF SUSPENSION TYPES

Sample	Sample Size	Systematic Error lbs (%)	Random Error lbs (%)
Air	18	-332 (-1.9)	155 (1.1)
Mechanical	440	-343 (-2.2)	258 (1.7)

The results have been examined for significant differences between the suspension types for both systematic and random errors (Appendix B.1). This analysis indicates that the variation between systematic errors is not significant, whereas that between random errors is significant. Consequently, it may be concluded that the SWIM outputs for air suspensions are more consistent than for mechanical suspensions. This was also concluded by the UK Transport and Road Research Laboratory in their tests in 1984.

Speed Evaluation

The results for both overspeed vehicles and vehicles traveling at the correct speed were presented in Table 5.4. Random errors for overspeed and correct speed vehicles are the same for both individual axle group weights and gross weights. Similarly, the systematic errors of both samples' gross weights are the same.

Systematic errors of axle weights are analyzed in Appendix B.2 and show no significant difference. It may therefore be concluded that the system accuracy is unaffected by vehicles registered as overspeed but traveling at less than 4 mph. Discussions with the manufacturer confirm the system has been designed to operate at speeds higher than 2.5 mph, but because no difficulties have been experienced in using the system at 2.5 mph in the UK there has been no necessity to increase the operating speed. Further tests are desirable to confirm that the speed does not impact on the system accuracy under different operating conditions.

Profile Effects

As described in Section 4.4, the effect of raising the approach and exit platforms of the scale was investigated using the test vehicles. Systematic and random errors were calculated for individual axle/axle group weights and gross vehicle weights, for each level. These are presented in Tables 5.20, 5.21 and 5.22 for each of the three test vehicles. For comparative purposes, systematic and random errors corresponding to a

TABLE 5.20 PROFILE EFFECTS (2-AXLE TEST VEHICLE)

Relative Scale Height	Systematic Error lbs(%)			Random Error lbs(%)		
	Axle 1	Axle 2	Gross	Axle 1	Axle 2	Gross
+3/8"	-96 (-1.1)	-524 (-2.5)	-620 (-2.1)	8 (0.1)	29 (0.2)	36 (0.1)
+1/4"	-88 (-1.0)	-316 (-1.5)	-404 (-1.4)	10 (0.1)	41 (0.2)	50 (0.2)
+1/8"	-86 (-1.0)	-254 (-1.2)	-340 (-1.2)	23 (0.3)	26 (0.1)	34 (0.1)
+1/16"	-109 (-1.3)	-254 (-1.2)	-363 (-1.2)	24 (0.3)	33 (0.1)	45 (0.2)
0"	-93 (-1.1)	-144 (-0.7)	-281 (-1.0)	61 (0.7)	59 (0.3)	63 (0.2)
-1/16"	-96 (-1.1)	-264 (-1.3)	-360 (-1.2)	15 (0.2)	20 (0.1)	28 (0.1)
-1/8"	-149 (-1.7)	-197 (-1.0)	-346 (-1.2)	48 (0.6)	23 (0.1)	58 (0.2)
-1/4"	-36 (-0.4)	-280 (-1.3)	-295 (-1.0)	41 (0.5)	22 (0.1)	30 (0.1)
-3/8"	+112 (1.3)	-284 (-1.4)	-172 (-0.6)	24 (0.3)	32 (0.1)	47 (0.2)

TABLE 5.21 PROFILE EFFECTS (3-AXLE TEST VEHICLE)

Relative Scale Height	Systematic Error lbs(%)			Random Error lbs(%)		
	Axle 1	Axle 2	Gross	Axle 1	Axle 2	Gross
+3/8"	84 (-1.47)	-104 (-0.36)	-288 (-0.68)	15 (0.11)	20 (0.05)	32 (0.08)
+1/4"	-170 (-1.37)	-263 (-0.90)	-433 (-1.38)	25 (0.11)	27 (0.20)	36 (0.17)
+1/8"	-171 (-1.4)	-337 (-1.13)	-523 (-1.24)	30 (0.24)	48 (0.141)	48 (0.11)
+1/16"	-183 (-1.47)	-294 (-0.97)	-477 (-1.13)	22 (0.18)	14 (0.07)	25 (0.06)
0"	-138 (-1.12)	-298 (1.0)	-434 (-1.03)	34 (0.28)	72 (0.25)	87 (0.21)
-1/16"	-252 (-2.06)	-432 (-1.44)	-684 (-1.62)	10 (0.05)	20 (0.08)	23 (0.06)
-1/8"	-268 (-2.2)	-520 (-1.74)	-788 (-1.87)	16 (0.13)	47 (0.16)	60 (0.14)
-1/4"	-220 (-1.8)	-533 (-1.8)	-753 (-1.79)	59 (0.49)	79 (0.27)	108 (0.26)
-3/8"	183 (+1.48)	-753 (-2.5)	-937 (-2.22)	74 (0.62)	98 (0.33)	109 (0.26)

TABLE 5.22 PROFILE EFFECTS (6-AXLE TEST VEHICLE)

	Systematic Error lbs(%)				Random Error lbs(%)			
Relative Scale Height	Lead	Tandem	Triple	Gross	Lead	Tandem	Triple	Gross
+3/8"	-140 (-1.4)	-164 (-1.06)	1436 (9.7)	1132 (2.82)	18 (0.18)	46 (0.28)	86 (0.58)	70 (0.17)
+1/4"	-168 (-1.68)	-180 (-1.12)	1124 (7.64)	788 (1.96)	32 (0.32)	50 (0.34)	50 (0.34)	57 (0.14)
+1/8"	-180 (-1.8)	-184 (-1.18)	672 (4.54)	308 (0.77)	28 (0.28)	29 (0.19)	78 (0.53)	56 (0.14)
+1/16"	-196 (-1.96)	-188 (-1.2)	644 (4.36)	260 (0.65)	32 (0.32)	32 (0.21)	32 (0.21)	81 (0.20)
0"	-172 (-1.72)	-216 (-1.40)	-180 (1.22)	-568 (1.41)	36 (0.36)	51 (0.33)	92 (0.63)	122 (0.30)
-1/16"	-208 (-2.08)	-252 (-1.6)	792 (-5.36)	-1252 (-3.11)	16 (0.16)	32 (0.21)	78 (0.51)	100 (0.25)
-1/8"	-208 (-2.08)	-348 (-2.24)	-852 (-5.74)	-1408 (-3.50)	16 (0.16)	280 (1.81)	87 (0.59)	250 (0.62)
-1/4"	-220 (-2.2)	-368 (-2.38)	-1168 (-7.88)	-1756 (-4.37)	28 (0.28)	289 (1.88)	102 (0.70)	315 (0.78)
-3/8"	-137 (-1.37)	-313 (-2.03)	-1363 (-9.22)	-1813 (-4.51)	41 (0.41)	60 (0.39)	68 (0.45)	85 (0.21)

level scale and approach/exit are also included. The relative scale height is tabulated as positive when the plywood sheets were placed upon the scale, effectively raising it above the level of the concrete approach and exit (Figure 4.2).

For all vehicles, random errors for individual axles and gross weights are largely unaffected by scale height. Systematic errors do show marked variations with height, particularly for the three-axle and six-axle test vehicles. The differences in systematic errors have been highlighted in Tables 5.23 to 5.25, by subtracting the scale calibration error for each test vehicle, derived with a level scale and apron. The mean differences are also plotted in Figures 5.7 through 5.14.

For the two-axle test vehicle, the results are inconclusive. Adjusting the relative scale height in either direction appears to bring about a negative change in systematic error for the second axle, with a smaller or positive change in systematic error for the lead axle. When combined to give the gross vehicle weight, there appears to be a downward trend, with a negative change in systematic error (corresponding to a decrease in the SWIM output) as the relative scale height increases.

For the three-axle test vehicle, however, the general trend is one of a positive change in systematic error as the relative scale height increases. This is more pronounced for the tandem axle output than for the lead axle.

The most striking result is obtained for the triple axle of the six-axle test vehicle. This shows a clear upward trend as the relative scale height increases, ranging from around -1,200 lbs to around 1,700 lbs. Although the lead axle and tandem axle are affected by a much smaller amount than this, the magnitude of variation for the triple axle is sufficient to ensure a similar trend for the gross vehicle weight.

5.5 LONG TERM TESTS

Due to the short evaluation period, as expected it has not been possible to obtain long-term data to assess the system performance and installation over an extended operating period. As a consequence, it is not yet possible to draw any firm conclusions about the long term reliability and durability of the Weighwrite system under US operating conditions. Experience of utilizing the equipment in the UK for enforcement over the last twelve years indicates that the system is highly durable, although the reliability of the output can fluctuate if the system is not regularly calibrated. The UK Code of Practice requires the scale to be routinely certified every six months, although it is not always necessary to make an adjustment to the calibration at this frequency.

Some system modifications were carried out by the manufacturer following the second test session to increase the weighing rate and simplify the operating procedures, but

TABLE 5.23 CHANGES IN SYSTEMATIC ERROR WITH SCALE HEIGHT (2-AXLE TEST VEHICLE)

	Change in Systematic Error lbs(%)		
Relative Scale Height	Axle 1	Axle 2	Gross weight
+3/8"	+24 (+0.3)	-284 (-1.4)	-260 (-0.9)
+1/4"	+32 (+0.4)	-76 (-0.4)	-44 (-0.2)
+1/8"	+34 (+0.4)	-14 (-0.1)	+20 (-0.1)
+1/16"	+11 (-0.1)	-14 (-0.1)	-3 (-0.0)
0"	0 (0.0)	0 (0.0)	0 (0.0)
-1/6"	+24 (+0.3)	-24 (-0.1)	0 (-0.0)
-1/8"	+31 (+0.4)	+23 (+0.1)	+54 (+0.2)
-1/4"	+84 (+1.0)	-40 (-0.2)	+44 (+0.2)
-3/8"	+232 (+2.7)	-44 (-0.2)	+188 (+0.6)

TABLE 5.24 CHANGES IN SYSTEMATIC ERROR WITH SCALE HEIGHT (3-AXLE TEST VEHICLE)

	Change in Systematic Error lbs(%)		
Relative Scale Height	Axle 1	Axle 2	Gross weight
+3/8"	-4 (-0.0)	+196 (+0.7)	+192 (+0.5)
+1/4"	+9 (+0.1)	+31 (+0.1)	+40 (+0.1)
+1/8"	+8 (+0.1)	-37 (-0.1)	-29 (-0.1)
+1/16"	-3 (-0.0)	+6 (+0.0)	+3 (+0.0)
0"	0 (0.0)	0 (0.0)	0 (0.0)
-1/16"	-72 (0.6)	-132 (-0.5)	-204 (-0.5)
-1/8"	-88 (-0.7)	-220 (-0.7)	-308 (-0.7)
-1/4"	-34 (-0.3)	-200 (-0.7)	-234 (-0.6)
-3/8"	-3 (-0.0)	-388 (-1.3)	-391 (-0.9)

TABLE 5.25 CHANGES IN SYSTEMATIC ERROR WITH SCALE HEIGHT (6-AXLE TEST VEHICLE)

	Changes in Systematic Error lbs(%)			
Relative Scale Height	Lead axle	Tandem axle	Triple axle	Gross weight
+3/8"	+32 (+0.3)	+52 (+0.3)	+1616 (+11.1)	+1700 (+4.3)
+1/4"	+4 (+0.0)	+44 (+0.3)	+1304 (+8.9)	+1356 (+3.4)
+1/8"	-8 (-0.1)	+32 (+0.2)	+852 (+5.8)	+876 (+2.2)
+1/16"	-24 (-0.2)	+28 (+0.2)	+824 (+5.6)	+828 (+2.1)
0"	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)
-1/16"	-36 (-0.4)	-36 (-0.2)	-612 (-4.2)	-684 (-1.7)
-1/8"	-36 (-0.4)	-132 (-0.9)	- 672 (-4.6)	-840 (-2.1)
-1/4"	-48 (-0.5)	-152 (-1.0)	-988 (-6.8)	-1188 (-3.0)
-3/8"	+35 (+0.4)	-97 (-0.6)	-1183 (-8.1)	-1245 (-3.1)

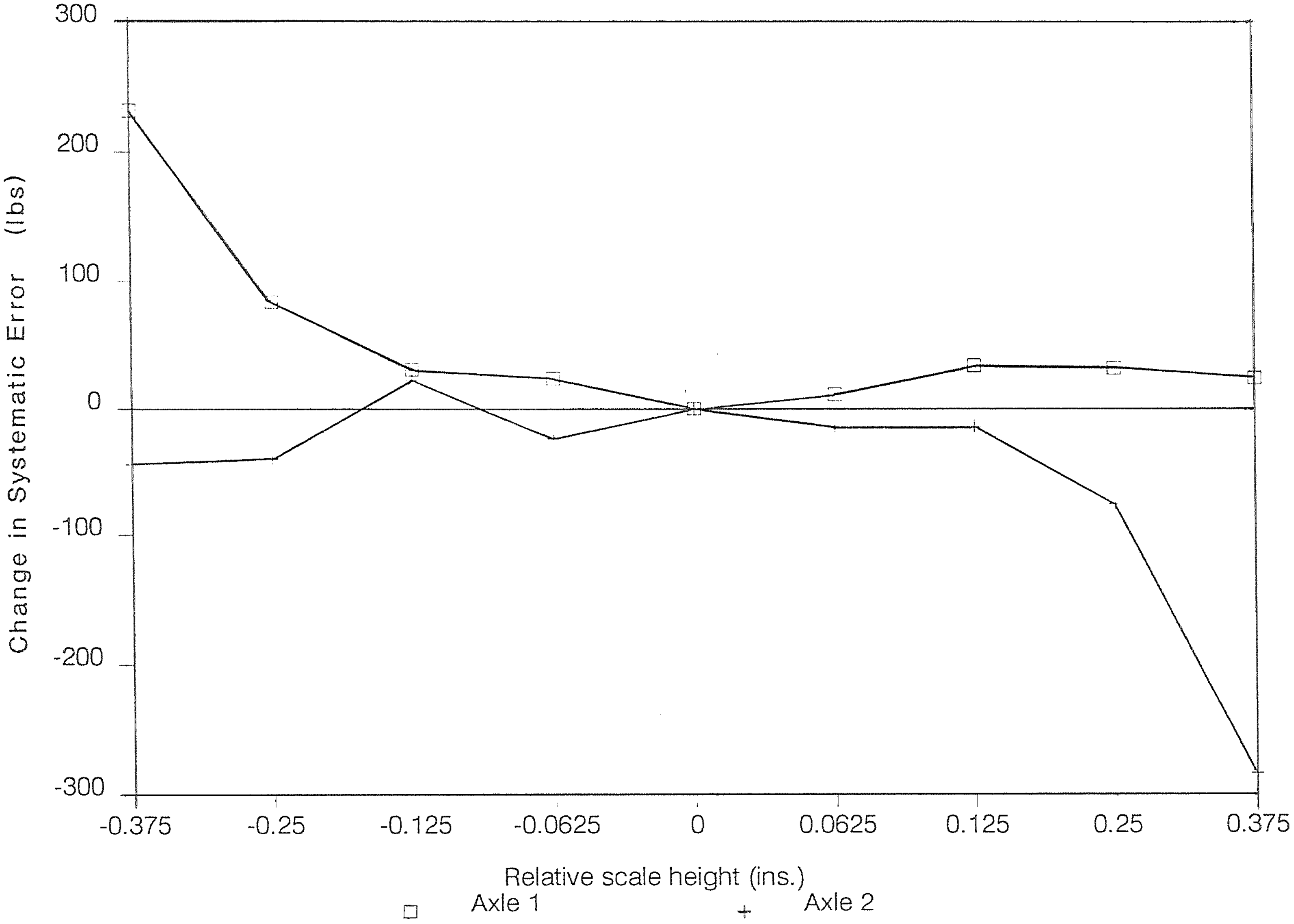

FIGURE 5.7 PROFILE TESTS - 2-AXLE TEST VEHICLE

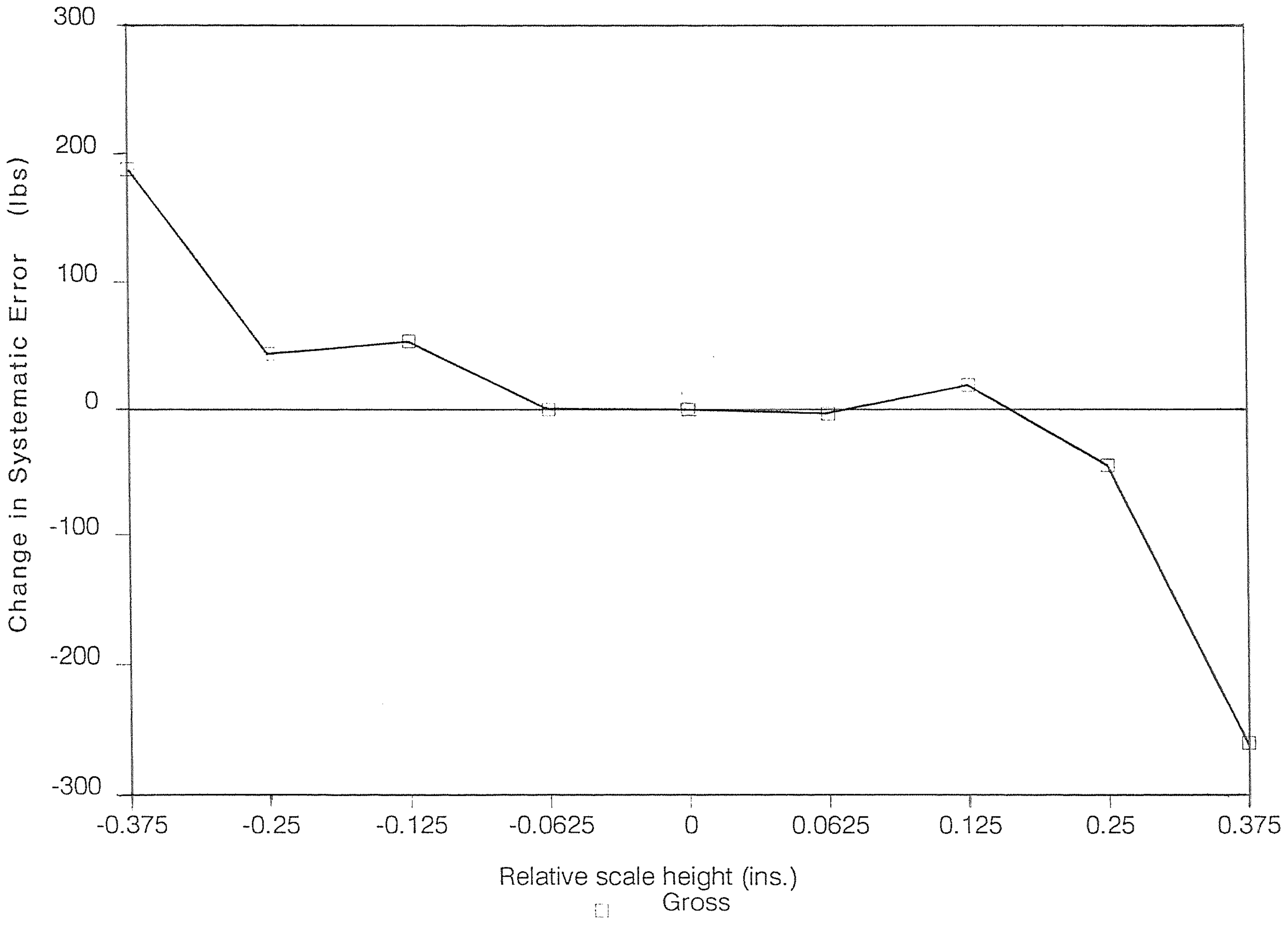

FIGURE 5.8 PROFILE TESTS - 2-AXLE TEST VEHICLE

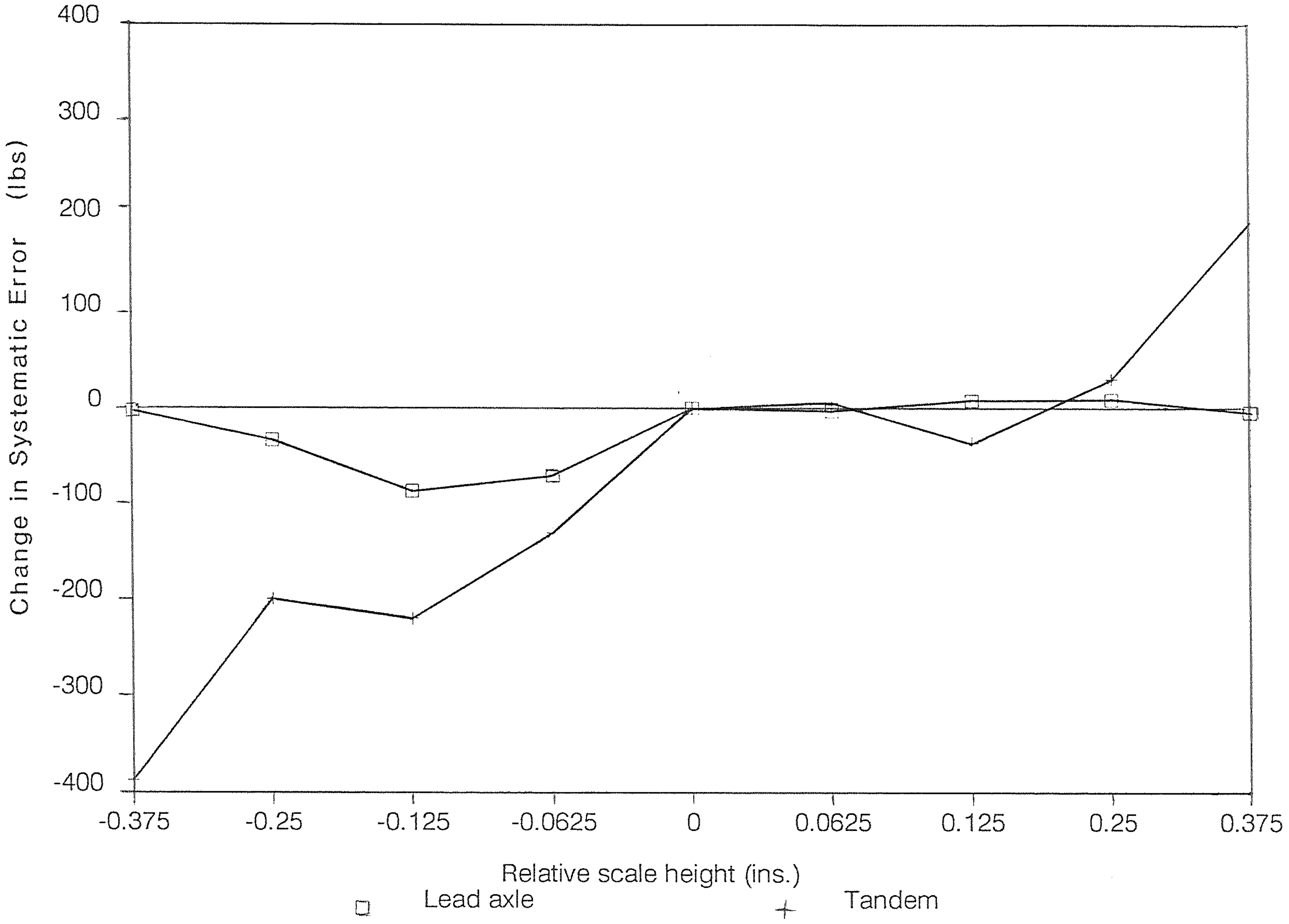

FIGURE 5.9 PROFILE TESTS - 3-AXLE TEST VEHICLE

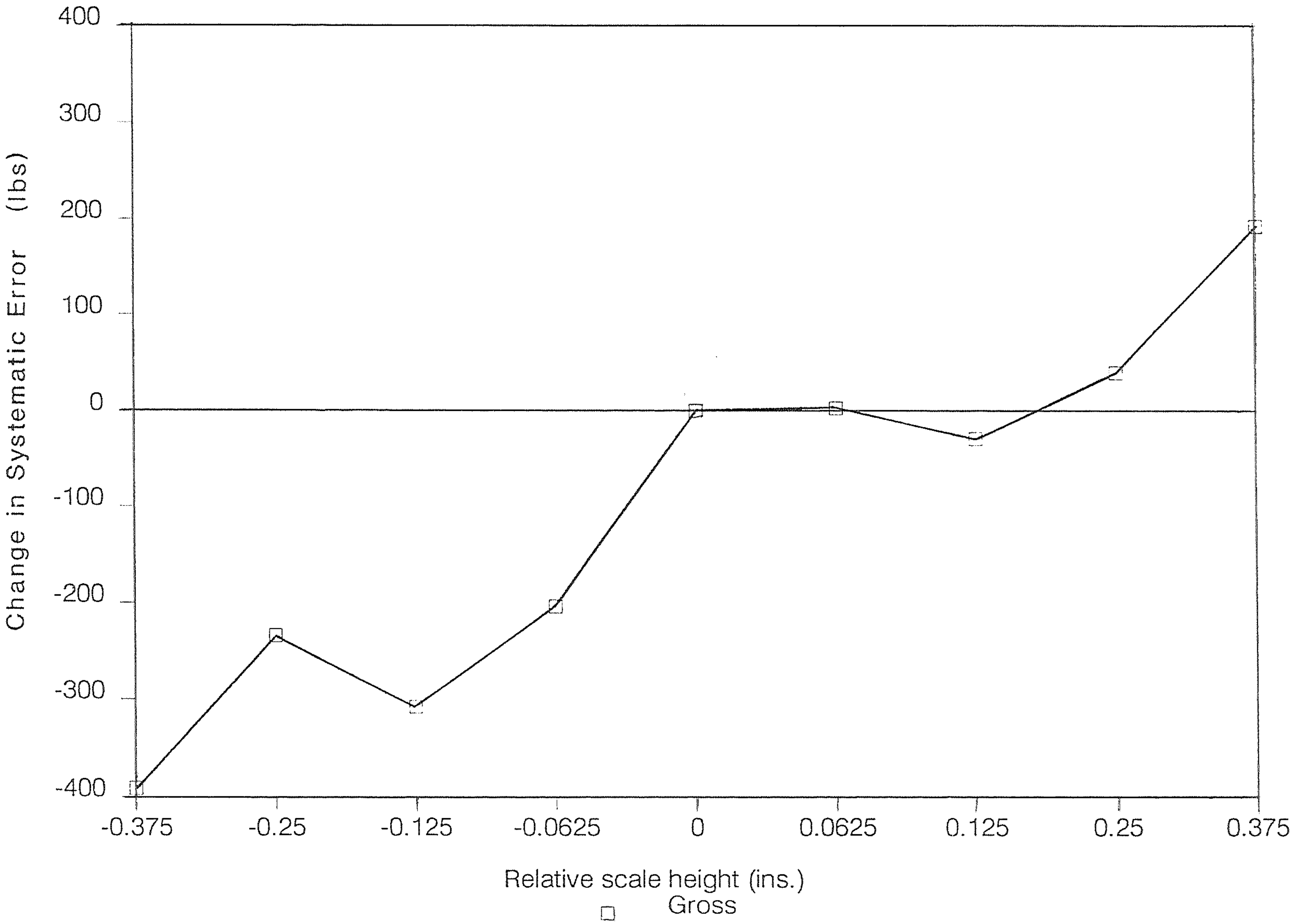

FIGURE 5.10 PROFILE TESTS - 3-AXLE TEST VEHICLE

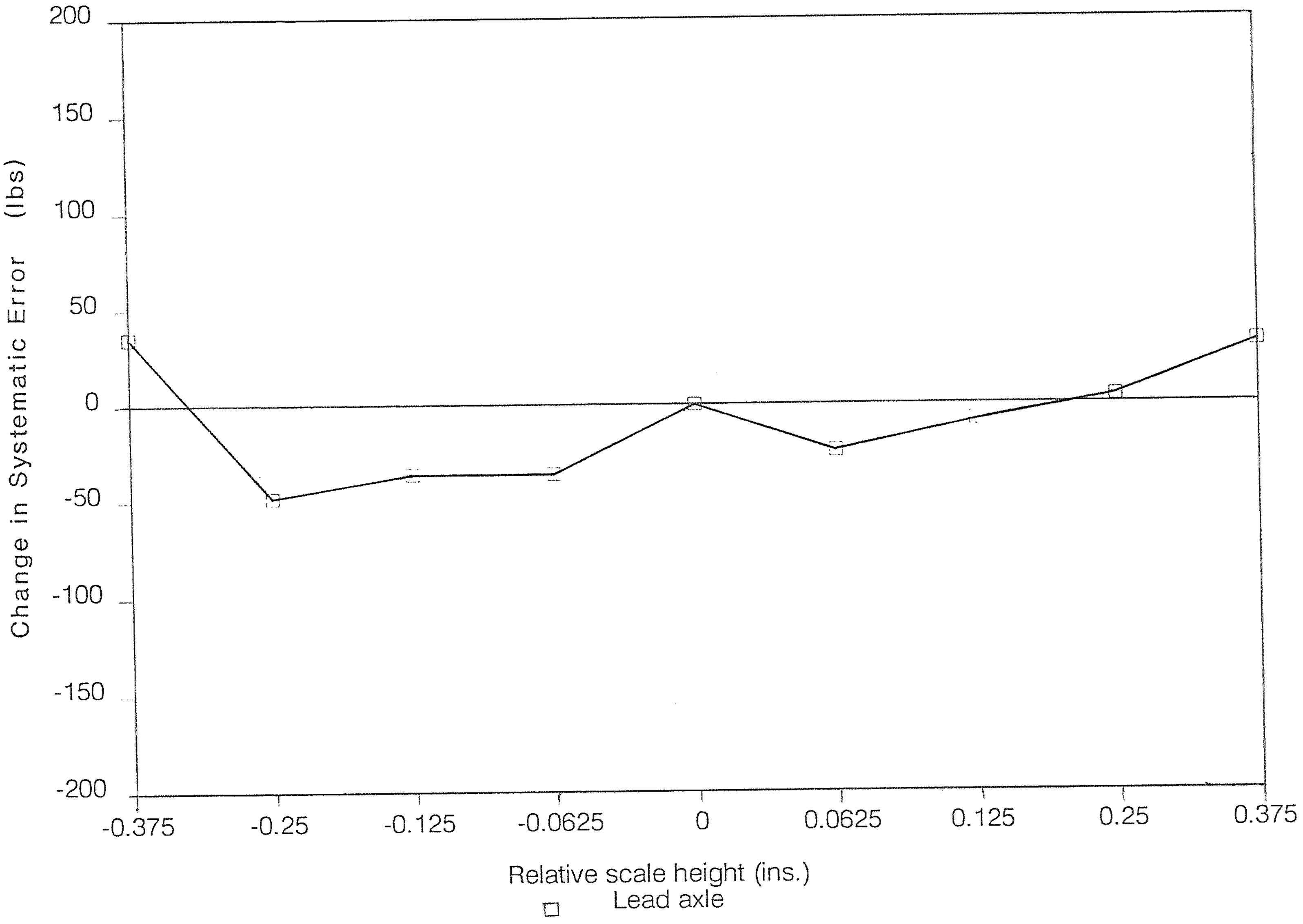

FIGURE 5.11 PROFILE TESTS - 6-AXLE TEST VEHICLE

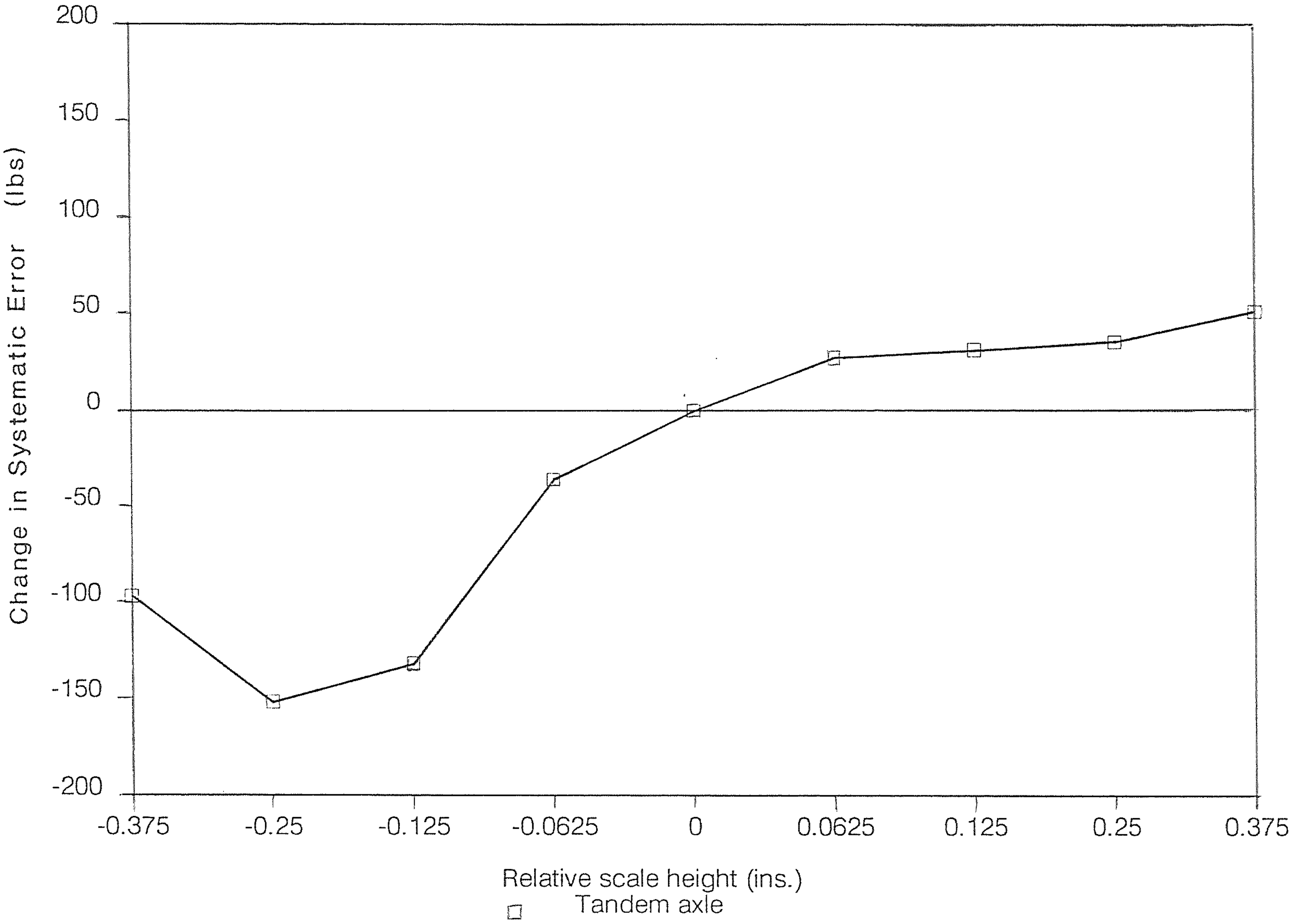

FIGURE 5.12 PROFILE TESTS - 6-AXLE TEST VEHICLE

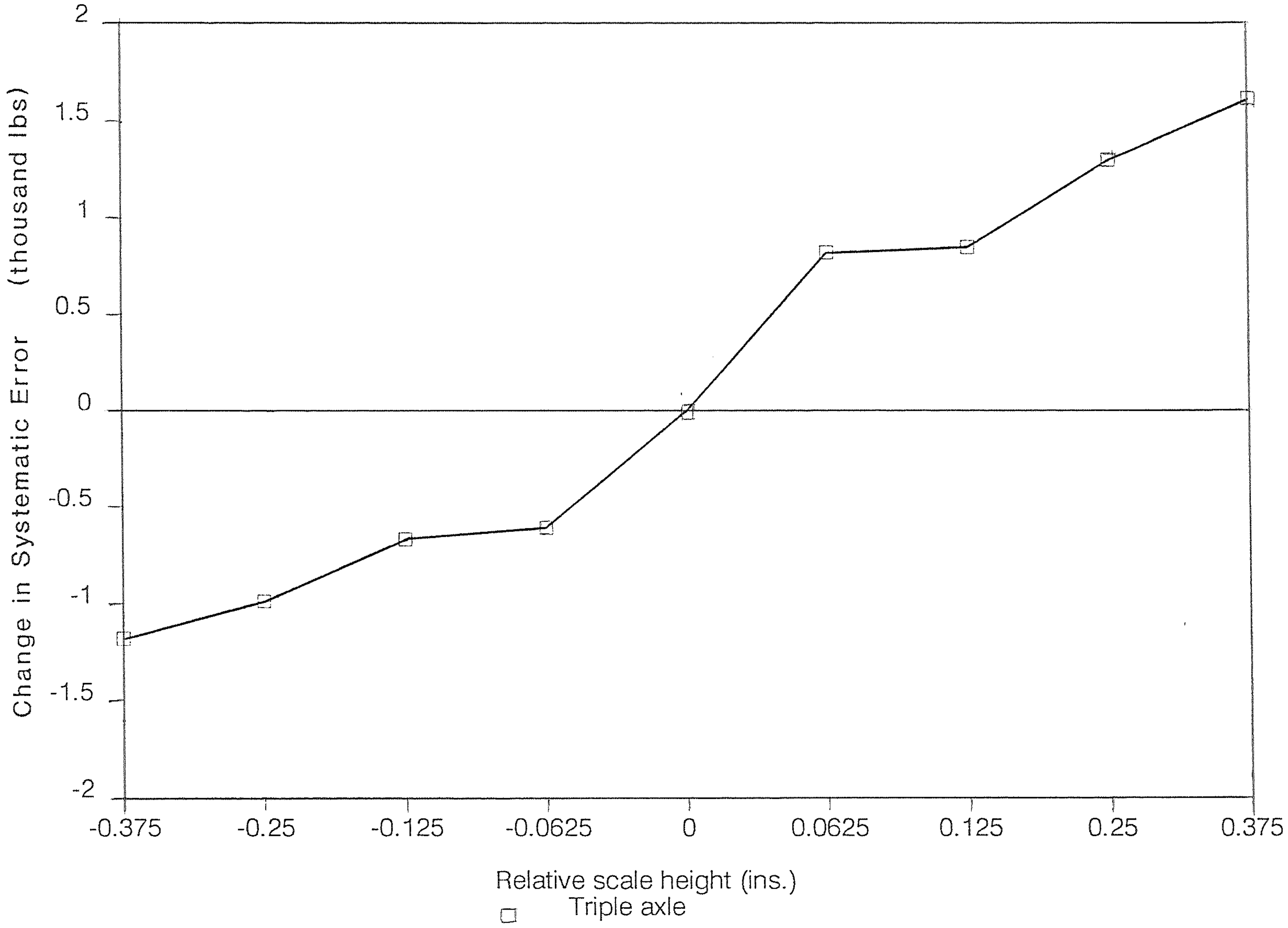

FIGURE 5.13 PROFILE TESTS - 6-AXLE TEST VEHICLE

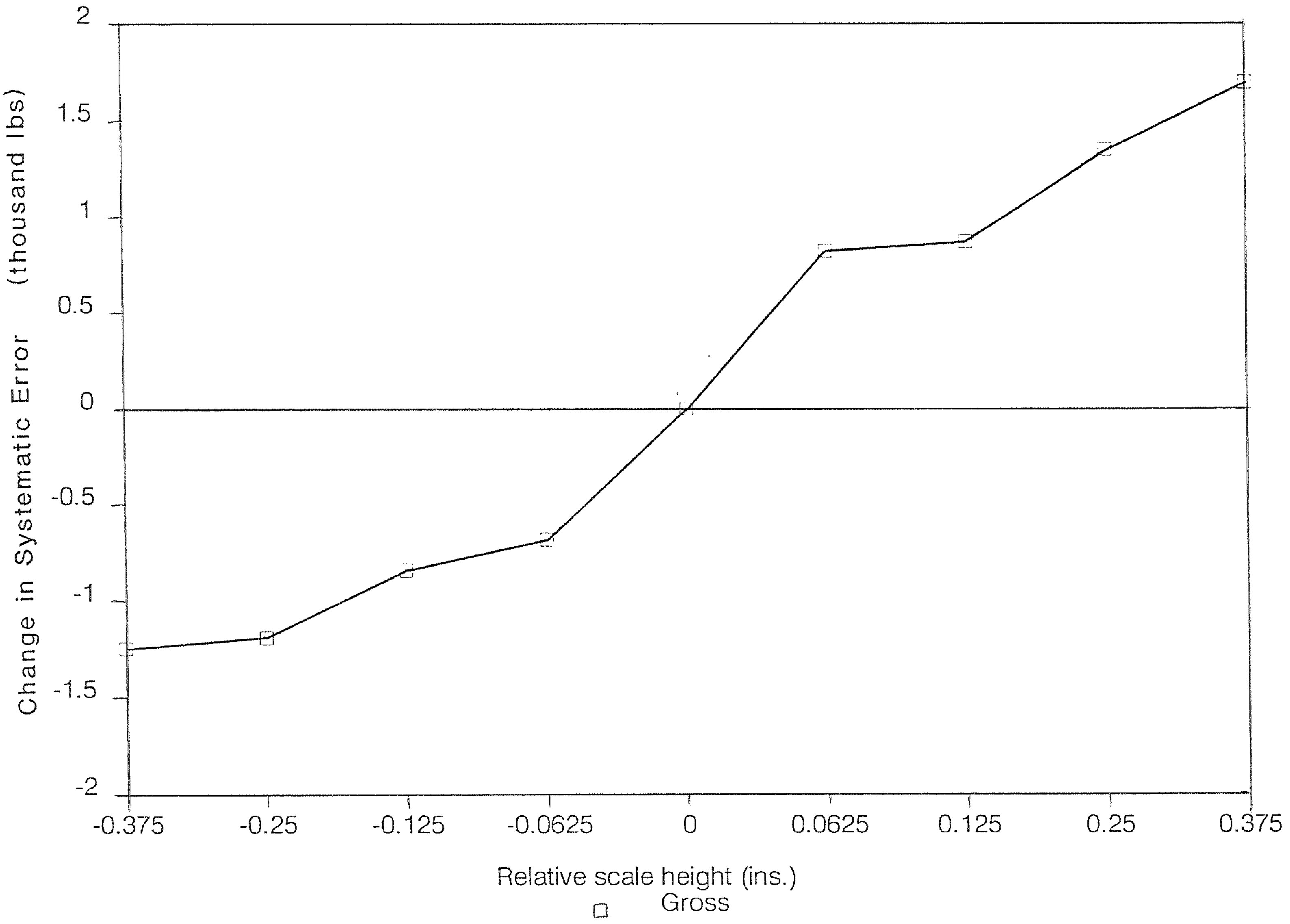

FIGURE 5.14 PROFILE TESTS - 6-AXLE TEST VEHICLE

this was an upgrade to the basic system rather than a repair. Details of the modifications are given below.

The system changes implemented by the manufacturer consisted of the following:

- increase in the operational speed for vehicles crossing the scale from 2.5 mph to approximately 4 mph, to make it easier for the truck drivers to maintain a constant speed;
- a default value for the vehicle class in the "enforcement mode" programmed as a 3S2 truck, due to the predominance of this truck at the Ehrenberg site; and,
- a reduction in the operational time headway between vehicles through an increase in the printer speed.

The consequence of these changes was that the weighing time was significantly reduced, allowing more vehicles to be weighed in a given period and preventing serious backups at the busy port of entry. Some bugs in the new software were identified but these did not affect the system operation in the final test session.

5.6 TEMPERATURE TREND ANALYSIS

The temperature trend analysis was undertaken by dividing gross vehicle weight data from each test session into groups corresponding to particular temperature ranges. This allowed any change in system response with variations in temperature to be identified. The results are presented in Tables 5.26, 5.27 and 5.28.

Examining first the January data, both systematic and random differences fluctuate as the temperature increases from 40 to 80 degrees fahrenheit with no obvious pattern emerging. In March, both systematic and random differences fell consistently as the temperature increased from 70 to 100 degrees fahrenheit. In June, however, as the temperature rose from 80 to 120 degrees fahrenheit, systematic differences consistently increased, while the random differences fluctuated.

Based on the temperature data gathered during these tests, therefore, there appears to be no identifiable temperature trend, despite the very high temperatures experienced in the final test session. The change in systematic error may be attributable to an increase in the concrete platform level, relative to the scale level, caused by the temperature.

TABLE 5.26 TEMPERATURE ANALYSIS - JANUARY DATA

Temperature (°F)	Sample size	Systematic Error % (lbs)	Random Error % (lbs)
40	18	-1.47 (-890)	0.45 (320)
50	18	-1.53 (-860)	0.56 (300)
60	16	-1.39 (-840)	0.50 (350)
70	40	-1.48 (-730)	0.69 (330)
80	40	-1.53 (-720)	0.58 (360)

TABLE 5.27 TEMPERATURE ANALYSIS - MARCH DATA

Temperature (°F)	Sample size	Systematic Error % (lbs)	Random Error % (lbs)
60	21	-2.04 (-1310)	0.75 (410)
70	38	-2.09 (-1000)	0.77 (330)
80	41	-1.91 (-1100)	0.62 (420)
90	33	-1.81 (-1020)	0.58 (370)
100	12	-1.80 (-1120)	0.28 (210)

TABLE 5.28 TEMPERATURE ANALYSIS - JUNE DATA

Temperature (°F)	Sample size	Systematic Error % (lbs)	Random Error % (lbs)
80	19	-1.61 (-1082)	0.71 (425)
90	19	-1.86 (-1022)	0.71 (423)
100	23	-2.17 (-1162)	0.66 (250)
110	20	-2.38 (-1099)	1.36 (302)
120	37	-2.42 (-1303)	1.02 (350)

5.7 SUMMARY

The chapter has outlined the test results, and the subsequent analyses undertaken by the study team to quantify the technical performance of the Weighwrite SWIM system based on three separate test sessions. Results indicate that the initial system calibration was not correct, leading to underweighing by 1-2%. Data gathered from random trucks were used to determine the accuracy of the system. These produced random errors of between 211 and 255 lbs (1.4% -1.7%) for individual axles/axle groups and 339 lbs to 381 lbs (0.6% - 1.0%) for gross weights. Some small fluctuations in both the systematic and random errors were evident between test sessions but no clear trends were evident.

Test vehicles were used in the evaluation to determine suspension effects, speed effects and profile effects. Consistent and repeatable results were obtained for all of the test vehicles with the largest random error being 92 lbs for the triple axle of the 3S3 test truck. Mechanical suspensions produced significantly more variation than those of air suspensions, with random errors of 258 lbs and 155 lbs respectively. No discernable difference in the results was observed when the test vehicles were operated at 4 mph, above the UK recommended 2.5 mph speed.

Profile effects were significant, particularly for the tandem and triple axle groupings. Altering the relative scale level produced a significant change to the SWIM output. For the triple axle of the 3S3 test vehicle, an increase in the relative height of the scale by + 3/8" produced an increase of 1700 lbs in the SWIM weight, compared to the SWIM weight with the scale level. This is a significant result, since concrete apron levels at Ehrenberg have been found to fall outside the tolerances permitted by the UK code of practice.

Insufficient data were available to draw any conclusions about the long term reliability and durability of the system at Ehrenberg. No temperature effects on weighing accuracy were detected over the course of the testing.

6. Recommendations

6.1 INTRODUCTION

Based on the findings of the previous tasks, CRC has produced recommendations on the accuracy, applicability and likely cost-effectiveness of the slow speed weigh-in-motion system installed at the Ehrenberg port-of-entry, with a further recommendation as the whether the system can be legally used by the Arizona Department of Transportation for enforcement weighing purposes. The future implementation of the technology has been examined, together with the nature and duration of further work, leading to the establishment of an automated port-of-entry.

6.2 SYSTEM ACCURACY

The comprehensive evaluation of the Weighwrite SWIM system has provided detailed information on the accuracy of the system and the effects which have significant influence on the results. Based on the results of the tests, recommendations relating to system accuracy have been formulated which could form the basis of an enforcement strategy.

Static calibration checks by Arizona Weights and Measures Division indicated that the system calibration was out by around 160 lbs, and this difference remained fairly constant with increasing load. Adjustment of the calibration could not readily be undertaken. Detailed instructions from the manufacturer would be required on this aspect if the system were to be adopted by the State of Arizona. Similarly, for the system to become certified, a high tolerance on the static calibration is essential, as unless the system can consistently weigh static weights, traceable to national standards, its credibility for determining dynamic weights could be seriously impaired. CRC recommends that, in static calibration tests, the SWIM output should agree with the static weight to within a tolerance of ± 25 lbs over the entire weight range when new and to ± 50 lbs maintenance.

The calibration did not appear to change over the wide temperature range observed. The majority of the tests were performed at high temperatures, however. It is therefore desirable that some evaluation of low temperature effects be considered before the SWIM system became widely adopted.

The tests with random vehicles have shown that there appears to be no significant difference between vehicles crossing the scale at the recommended speed of 2.5 mph and those crossing at speeds up to 4 mph. A similar result was found in the UK by Surrey Trading Standards Department when they evaluated a Weighwrite system in 1976. Closer examination of the speed effect, would be desirable prior to full-scale implementation of this technology.

Results obtained by operating the system at a speed of 4 mph suggest that there was a gradual deterioration in the calibration, in terms of an increasing systematic error over the test period. This suggests that it is essential to regularly examine the calibration. As mentioned previously, UK practice is to verify the scale every six months with three test vehicles. However, UK SWIM scales are not utilized on a continuous basis as would be the case with a system at a port of entry. Therefore, it would be desirable to check the scale more frequently, for example every three months, until the stability of the calibration had been established. In practice, checks every twelve months may prove sufficient as is the case in Hungary, where eighteen Weighwrite SWIM systems are in regular use in port-of-entry environments.

With trucks continuously crossing the scale, whether or not the system is being used for enforcement, there are likely to be significant changes in the levels of the approach and exit platforms over a period of time. Frequent monitoring of the levels is desirable to ensure they remain within tolerance. The verification procedure needs further consideration to ensure that it meets current standards, is effective and is not unduly expensive to perform.

The standard deviation of the weight differences, the random error, ranged between 211 lbs and 255 lbs (1.4% - 1.7%) for individual axles/axle groups. The corresponding range for gross weights was 339 lbs - 381 lbs (0.6% - 1%). 95% of the axle weights therefore lie within ± 414 lbs and ± 500 lbs of the mean. For gross weights the 95% limits range between ± 664 lbs and ± 747 lbs.

To utilize the SWIM scale for enforcement a tolerance must be specified within which the system should operate. In the UK the operational accuracy limits are ± 330 lbs (150 kgs) per axle. Examination of individual vehicle weights reveals that in the January session, out of the 392 axle groups weighed, 360 (91%) were within this specification. Adjustment of the SWIM calibration by an increase of 160 lbs would increase the proportion within the specification to 95%. The corresponding analysis of gross weights indicates that almost all vehicles are within the specification.

Based on the data collected it would be necessary to use a tolerance of ± 660 lbs per axle to ensure all individual axles were within specification, or ± 500 lbs for 99%. This high margin would probably be unacceptable to the enforcement community. The alternative approach recommended by CRC is therefore to correct the calibration and take steps toward improving the concrete apron profile.

The random vehicle tests tend to confirm the view that the type of suspension on the trucks does influence the output. Air suspended bogies appear more efficient than mechanically suspended bogies, leading to more reliable and consistent results from the SWIM scale.

The interaction between the suspension and the height of the approach and exit platforms has also been shown to be particularly important. Large changes in the SWIM output can be produced by raising the relative scale level by only a small amount, especially for tandem and triple axle groups with mechanical suspensions. CRC therefore recommends that the specification suggested by the manufacturer, ± 1/8" (3 mm), be adhered to if high tolerances are required.

6.3 APPLICATION OF SWIM TECHNOLOGY TO PORT-OF-ENTRY OPERATIONS

The obvious case for the use of SWIM is the efficiency derived from the short period of time taken to determine axle weights and gross weight of any vehicle type. For example a vehicle with a 50 foot wheelbase travelling at 4 mph can be weighed in approximately 11 seconds, regardless of the number of axles. In practical terms, the use of SWIM will reduce weighing time to about one third of the required using current practices.

A less obvious case, but one of equal importance, is accuracy. To stick to the letter of the Federal Highway Administration requirements for an effective weight enforcement process, individual axle loads should be measured, rather than tandem and triple axle loads as are usually measured for axle groups. The Standards and Tolerance Committee of the National Conference on Weights and Measures in a report presented several years ago noted the following.

"The measurement of individual axle loads statically is subject to much potential error, due to weight distribution shifts between axles caused by starting/stopping, brakes being applied, etc. Weighing of axle loads in motion largely eliminate these errors and will in general be more accurate than static weighing, at least at low speed".

The use of a slow speed weigh-in-motion scale for port-of-entry operations offers many benefits over the conventional means of static weighing, notably:

- Improved weigh station efficiency
- Increased truck throughput
- Reduced queues and delays

- Improved axle weighing accuracy

As a result there may be lower manpower requirements and improved relationships with the trucking industry. The results of the recent test program at the Ehrenberg port of entry indicate that slow speed weigh-in-motion is cost effective to install and operate. Some refinements to the system tested would be required before it could be routinely utilized in a port of entry application.

6.4 LEGAL ENFORCEMENT OF WEIGHT LIMITS USING SWIM

A review of existing legislation on truck weight enforcement has shown that it is not absolutely necessary to amend either statutes or regulations for the use of SWIM scales for enforcement purposes.

One possible exception would be the Arizona Administrative Rule and Regulation R4-31-207(D) concerning the installation of scales. Arizona Regulation R4-31-207(D) must be compiled with as far as specifications on vehicle scales installation. Assuming SWIM scale installation is in accord with this regulation, no modification would be necessary. If it is not, either this regulation might be amended by revision or an exception to this regulation for SWIM scales could be added or a separate regulation for SWIM scales could be provided.

There is no reference to either the type of scale necessary, or any requirements for certification found in Title 28 of the Arizona Revised statutes. Title 41 of the Arizona Revised Statutes adopts Handbook 44. A.R.S. Section 41-2064(8) exempts government scales from licensing. If it is assumed that no licensing is required and there is no independent requirement for certification, it is safe to assume no certification be required. Arizona Regulations R4-31-104 allows the weights and measures division to inspect the weighing devices of the state, but does not require and/or establish any particular standards.

One problem envisioned is that in the prosecution of an overweight ticket by the state, as in all criminal forms of certification of accuracy, an enterprising defense attorney could easily convince many trial courts that certification is a necessary element of the state's case and a system of certification of SWIM scales should be adopted, even if there is no formal requirement. To overcome this potential problem the State of Arizona could create a SWIM handbook and utilize the same as a standard for SWIM scales and certification thereof and, in essence, do nothing more in the way of statutory or rule and regulation revision.

Lastly, there appears to be nothing in Federal law or regulations which prevent the use of SWIM scales for state weight enforcement, and the federal authorities seem to encourage the same.

6.5 FURTHER WORK

Two further areas of work have been identified which are closely associated with the results of this feasibility study: an evaluation of the contribution made by the slow speed weigh-in-motion system to weigh station efficiency, and an evaluation of other technologies such as high speed weigh-in-motion and automatic vehicle classification in an automated port-of-entry.

Weigh-in-motion, together with automatic vehicle classification, can increase truck throughput and improve weight limit enforcement in several ways.

- Sorter scales can pre-select potentially overweight vehicles based on axle and gross weight measurements and vehicle class, allowing other vehicles to proceed unhindered;
- Slow speed weigh-in-motion can increase productivity at the enforcement scale; and
- Axle spacings derived from the classification procedure allow bridge formula violations to be checked automatically.

As a consequence, weigh station efficiency could be increased, with the possibility of lower manpower requirements. Queues and back ups can be minimized, which could reduce a significant safety hazard, and relationships with the trucking industry would be improved as dollar costs to vehicle operators are also reduced.

To ensure that changes in current practices are shown to be soundly based, an incremental study approach is recommended, whereby the contribution of individual technologies to weigh station productivity is assessed over a period of evaluation.

An initial study of slow speed weigh-in-motion operations compared with static weighing for the enforcement of weight limits, using existing equipment upgraded to overcome current deficiencies, will provide the necessary data to assess the cost effectiveness of SWIM in improving weigh station efficiency.

Performance data for each operating procedure will need to be collected over a period of time. Comparisons can then be drawn between enforcement efficiencies for static and slow speed weigh-in-motion systems based on such parameters as vehicle throughput, and consequential delays, personnel requirements and detection rates.

Once the evaluation of the SWIM scale operation is complete the system could be enhanced by the addition of higher speed weigh-in-motion and automatic vehicle classification technologies. These will be used for the preselection of vehicles for enforcement weighing and the calculation of bridge weight formulas. Similar performance data would be collected as before to allow comparisons to be drawn between the basic and enhanced systems.

Finally, a fully automated port-of-entry could be established with the continuous checking of all trucks on the highway with only those vehicles which appear to be overloaded beyond a specific tolerance being stopped for precise weighing on the slow speed scale. Signalling and control devices will be required to instruct drivers on how to proceed. Stops for document checks could also be eliminated through the introduction of automatic vehicle identification. This application is being actively examined through the heavy vehicle electronic license plate program, in which Arizona is heavily involved.

An automated port-of-entry demonstration project would permit the assessment of potential benefits to government and industry from the adoption of new truck weighing technology. This project would offer a unique opportunity for Arizona to take the lead in this exciting area of new development.

APPENDIX A - STATISTICAL ANALYSES - RANDOM VEHICLES

A.1 January data

Measurement accuracy

Test the null hypothesis that the sample mean (systematic error) is not significantly different to zero for; a) axle weights, and b) gross weights.

As the sample sizes are large, it is reasonable to assume a normal distribution. Limits for 95% and 99% confidence are therefore given by ± 1.96 and ± 2.58 respectively. Table A1 has been produced using these values.

TABLE A1 MEASUREMENT ACCURACY FOR JANUARY DATA

Sample	Mean (%)	Standard Deviation (%)	95% Limits	99% Limits
Axle weights	-1.7	1.4	± 2.74	± 4.39
Gross weights	-1.5*	0.6	± 1.18	± 1.55

* Significant at the 5% level.

Weight range comparison

The abbreviations used in this table 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 (N2-2)
S1 = random error (standard deviation) of sample 1
S2 = random error (standard deviation) of sample 2
F = F distribution value

F5% = F-value contained in statistical tables for the 5% significance level.

F1% = F-value contained in statistical tables for the 1% significance level.

TABLE A2 WEIGHT RANGE COMPARISON FOR JANUARY DATA

Range 1000 lbs	V1	V2	S1	S2	F	F5% 1 tail	F1% 1 tail
10/20	78	156	1.42	1.50	1.16	1.39	1.60
10/20+	78	161	1.42	0.98	2.10*	1.37	1.58
20/20+	155	161	1.50	0.98	2.34*	1.30	1.38

* Significant at the 1% level

A.2 March data

Measurement accuracy

Test the null hypothesis that the sample mean (systematic error) is not significantly different to zero for; a) axle weights and b) gross weights.

Table A3 Measurement accuracy for March data
Weight range comparison

Sample	Mean (%)	Standard Deviation (%)	95% Limits	99% Limits
Axle weights	-2.15	1.66	± 3.25	± 4.28
Gross weights	-1.93*	0.67	± 1.31	± 1.73

* Significant at the 1% level.

The abbreviations used in this table are as used previously in this Appendix.

TABLE A4 WEIGHT RANGE COMPARISON FOR MARCH DATA

Range (x 1000 lbs)	V1	V2	S1	S2	F	F5% 1 tail	F1% 1 tail
10/20	89	167	1.63	1.77	1.18	1.38	1.58
10/20+	89	199	1.63	1.12	2.12*	1.32	1.53
20/20+	167	199	1.77	1.12	2.50*	1.28	1.46

* Significant at the 1% level

A.3 June data

Measurement accuracy

Test the null hypothesis that the sample mean (systematic error) is not significantly different to zero for; a) axle weights, and b) gross weights.

TABLE A5 MEASUREMENT ACCURACY FOR JUNE DATA

Sample	Mean (%)	Standard Deviation (%)	95% Limits	99% Limits
Axle weights	-2.40	1.46	± 2.86	± 3.77
Gross weights	-2.27*	0.98	± 1.92	± 2.53

* Significant at the 5% level.

Weight range comparison

The abbreviations used in this table are as used previously in this Appendix.

TABLE A6 WEIGHT RANGE COMPARISON FOR JUNE DATA

Range (x 1000 lbs)	V1	V2	S1 (%)	S2 (%)	F	F5% 1 tail	F1% 1 tail
10/20	81	152	1.92	1.39	1.91	1.37	1.60
10/20+	81	197	1.92	0.86	4.98	1.38	1.54
20/20+	152	197	1.39	0.86	2.61	1.29	1.40

* significant at the 1% level

A.4 Comparison of data

Comparison of sample means

Test the null hypothesis that there is no significant difference between the sample means for different data sets. This is done using a two-tailed t-test. The null hypothesis is that 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:

$$t = \frac{X1 - X2}{SD}$$

Where X1 = mean of sample 1
X2 = mean of sample 2

SD is defined by:

$$SD = \left(\frac{(N1 - 1)\, S1^2 + (N2 - 1)\, S2^2}{N1 + N2 - 2} \right)^{\frac{1}{2}} \left(\frac{1}{N1} + \frac{1}{N2} \right)^{\frac{1}{2}}$$

Where N1 is the size of the first sample
N2 is the size of the second sample.

S1 is the standard deviation of the first sample
S2 is the standard deviation of the second sample.

TABLE A7 COMPARISON OF SYSTEMATIC ERRORS - INDIVIDUAL AXLES

Samples	SD	t	t 5% 2 tail	t 1% 2 tail
Jan/March	0.106	4.25*	1.96	2.58
Jan/June	0.099	7.04*	1.96	2.58
March/June	0.105	2.38*	1.96	2.58

* Significant at the 1% level

TABLE A8 COMPARISON OF SYSTEMATIC ERRORS - GROSS WEIGHTS

Samples	SD	t	t 5% 2 tails	t 1% 2 tails
Jan/March	0.077	5.58*	1.97	2.60
Jan/June	0.099	7.81*	1.97	2.60
March/June	0.098	3.46*	1.97	2.60

* Significant at the 1% level

Comparison of sample variances

The abbreviations used in Table A9 and A10 as used previously in this appendix.

TABLE A9 COMPARISON OF RANDOM ERRORS - INDIVIDUAL AXLES

Samples	V1	V2	S1	S2	F	F5% 1 tail	F1% 1 tail
Jan/March	396	457	1.4	1.66	1.41*	1.18	1.40
Jan/June	396	432	1.4	1.46	1.09	1.19	1.40
March/June	457	432	1.66	1.46	1.29*	1.16	1.40

* Significant at the 1% level

TABLE A10 COMPARISON OF RANDOM ERRORS - GROSS WEIGHTS

Samples	V1	V2	S1	S2	F	F5% 1 tail	F1% 1 tail
Jan/March	131	144	0.6	0.67	1.25	1.33	1.45
Jan/June	131	147	0.6	0.98	2.67*	3.32	1.45
March/June	144	147	0.67	0.98	2.14*	1.31	1.45

* Significant at the 1% level

A.5 Frequency analysis

Assuming a data set of known mean and standard deviation is normally distributed, it is possible to calculate the proportion of that data set that will lie within specified limits of accuracy as follows:

The sample is normally distributed with mean "X" and standard deviation "S".

The specified accuracy limits are "within + P% of the mean"

Therefore, the required proportion is represented by the probability

$$\left(-\frac{P}{S} \quad Z \quad \frac{P}{S} \right)$$

where "Z" is the random variable distributed as the standardized normal distribution N (0,1)

Hence the proportion is given by

$$2\,\Phi\,(P/S) - 1$$

where $\Phi\ (Z) = \Phi\ (P/S)$ is the probability density of the standardized normal distribution N (0,1).

Alternatively, the specified accuracy limit of P% can be calculated for a certain proportion.

eg for 95%

$$2\,\Phi\,(P/S) - 1 = 0.95$$

$$\Phi\,(P/S) = 0.975$$

$$P/S = 1.96$$

$$\text{therefore } P = 1.96 \times S$$

APPENDIX B. STATISTICAL ANALYSES - TEST VEHICLES

B.1 Suspension type

January data

Use a two-tailed t-test to test the null hypothesis that there is no significant difference between the sample means for different test vehicles. The t value is defined by:

$$t = \frac{X1 - X2}{SD}$$

Where X1 = mean of sample 1
X2 = mean of sample 2

SD is defined by:

$$SD = \left(\frac{(N1-1)\ S1^2 + (N2 - 1)\ S2^2}{N1 + N2 - 2}\right)^{\frac{1}{2}} \left(\frac{1}{N1} + \frac{1}{N2}\right)^{\frac{1}{2}}$$

where N1 is the size of the first sample
N2 is the size of the second sample
S1 is the standard deviation of the first sample
S2 is the standard deviation of the second sample

TABLE B1 COMPARISON OF TEST VEHICLES' SYSTEMATIC ERRORS - AXLE WEIGHTS

Samples	SD	t	t 5% 2 tail	t 1% 2 tail
2 ax/3 ax	0.091	1.76	1.99	2.62
2 ax/6 ax	0.165	3.34*	2.00	2.66
3 ax/6 ax	0.096	4.07*	2.00	2.66

* Significant at the 1% level

TABLE B2 COMPARISON OF TEST VEHICLES' SYSTEMATIC ERRORS - GROSS WEIGHTS

Samples	SD	t	t 5% 2 tails	t 1% 2 tails
2 ax/3 ax	0.061	1.14	2.02	2.70
2 ax/6 ax	0.115	3.83*	2.05	2.77
3 ax/6 ax	0.110	3.36*	2.05	2.76

March data

Use a two-tailed t-test to test the null hypothesis that there is no difference between the sample means for different suspension types.

Air suspension;
N1 = 18
X1 = -1.86%
S1 = 1.09%

Mechanical suspension;
N2 = 440
X2 = -2.16%
S2 = 1.68%

$$SD = \left(\frac{(18 - 1) \times 1.09^2 + (440 - 1) \times 1.68^2}{18 + 440 - 2}\right)^{\frac{1}{2}} \left(\frac{1}{18} + \frac{1}{44}\right)^{\frac{1}{2}}$$

$$SD = 0.40$$

$$t = \frac{2.16 - 1.86}{0.40}$$

$$t = 0.75$$

With 456 degrees of freedom the required two-tailed t-values are:
1.96 (5% significance)
2.58 (1% significance)

Therefore uphold the null hypothesis at the 5% level and conclude that there is no significant difference between the sample means.

Use a one-tailed F-test to test the null hypothesis that there is no difference between the sample variances for different suspension types

$$\frac{S2}{S1} = \frac{1.68}{1.09} = 2.38$$

$$V2 = 440 - 1 = 439$$
$$V1 = 18 - 1 = 17$$

Therefore, F-values are 1.98 (5% significance)
2.65 (1% significance)

Reject the null hypothesis at the 5% level and conclude that there is a significant difference between the sample variances.

B.2 Speed evaluation

Use a two-tailed t-test to test the null hypothesis that there is no significant difference between the sample means for correct speed vehicles and overspeed vehicles.

Correct speed vehicles; N1 = 333
X1 = -1.7%
S1 = 1.4%

Overspeed vehicles; N2 = 64
X2 = -1.8%
52 = 1.4%

$$SD = \left(\frac{(333 - 1) \times 1.4^2 + (64 - 1) \times 1.4^2}{333 + 64 - 2}\right)^{\frac{1}{2}} \left(\frac{1}{333} + \frac{1}{64}\right)^{\frac{1}{2}}$$

$$SD = 0.19$$

$$t = \frac{1.8 - 1.7}{0.19}$$

$$t = 0.52$$

With 395 degrees of freedom, the required t-values are;

1.96 (5% significance)
2.58 (1% significance)

Therefore, uphold the null hypothesis at the 5% level and conclude that there is no significant difference between the sample means.