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Simulation of dynamic traffic loading for use in accelerated pavement testing (APT)

WJvdM Steyn
M de Beer
W du Preez

Programme : Transport Infrastructure
Programme Manager : BMJA Verhaeghe
Technical Reviewer : SV Kekwick

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PREPARED BY
TRANSPORTEK, CSIR
PO Box 395
Pretoria 0001
Tel +27 12 841 2905
Fax +27 12 841 3232

Title: SIMULATION OF DYNAMIC TRAFFIC LOADING FOR USE IN ACCELERATED PAVEMENT TESTING (APT)

Author: WJvdM Steyn; M de Beer; W du Preez;

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Abstract:

The Heavy Vehicle Simulator was developed in the late 1960s. The prototype and first operational machine were succeeded by the HVS Mark III. These HVS Mark IIIs have been operated successfully for over 20 years in South Africa and California. Modern technology and research needs led to the development of modernised versions of the HVS. These versions are equipped with modern control systems and dynamic load simulation capabilities.

The HVS Mark IV⁺, its history, specifications and capabilities are introduced in this paper, and compared to that of the HVS Mark III. The development of some HVS instrumentation are discussed.

The primary innovation in the capabilities of the HVS Mark IV⁺ lie in the simulation of dynamic traffic loading. Automation of the HVS ensures better repeatability of tests and control over applied parameters. Definitions are proposed for a description of the dynamic load capabilities from a loading and a pavement response viewpoint.

Initial results from the pilot study using the Moving Dynamic Load option are shown. The effect of the varying load can be observed on the permanent deformation behaviour of the pavement. Interesting data regarding the HVS and tyre behaviour during a long-term test are also provided.

The HVS Mark IV⁺ will be used in studies concerning tyre-pavement contact stresses and the dynamic response of pavements various vehicular load modes. It is foreseen that the application of this technology can increase the effectiveness of pavement analysis and design to ensure more mileage for the same money for longer lifetimes.

Keywords: Accelerated Pavement Testing, Heavy Vehicle Simulator Mark IV⁺, Dynamic simulation

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Signatures:

SV Kekwick

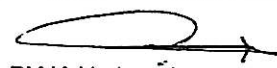


Language Editor

SV Kekwick



Technical Reviewer



BMJA Verhaeghe

Programme Manager



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1. INTRODUCTION

The objective of this paper is to introduce the latest Heavy Vehicle Simulator (HVS) technology, its capabilities and expected impact on pavement analysis. The paper starts with a short history of HVS technology. This is followed by a description and discussion of the latest technology included into the most recent HVS Mark IV⁺, including the innovations that put these HVSs at the forefront of APT technology. The proposed application of this HVS in pavement engineering, together with the reasons for its development from a pavement analysis viewpoint are discussed. A short discussion regarding the anticipated pavement response monitoring technology is included. Finally, the current project in which the HVS is involved is discussed indicating the objectives, preliminary results and anticipated effect on pavement analysis procedures.

2. BACKGROUND

2.1 History of HVS Developments

The HVS was developed by the National Institute for Transport and Road Research (currently the Division for Roads and Transport Technology, or Transportek) of the Council for Scientific and Industrial Research (CSIR) in Pretoria, South Africa in the late 1970s. Through various research projects and field evaluations of pavements, it was realised that a facility was needed for testing of real full-scale pavement structures in relatively short time periods to assist in development of better pavement structures for the country. This was mainly because of the difference in environment, traffic and materials from those areas where the empirical design methods of the time were developed. Use of these empirical design methods without adequate provision for the differences in these factors led to non-economical pavement construction and early failures of pavement structures (1,2).

A mobile Accelerated Pavement Testing (APT) device that could be used for pavement evaluation anywhere in the country on either normally constructed pavements or specially constructed test sections was designed. The first prototype was a stationary conceptual model. The second generation HVS was the first mobile version. It could deliver a single rolling wheel constant load of between 20 kN and 75 kN to a pavement test section that was 8 m long and 1 m wide. The rate of load application was 480 repetitions per hour at a speed of 8 km/h.

The third generation HVSs (Figure 1) were the main APT technology used in South Africa for the past 21 years. These were improvements on the Mark II version in terms of the load types and load ranges. The ability to use single, dual or aircraft tyres was now available on the HVS tests. The load range for these HVSs was increased to 100 kN using normal dual truck tyres and 200 kN using an aircraft tyre (3).

The loads applied by the HVS Mark III were at a constant preset load magnitude. No controlled variation in load was possible during testing. These HVSs were used on numerous pavement types to verify existing design and analysis concepts, and to develop new concepts and design functions. Pavement types evaluated included high quality granular pavements, stabilised pavements, concrete pavements and block pavements. Tests included work conducted on both normal and aircraft pavements (4,5).

The operation of the Mark III HVSs was fully manual. All hydraulic and electrical equipment had to be tuned and monitored regularly to ensure that the performance of the HVS was within the intended ranges. This caused the operation of the HVS to be a fairly labour-intensive operation (3).

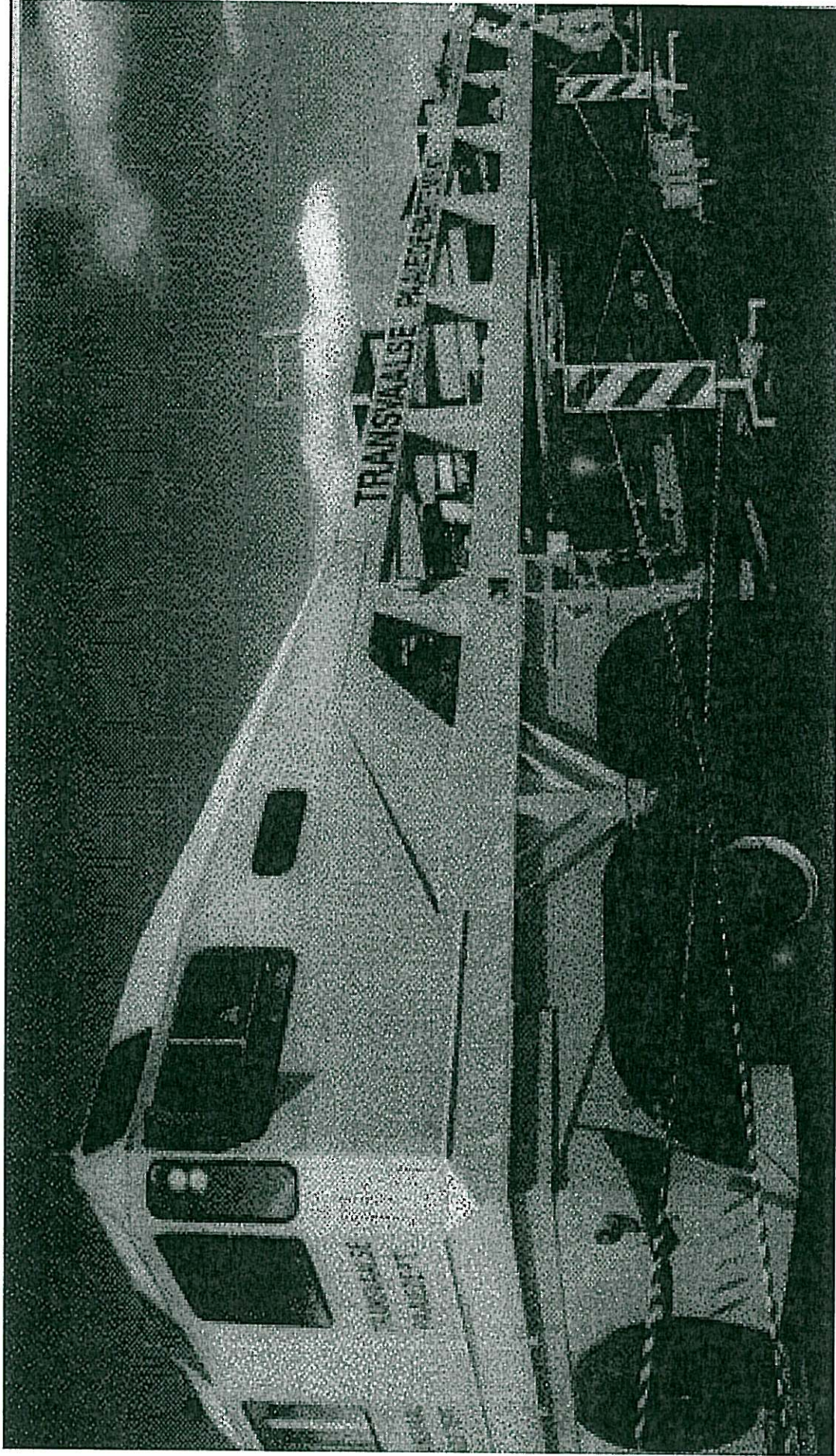


Figure 1: HVS Mark III (1976 - 1999).

TR-99/057: Background

The Mark III HVSs gave very good performance over the years. Typical productivity (trafficking time) from these HVSs rose to 80 per cent when operated on a 24 hour basis. Between the three Mark III HVSs built, more than 175 million actual repetitions were applied to 260 test sections in 21 years. This is a total of more than 1,4 million kilometres of actual travel on test sections. Typical application rates of 600 load applications per hour (including measurements and maintenance time) could be achieved with the HVS Mark III on a long term basis. Actual trafficking rates (excluding maintenance and measurements) of 850 to 900 load applications were achieved.

2.2 Associated Technology

The associated technology for these HVSs included all the instruments that were developed and used for monitoring of the pavement response to the accelerated loads. The use of an HVS without these technologies is inappropriate as the information gathered from the various instruments is needed to determine the changes in the response of the pavement to different load conditions.

The measurement process entails four distinct actions: observation, comparison, recording and interpretation. For pavement performance, most modern day measuring systems make use of electronic devices to perform the observation, comparison and recording functions. Transducers are used to convert the physical parameter to be observed into an electric signal for further processing. Pavement engineers are interested in measuring parameters which will allow them to assess the performance of their designs. Not all parameters are directly accessible (i.e. strain) and indirect methods are often used to obtain the required information. To this end a wide assortment of sensors has been developed by various centres of excellence around the world, each finding an application in determining the behaviour of a selected parameter.

2.2.1 Early HVS Measurements (1970 - 1980)

Initially, peak surface deflections were measured using a Benkelman beam and a straight-edge was used to measure surface rut (permanent deformation). All data were recorded manually and processed in the laboratory. Performance of the different layers in the pavement is still a critical parameter and the Multi-Depth Deflectometer (MDD) was developed using alternating current (AC) Linear Variable Differential Transducers (LVDT). The Benkelman beam was also modified to use an LVDT to measure the deflection. A crude manually propelled profilometer using an LVDT also was introduced.

The state of the art instruments of the day (1971) consisted of a bank of AC LVDT conditioners feeding its output to a multi channel ultra violet (UV) paper recorder. This produced many operational problems in the field. The conditioners had six variable controls per channel that field staff had to set up and record. The high altitude resulted in above average UV radiation and the UV paper had to be rolled up to preserve the data traces. These records were digitized and the

resulting punched cards transferred to the processing computer. Results were available a day or two after the measurements were taken.

From these early methods it was learned that there should preferably be no operator adjustments on the recording system and, if unavoidable, all these should also be recorded. Further, the complete time-history curve of pavement response should be recorded in all time related measurements.

The arrival of the microprocessor opened new possibilities in the field of data logging. A new conditioner system was designed to eliminate some of the shortcomings of the commercial units mainly in the area of changes in DC (direct current) offsets caused by permanent deformation of the pavement layers.

A lack of sufficient memory in the early microcomputer systems prevented the direct recording of conditioner settings. Site related information such as the number of wheel repetitions and test position were stored with the test data on magnetic tape. The system also provided a real time graphic display which enabled the operator to detect any malfunction of the transducer being recorded. In later models the microprocessor was replaced with a personal computer (PC) and the 5.25" floppy disk became the recording medium. Such developments in the data processing area made results available on the same day.

2.2.2 Intermediate HVS Measurements (1980 - 1996)

During the ensuing years great advances were made in the electronics sector in general and PC systems in particular. A new data recording system was designed using a basic conditioner board containing a digital offset control, a digitally controlled low pass filter and a programmable gain amplifier. The board is matched to any required sensor by a plug-in personality module, the type of which is also recognised by the controlling PC. A standard rack can accommodate sixteen such cards together with the power supply unit. There are no operator controls on the front panel other than the power switch as all system settings are software controlled. The software was written using page setups where all the relevant information has to be entered before proceeding to the next stage. This ensured that the recorded data is complete in all respects. During the recording process the operator is presented with real time graphic output in order to monitor sensor behaviour. This same graphical output is also available during the mechanical setup or calibration phase of the sensors.

The profilometer (Figure 2) was re-designed to speed up the profile measurements. The new unit consisted of a 2.5m long rigid beam on which a carriage is driven by a stepper motor. A laser displacement transducer is attached to the carriage and measures the pavement surface profile. The unit is controlled from the logging PC.

The main limitations of this system were that only sixteen channels were available, the system could not be used with a laptop computer due to the A/D (analog to digital) card and the profilometer was not fully controlled from the computer.

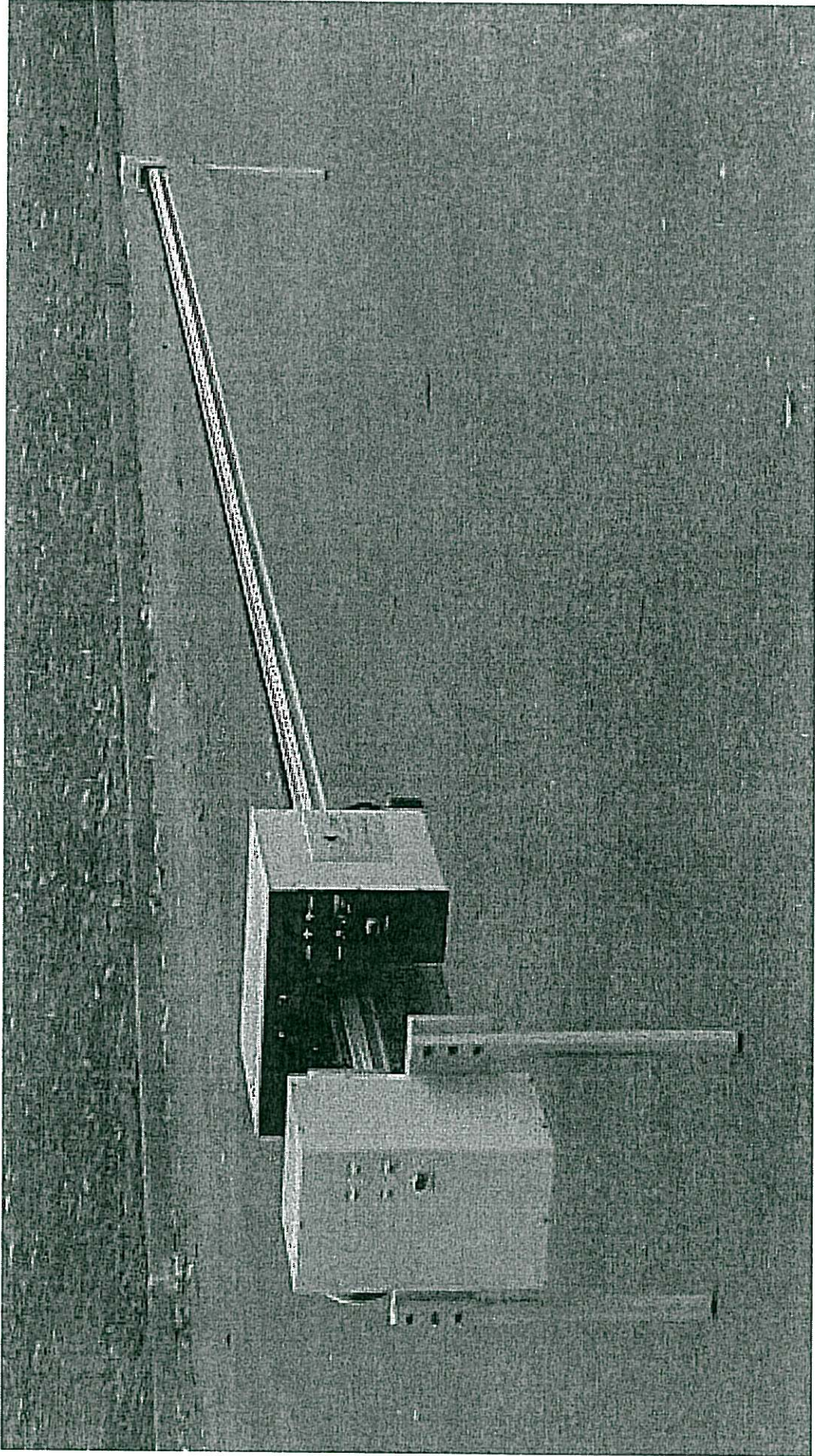


Figure 2: Laser profilometer used on HVS test sections for measuring permanent surface deformation.

2.2.3 Present HVS Measurement System (1996 - 1999)

International use of the HVS exposed shortcomings of the previous system. It was decided to use a modular commercial data acquisition system which has global availability and technical support (6). The hardware is supported by a high level programming language optimized for data acquisition and control applications and boasts a formidable arsenal of signal processing functions that are easily incorporated in the software (6). This approach allows the standard HVS measurements to be used and at the same time allows the end user to add to or modify both the software and hardware to accommodate any particular requirement that may arise.

The profilometer was redesigned to be almost a selfstanding unit and is fully controlled by the logging PC via a standard serial port. An infrared data transceiver replaced the previous cable connection and there are no connecting wires between the carriage and the control end of the beam. These modifications form part of the process to make all the sensors independent units that could later function as stations in a network.

2.2.4 Future HVS Measurement Systems (1999 -?)

Advances made with the design of the new HVS machines as well as the availability of low cost wireless data transceivers operating in the license free ISM (Industrial, Scientific and Medical) bands have presented a unique opportunity to integrate the test and measurement facilities of the HVS. The new generation of HVSs have their on-board control computers linked to the outside master computer by a spread spectrum wireless network system. It is possible to connect the data logging computer to the same network and extract wheel speed, wheel position and wheel load without compromising the control functions. The wheel position data could be used to obtain data from buried sensors such as the MDD or strain meters without slowing down or stopping the machine. This would require processed data to be transmitted wireless to the data logger from these sensors.

The development of a wireless MDD together with on-board processing is well under way but, using the present instruments, still requires the machine to be stopped for surface deflection and profile measurements. Technology developed elsewhere for the determination of rolling wheel deflections and rutting show promising results and could be used to overcome this problem (7,8). To date this system has not been tried on an HVS.

The solutions outlined above only take care of the standard HVS measurements. Other simulators and field measuring systems share most of the problems encountered on HVS sites. Of these, problems encountered with signal cables are the most frustrating. The ever shrinking size of high complexity, low power electronic building blocks enable us to put the processing power right at the sensor. Furthermore, standards have been emerging that govern the protocols in both infrared and spread spectrum radio data transmission. Without these standards, which define the communication protocol, a non-cabled link is inherently not robust. Backed by this robustness, we may now proceed to connect all our site sensors in a network and treat each sensor or sensor group as a workstation on our network.

CSIR-Transportek have been conducting trials using three sensor groups in a 2.4GHz wireless network (9). The preliminary results are very promising but a long way from permanent field installation as the processing problems at the sensor end have not been fully resolved. CSIR-Transportek have also been evaluating commercial infrared data transceivers (10) for very short distances and have had reliable data transfer over on-axis link distances up to 12m. In both the wireless and infrared systems the data transfer rate is high enough to provide real time observations of most sensors or group of sensors encountered on typical sites.

The measurement of displacement and strain, both directly and indirectly, as well as temperature and applied load constitute the basic pavement measurements. A large number of transducers for these parameters are available off the shelf and many manufacturers can produce custom versions for special applications. Some research organisations have developed non-standard transducers to suit their particular need and these are often available for sale by special arrangement. Of particular interest is the new generation of intelligent transducers (11) being developed by a number of manufacturers. These devices normally produce outputs directly in engineering units and do not require any external processing. One of the reasons for doing this is that some modern sensors, like fibre optic based devices, require extensive processing to produce useable output. At the same time the post-measurement processing to be done by the end user is greatly reduced. This type of transducer would fit in very well with the network concept outlined previously.

Recent developments in optical sensors are particularly interesting as these are now being integrated in sensor arrays avoiding the conversion between photonics and electronics at each sensing site. Optical fibres further have the capacity to send and receive optical signals over long distances and retain their freedom from electromagnetic interference. Their greater sensitivity, wide dynamic range and multiplexing capabilities combined with their electrical passivity render them worthwhile transducers. Optical sensors do, like all other sensors, suffer from the interference of multiple effects: a strain sensor may also be temperature sensitive. A further concern may be the inherent fragile nature of these sensors and the problems that may arise during installation. Unfortunately, little has been published about their application in pavement assessment.

The powerful signal processing capabilities available in both hardware and software enable us to take a fresh look at some of the older and often discarded transducers that are not capable of meeting the high signal to noise ratios that are required for analogue to digital conversion. By using signal processing routines the very small desired signals can be extracted from the raw signal plus noise mixture produced by the transducer and successfully converted for computer processing.

3. DEVELOPMENT OF HVS MARK IV AND HVS MARK IV⁺

Two of the Mark III HVSs were sold to the Californian Department of Transport (Caltrans) in 1995 and are still operational on various test sections (12). The third Mark III HVS belongs to the Gauteng Department of Transport and Public Works (Gautrans, previously the Transvaal Provincial Administration, TPA) (5) where it is still used on various test sections.

The possibility of upgrading of the Mark III HVS fleet was investigated regularly, and several small improvements were made to the machines. However, it proved expensive to upgrade the existing HVSs in terms of automation and changes to the load application systems. This, together with market demands for more HVSs led to the development of the new HVS Mark IV versions.

The HVS Mark IV (Figure 3) was an improvement on the Mark III HVS mainly in terms of the automation of the operational aspects of the HVS and the automatic monitoring of applied loads. The physical size of the HVS stayed virtually unchanged as did the load configurations (13). A number of design changes were introduced. These include an upgraded and more modern hydraulic system, a complete automatic and computer assisted control system, a different cabin end suspension and a differently styled cabin (13). One of the HVS Mark IVs were sold to the Cold Regions Research and Engineering Laboratories (CRREL) in New Hampshire, USA, and another HVS Mark IV to a joint Finland / Sweden consortium. The Finland / Sweden consortium had some modifications added to their HVS, which enabled them to apply not only a constant load to the pavement but to vary the load level dynamically over the length of the test section. A limit was placed on the ranges for these variations, and currently one sinusoidal variation of ± 20 per cent around the average load can be applied (13).

New interest in the response of pavement structures to dynamically changing loads led to the development of the HVS Mark IV⁺. The HVS Mark IV⁺ is similar to the Dynatest/CSIR HVS Mark IV with the following changes. An upgraded mechanical structure was used to withstand the effects of dynamic loading up to 15 Hz traffic loading frequency, a wider test carriage was introduced to accommodate 315/80 R22.5 dual test wheels, the tow end wheels were modified to allow positioning of the HVS over the test section without the tow end wheels damaging the test section, and the trestles were upgraded to prevent sliding of the HVS when operational (13).

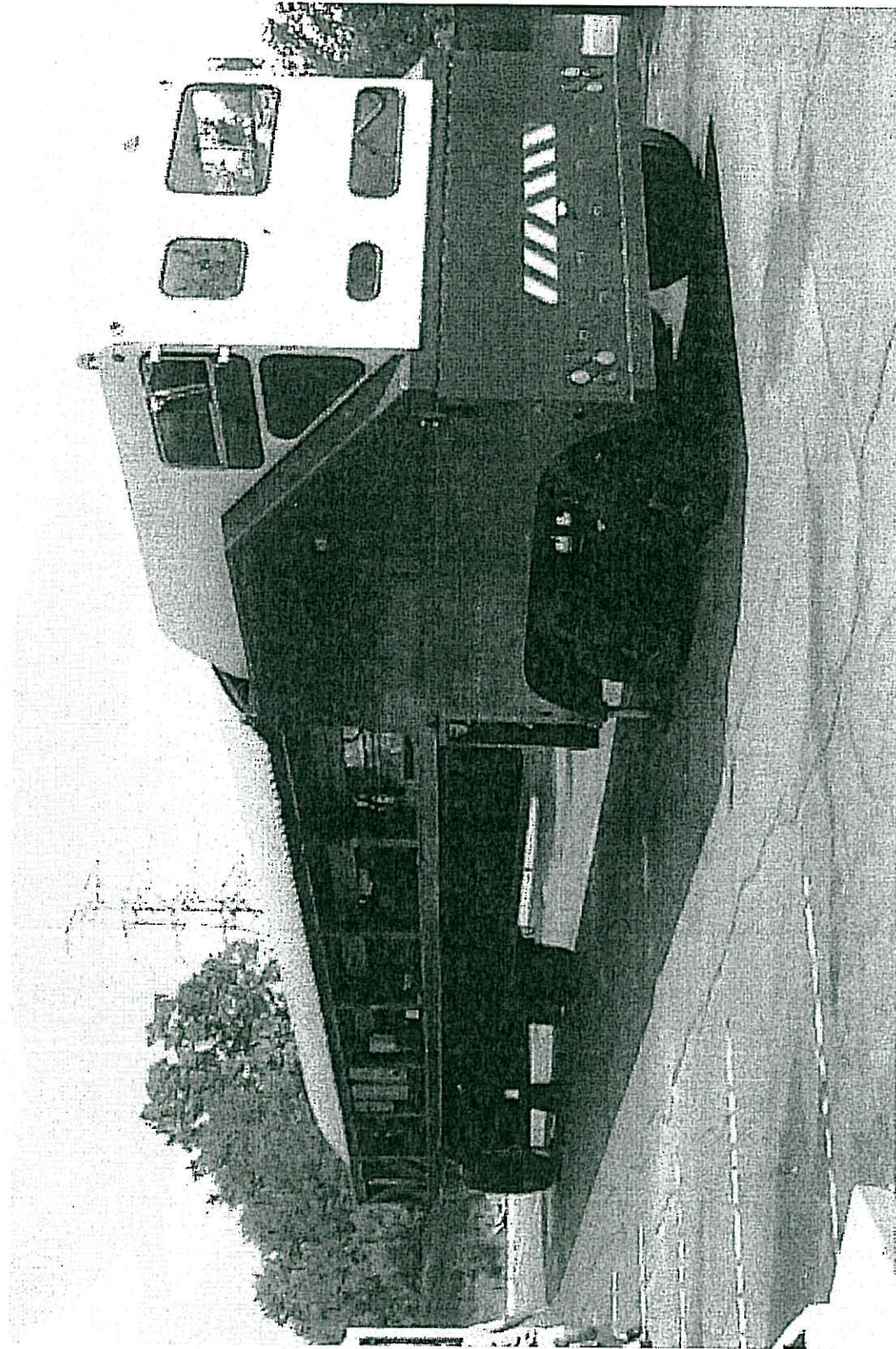


Figure 3: HVS Mark IV* (1999 -).

TR-99/057: Development of HVS Mark IV and HVS Mark IV+

3.1 HARDWARE DESCRIPTION

3.1.1 Specifications of HVS Mark IV⁺

The main dimensions and weights of the HVS Mark IV⁺ that was constructed for the CSIR are shown in Table 1, together with those of the older HVS Mark III for comparison. The HVS Mark IV⁺ is capable of applying both uni- and bi-directional loading to a pavement test section 8m long. The applied loads and speeds are controlled over the central 6 m of the test section. The test carriage can apply loads at speeds of up to 12,8 km/h for loads of between 30 kN and 110 kN over this section at an accuracy of ± 5 per cent, and at speeds of up to 6,4 km/h for loads of between 110 kN and 205 kN at an accuracy of ± 5 per cent. At the speed of 12,8 km/h a maximum of 32 000 load repetitions can be applied in 24 hours (13). An operational application rate of over 1 000 load applications per hour (including measurement and maintenance time) was reached during the first projects. This represents a 67 per cent increase in productivity over the HVS Mark III, using a similar sized operational team.

TABLE 1: Dimensions and weights of HVS Marks III and IV⁺.

Property	HVS Mark III	HVS Mark IV ⁺
Length [m]	22,56 m	22,78 m
Width [m]	3,73 m	3,50 m
Height [m]	3,70 m	3,97 m
Gross Mass [kg]	60 000 kg	47 000 kg

3.2 INNOVATIONS

The main innovations that were added to HVS Mark IV⁺ are the ability to apply a user-defined dynamically (pseudo-sinusoidal) changing load to the pavement section, the ability to apply load repetitions in a user-defined pattern to the pavement section, and the ability to use wider dual tyres than with the Mark IV. The specifications for the dynamically changing load variations are shown in Table 2.

TABLE 2: Load variation specifications for HVS Mark IV*(Eloff, 1999).

Mean Load Range [kN] Peak Load	36 - 88 kN Mean Load \pm 20 per cent (30 kN - 105,6 kN)					
Frequency [Hz] (at a test carriage speed of 12,8 km/h)	0,3	0,6	0,89	1,19	1,48	1,78
Spatial frequency [waves/m] ^a (over the central 6 m of the test section)	0,083	0,167	0,250	0,333	0,417	0,500
Number of load waves over central 6 m of test section.	0,5	1,0	1,5	2,0	2,5	3,0

^a A wave refers to a full sinusoidal wave.

The load variation options on the HVS Mark IV* consist of the following:

- a constant load along the length of the test section;
- a dynamically changing load at a specific position on the test section, and
- a varying moving load along the length of the test section.

The applied loads can range between 30 kN and 205 kN on single or dual wheels. These loads are controlled via an hydraulic feedback loop to provide an average load of within \pm 5 per cent of the selected load for at least 90 per cent of the time for long tests at any of the specified load levels. When dynamic loads are simulated a load variation of up to \pm 20 per cent of the average constant load may be applied. Normally dual or super single truck tyres are used for the loads up to 110 kN while an aircraft tyre is used for loads between 110 kN and 205 kN (13).

Typical operational data collected during the Factory Acceptance Testing (FAT) of the HVS Mark IV* indicated that the accuracy and repeatability of the applied loads are extremely good and well within the specified limits set by the CSIR. Typical data are shown in Table 3.

TABLE 3: Typical load statistics collected during Factory Acceptance Testing of HVS Mark IV*.

	30 kN Target Load	70 kN Target Load	110 kN Target Load
Average [kN]	29,98 kN	70,10 kN	110,51 kN
Standard Deviation [kN]	0,46 kN	0,37 kN	0,41 kN
Number of measurements	8 000	8 000	8 000
Percentage difference from target load	0,05 %	0,14 %	0,47 %

The varying moving load option allows the user to select any one of 6 spatial frequencies for the sinusoidal load applications. These options are shown in Table 2. The same accuracy as for the constant loads are applicable to the dynamic loads. The dynamic loads can either be applied at a specific position on the test section without any horizontal movement of the test carriage, or as a moving test load along the test section. A typical load history graph for bi-directional loading with an average load of 63 kN, a variation of ± 20 per cent in load and three load cycles per repetition, is shown in Figure 4. The two blocks indicate the load cycle while the test carriage is running on the central 6 m of the test section, while the load history between the two blocks indicate the outer 1 m of the test section at both ends, where the test carriage is stopped and the direction of travel is reversed.

The dynamic capabilities of the hydraulic system of the HVS limits the range of frequencies that may be applied. The hydraulic system allows a maximum load frequency of 1,8 Hz. The HVS Mark IV* structure was analysed for dynamic fatigue and was shown to be capable of withstanding up to 2×10^9 lifetime load applications (equivalent to 20 years of 24 hours per day less 8 per cent maintenance trafficking) before fatigue may start to develop in the test load carrying beam at a frequency of 15 Hz.

The transverse or lateral load pattern of the HVS Mark III could only be defined as being either channelized or wandering. Channelized trafficking was defined as load applications where the wheel carriage did not move transversely over the test section during a test, while wandering trafficking was defined as load applications where the test carriage was moved transversely over the test section during a specific test program. This transverse movement was introduced to enable simulation of traffic wander over a road. The options for setting this wandering mode mainly consisted of control over the distance by which the test beam (to which the test carriage is attached) could move in one direction after completion of a specific load repetition (3).

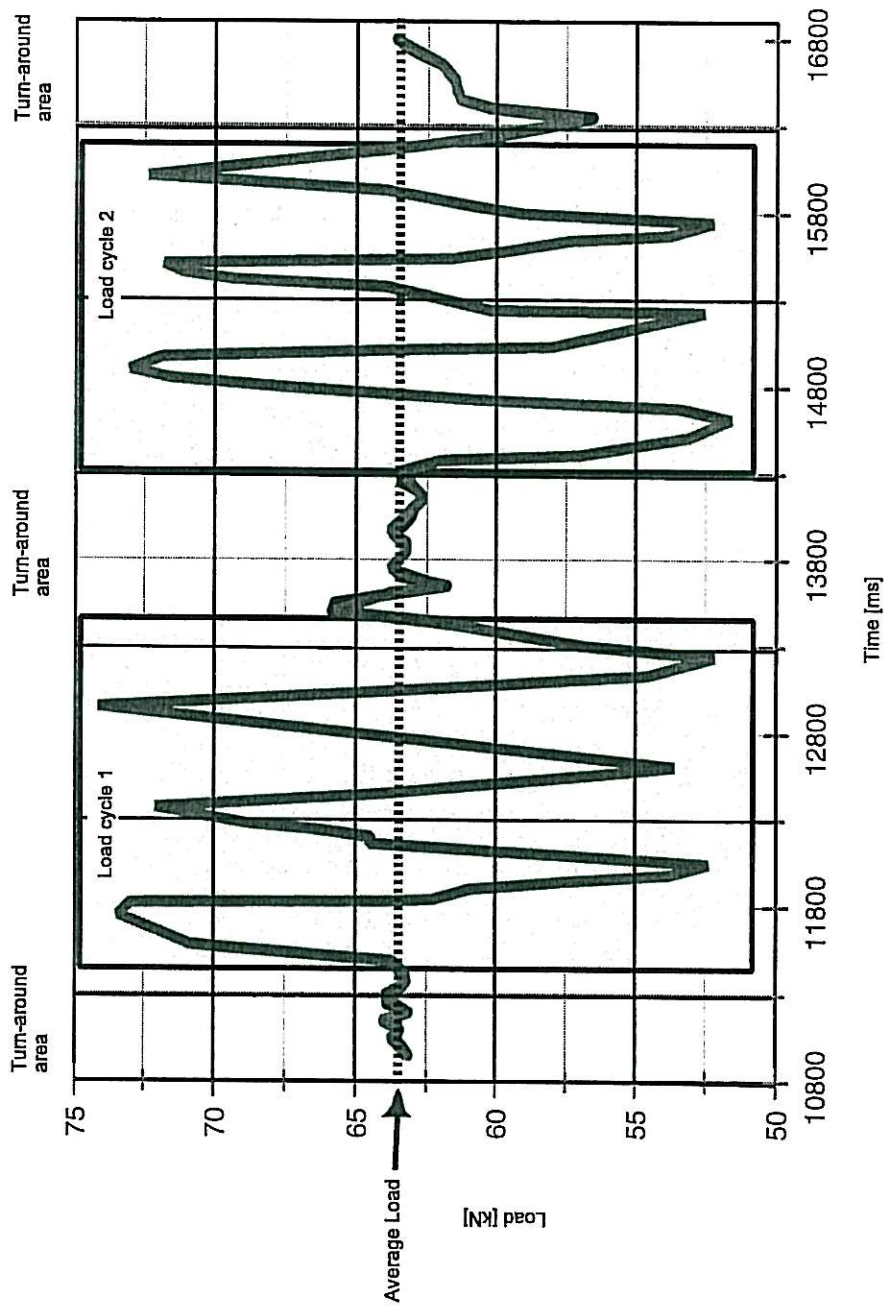


Figure 4: Load history of dynamically varying load with (pseudo-sinusoidal) average load of 63 kN, ± 20 per cent variation and spatial frequency of 0,5 cycles/m.

On HVS Mark IV⁺ the transverse load pattern option allows the user to define the load application pattern as a channelized pattern (similar to the Mark III option), a constant transverse movement wandering option (similar to the Mark III option) or a quasi-random pattern. In the quasi-random pattern the number of load applications on a specific position can be altered between the various positions at which the test beam can be located transversely over the test section, as well as the sequence in which positions may be selected, and the load level at each of these load positions. This allows for the test to be constructed in such a way that the actual measured traffic distribution on a pavement may be approximated during an HVS test in terms of both the load positions and load levels. In an initial project a double exponential wheeltrack load variation was simulated. This has been shown to be typical of highway traffic (14).

The HVS Mark IV⁺ can accommodate three types of tyres. These are dual and super single truck tyres and single aircraft tyres. Previous HVSs (up to Mark IV) were only capable of using single or dual truck tyres with a total width of 660 mm (equivalent to a set of dual 11.00x20 tyres). With increases in tyre sizes operational on national routes (15) the maximum dual truck tyre size was increased on the HVS Mark IV⁺ to accommodate a set of dual tyres with a total width of 710 mm (equivalent to a set of dual 315/80 R22.5 tyres). A super single tyre (425/65 R22.5) can also be fitted to the test carriage. The aircraft tyre supplied for use with the HVS is a 46x16 SP44 tyre, typically used on Airbus aeroplanes (13).

3.3 PLANNED APPLICATIONS

The work planned for the HVS Mark IV⁺ currently centres around further investigations into tyre-pavement contact stresses and the effects of varying loads on pavement response. Some definitions and terms need clarification for these tests to be developed and performed. This section provides some of these definitions and an overview of the intended tests.

3.3.1 Tyre-pavement contact stresses

Tyre-pavement contact stresses have been investigated in South Africa in detail for the past 5 years. This started with the development of the Vertical Road-Surface Pressure Transducer Array (VRSPTA) (18). The VRSPTA was developed with the aid of the Mark III HVSs to enable detailed measurements of tyre-pavement contact stresses. It consists of a rigid plate on which an array of 1 041 pins is located. Twenty one of these pins in the centre of the plate are instrumented with strain gauges which measure the tyre-pavement contact stresses in orthogonal directions (16).

As the load levels and speeds on the Mark III HVSs were controlled manually, difficulties were encountered with load verifications on the VRSPTA measured data. The ability of the HVS Mark IV⁺ to control both the applied loads and speeds to within 5 per cent of the set targets allows much refined resolution of tyre-pavement contact stresses. This type of work is needed in the ongoing project where the measurement and analysis of tyre-pavement contact stresses is transferred to application on normal pavements with normal traffic.

3.3.2 Varying Load Capability

The effect of varying traffic loads applied to pavements is the topic of much research (17). These loads can vary in two distinct ways. The first is the variation of load between different vehicles travelling on a pavement, while the second is the varying loads applied by a specific vehicle which are induced mainly by pavement roughness.

The first type of variation has traditionally been accommodated in pavement analysis through the use of equivalent load concepts. The traditional power law for estimation of the damage caused by axle loads other than the standard was developed mainly after the AASHO road test (18) and subsequently applied internationally. Later research indicated that the value of the exponent of the power law could vary substantially depending on the type of pavement being trafficked (19,20).

The effect of different pavement structures on the value of the exponent has been evaluated using the HVS in numerous experiments (19). The effect of different loading conditions caused by different vehicle configurations could however not be evaluated up to now. The fact that different vehicle configurations cause different and typical load functions (in terms of load level and frequency) contributes to the possibility of monitoring the effect of different vehicle configurations on pavement response by varying the load function applied to a specific pavement section. It is the intention that a research programme be developed where the effect of different load functions (using similar load levels but different load frequencies) on a specific pavement type be evaluated. This may lead to a better understanding of the effect of vehicle configurations on pavement response and deterioration. Subsequently a more realistic indication of the equivalence of different loads on a specific pavement may be developed.

The second type of variation in loads is that caused by the pavement roughness induced vertical movement of the suspension of a vehicle. This is traditionally termed dynamic pavement loading (17). The use of the term *dynamic* in pavement analysis can however cause some confusion, since a load with a constant magnitude that is moving along a pavement and a load that is stationary along the length of a pavement but varying with respect to time in load magnitude, are both dynamic, and both cause a dynamic response from the pavement. It is thus proposed that the terminology to be used be defined as follows:

1. A load that is independent of time and dependent on position (thus constant load magnitude and static position) is termed a Static Load (SL);
2. A load that is independent of time and position (thus constant load magnitude but changing position) is termed a Moving Constant Load (MCL);
3. A load that is dependent on time and position (thus the load magnitude changes according to some time-based function and the position is static) is termed a Dynamic Load (DL), and
4. A load that is dependent on time and independent of position (thus the load magnitude changes according to some time-based function and the position also changes) is termed a Moving Dynamic Load (MDL).

Typical examples of these four categories of load conditions are a parked vehicle (static load), an HVS Mark III load (Moving Constant Load), an FWD (Dynamic Load) and a real vehicle driving on a real pavement (Moving Dynamic Load). It can be seen that real traffic causes either Static or Moving Dynamic Loads, and that the Dynamic and Moving Static Loads are mainly used in research to simplify the understanding of pavement response. Using these definitions it can also be seen that an HVS Mark III can apply either Static or Moving Constant Loads and that an HVS Mark IV can apply Static, Moving Constant, Dynamic or Moving Dynamic Loads. The Dynamic and Moving Dynamic Loads are not exactly similar to that caused by real traffic. This is mainly because for real traffic the actual load function depends on the interaction between the pavement roughness, the tyre and the suspension of the specific vehicle, while on the HVS the load functions are defined and independent of these factors, although it simulates these effects. The four types of loading conditions are schematically shown in Figure 5.

The convention defined for description of the load conditions is that for vehicular loading functions the wheel is used as the reference point while for pavement analysis purposes a position in the pavement structure is defined as the reference point. This causes the vehicle to experience the pavement surface as a time-dependent input, while the pavement experiences the vehicular loading as a time-dependent input.

Ideally, the response analysis of the pavement should be dictated by the type of loading applied. Therefore static pavement response analysis should be performed for time-independent loading (i.e. Static Loading) and dynamic pavement response analysis should be performed for time-dependent loading (i.e. Moving Constant, Dynamic and Moving Dynamic Loading). The two types of pavement response are shown schematically in Figure 6.

Based on this discussion it is the intention of the HVS Mark IV⁺ plan to investigate the different effects that the four types of pavement loading conditions have on pavement response. This would entail applying load functions with similar average load magnitudes but different load functions to identical pavement structures and monitoring of the subsequent pavement response.

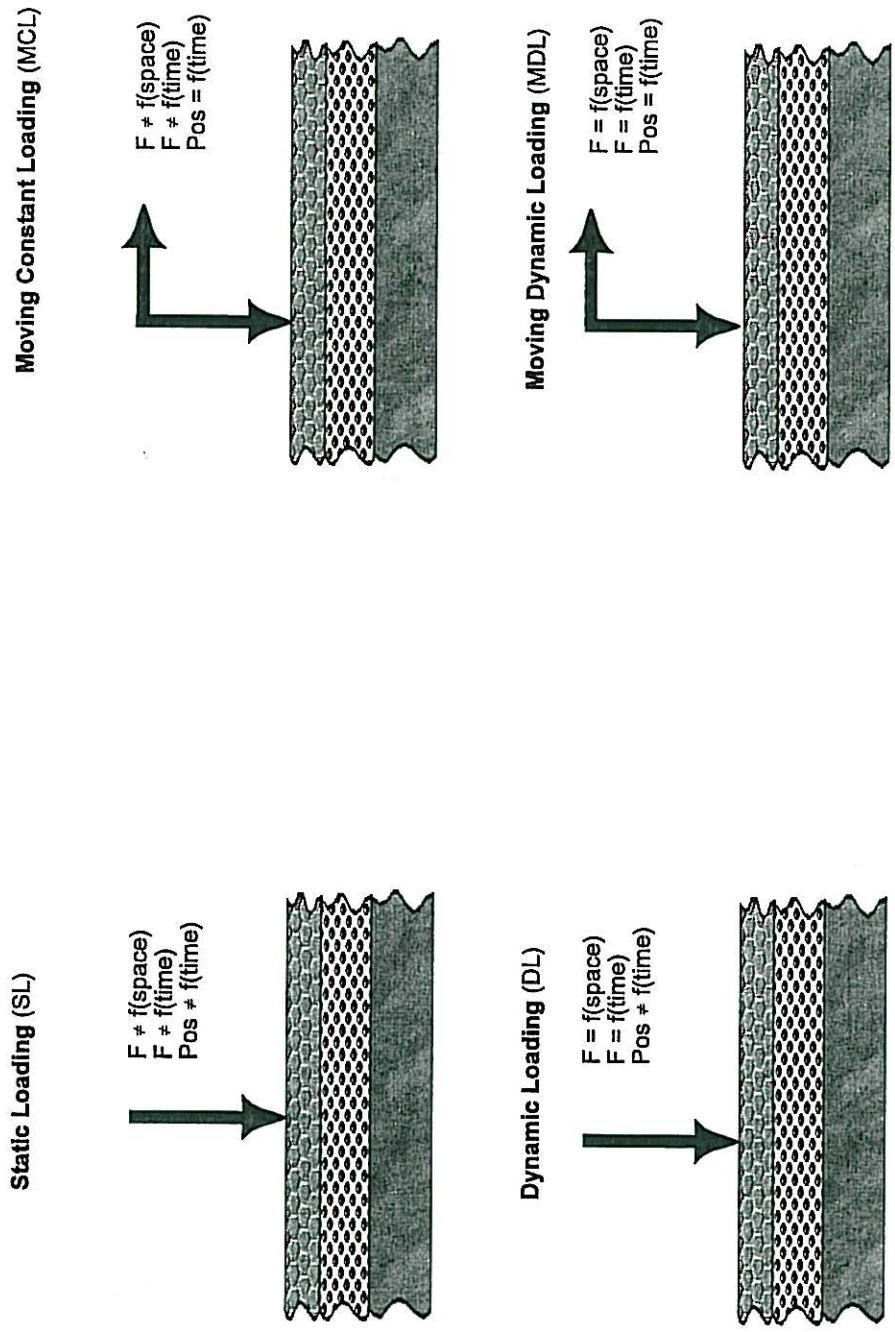


Figure 5: Four types of vehicular loading scenarios or conditions.

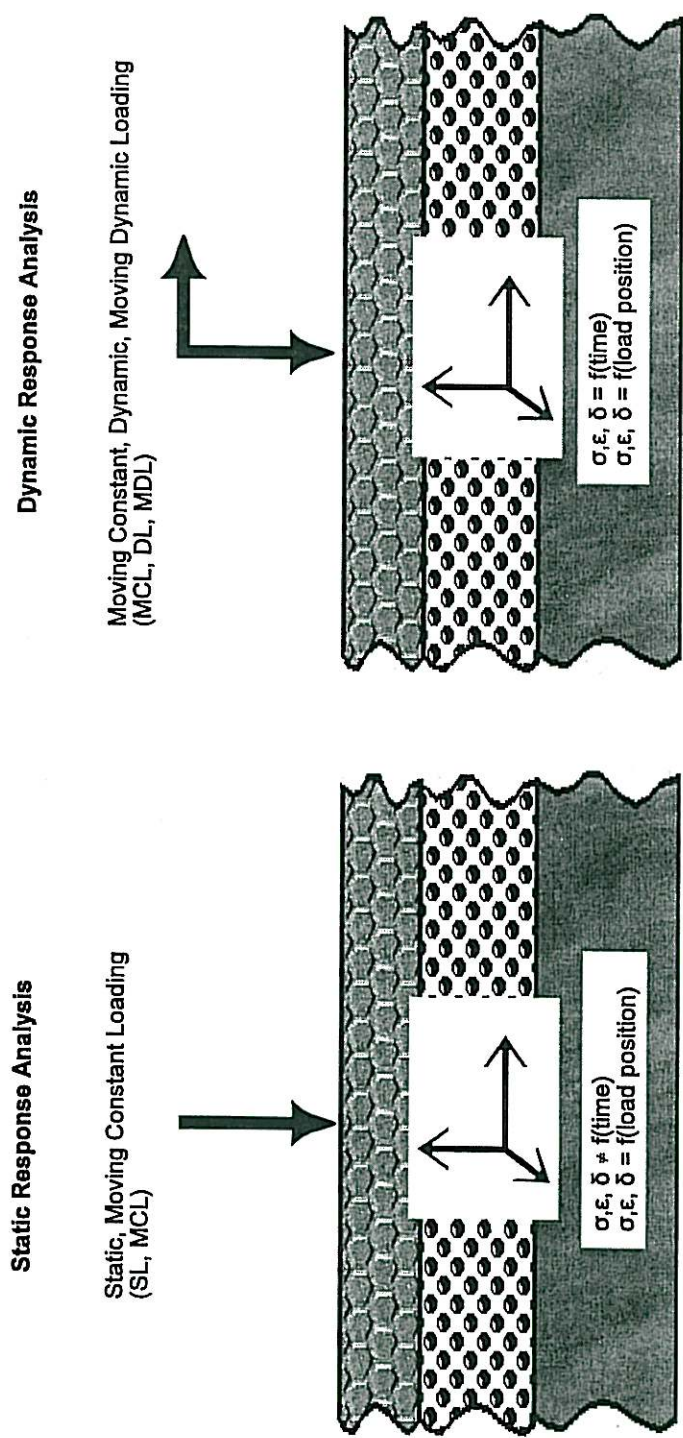


Figure 6: Two types of pavement response as a result of loading scenarios defined in Figure 5.

3.4 Limitations

As with any instrument the HVS Mark IV⁺ also has some limitations in its application towards its goal of simulated pavement loading. The limitations are mainly areas in which the simulation nature of the HVS causes a difference between real traffic applications and the HVS loading capabilities. The main limitations with the HVS Mark IV⁺ are the operational speed, unsuspended test carriage design and load principle.

The HVS is capable of loading the test pavement up to a speed of 12,8 km/h for extended periods. This is attributable to the mechanical and hydraulic limitations of accelerating and decelerating a test carriage to higher speeds in the short length available. To ensure that the HVS stays a mobile system, the length cannot be increased substantially. The level of hydraulic energy needed to attain higher speeds also causes possible safety hazards, and becomes too expensive to maintain.

The design of the HVS does not allow for a suspension system incorporated into the test carriage. The load principle on which the HVS operates is thus a controlled load principle without any feedback from the pavement surface, as would normally happen for real traffic. This causes the effect of pavement roughness on the vehicle (test carriage) and the subsequent generation of dynamic loads to be ignored in the HVS. Although this limits the level to which real vehicle-pavement interaction can be simulated, it adds to the control that the operator has over the actual applied loads. In the research environment it is often better to have exact control over input parameters and extrapolate the results from certain experiments to other cases, than to have less control over more real input parameters and have difficulty in interpretation of the results of the experiment.

The load principle that the HVS operates on (load control) also causes the HVS test sections to be excluded from functional pavement roughness deterioration measurements. This is because most of the normal traffic-induced pavement roughness on pavements is due to the vehicles reacting to the unevenness on the pavement and causing a dynamic load pattern on the pavement (19). Apart from this, the physical length of the HVS test section also prevents longer wavelengths of pavement roughness to be measured on the 6 m test section.

3.5 WORK-IN-PROGRESS

3.5.1 Pavement Tests

The first project for the HVS Mark IV⁺ consists of a training and commissioning project for the staff on the HVS. It consists of a range of tests using permutations of the options regarding load magnitudes, load patterns, load types and uni/bi-directional testing. The main objective of this project is to familiarise the new HVS team with the various options, and to obtain baseline information regarding the operational capabilities of the new HVS.

The first pavement response project consisted of a dynamically varying load with a spatial frequency of 3 cycles per 6 m and a load magnitude of 88 kN \pm 20 per cent to be applied to a relatively strong pavement section. The objective of this test was to monitor the specific effect of the change in load magnitude along the length of the test section on parameters such as permanent deformation.

The main results from this test are shown in Figures 7 and 8. In Figure 7 a surface plot of the test section after a total of 250 000 single load applications is shown. The maximum loads were applied at positions as indicated on the figure, and the direct effect of the increased loads and confined lateral distribution of traffic can be observed.

The load ratio between the maximum and minimum loads is 1,5:1,0. The relative damage coefficients (in terms of permanent deformation and relative to the 70 kN minimum load locations) for the test section were calculated as between 1,1 and 1,3.

The difference in permanent surface deformation due to different load levels can also be seen in Figure 8, where the development of permanent surface deformation with number of load applications for the maximum (105 kN) and minimum (70 kN) positions on the test section are shown. Currently further work is planned where a test will be performed on an asphalt surfaced pavement section which will be heated to evaluate the applicability of the Moving Dynamic Load option on such pavement sections. More dramatic differences in permanent deformation rates may be expected for the heated asphalt sections, as the permanent deformation is expected to occur mainly in the asphalt layer and not in the granular base layer, as for the results shown.

The use of the three locations at which the three different loads (105 kN, 88 kN and 70 kN) were applied as three sets of data, allows for the HVS test to be interpreted as three individual test sections on one type of pavement. Where this traditionally required three complete HVS tests to be performed, the Moving Dynamic Load capability now effectively allows three times the productivity and data to be derived from a test section provided it is well instrumented and monitored, within the limitations of the short test sections. In this sense, with the added increase in load application rate, the operational productivity of the new HVS when used in the Moving Dynamic Load mode, is approximately 4 times higher than that of the HVS Mark III.

HVS Mark IV⁺ monitors various HVS parameters during a test. The most important of these from a pavement viewpoint are the average load per repetition, standard deviation in load per repetition, average tyre inflation pressure and tyre temperature per repetition. Preliminary investigation of this data from the first pilot pavement response HVS test, revealed an interesting factor to be considered in pavement design philosophy. It has long been understood that the tyre temperature and inflation pressure increase due to roll resistance and deflection of the tyre. It has, however, been the perception that these factors reach an optimum level and that the tyre inflation pressure (and subsequently the tyre-pavement contact stress) are relatively constant once this optimum was reached.

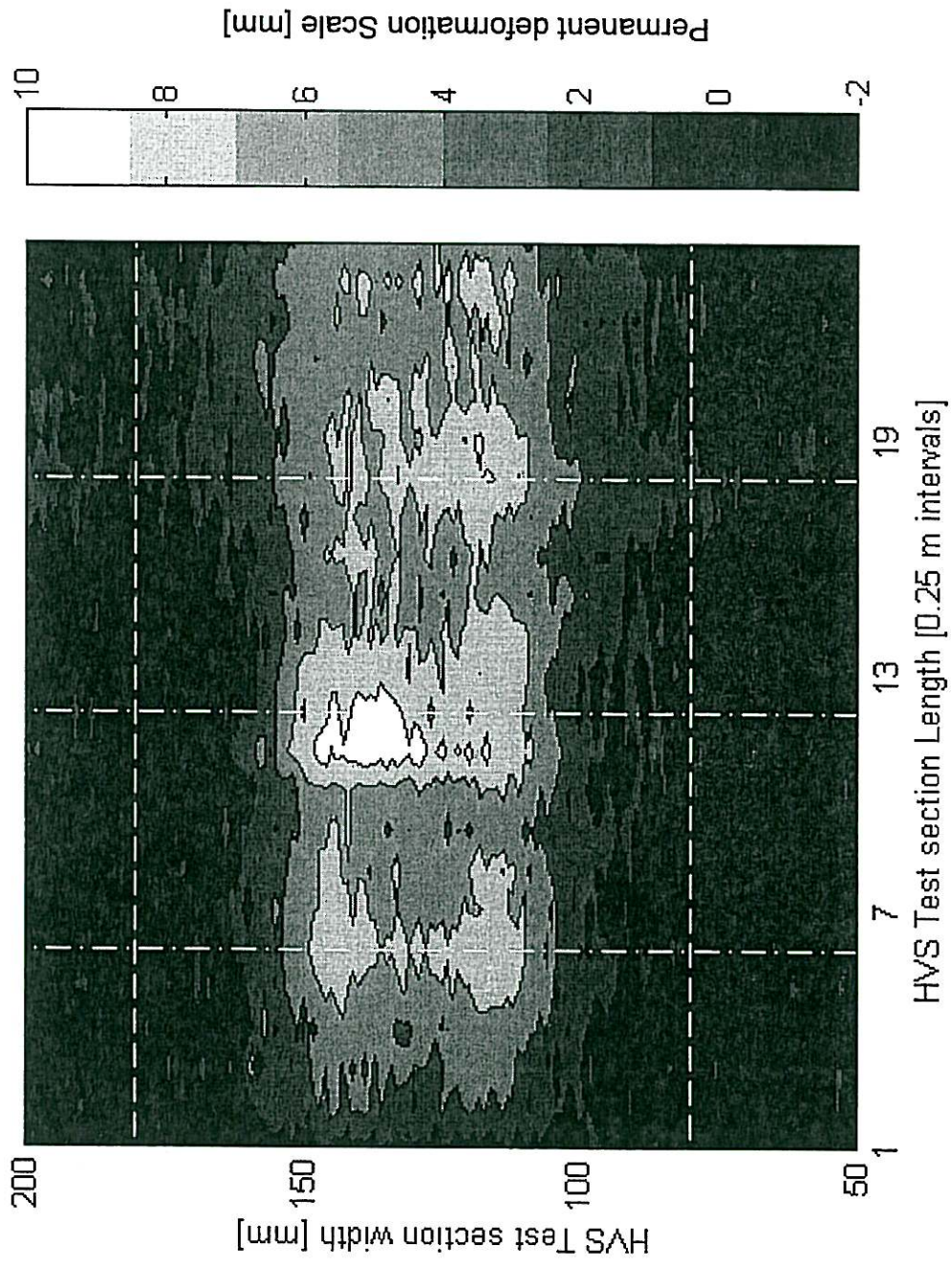


Figure 7: Surface plot of permanent deformation on HVS test section after 250 000 Moving Dynamic Load applications at spatial frequency of 3 cycles per section.

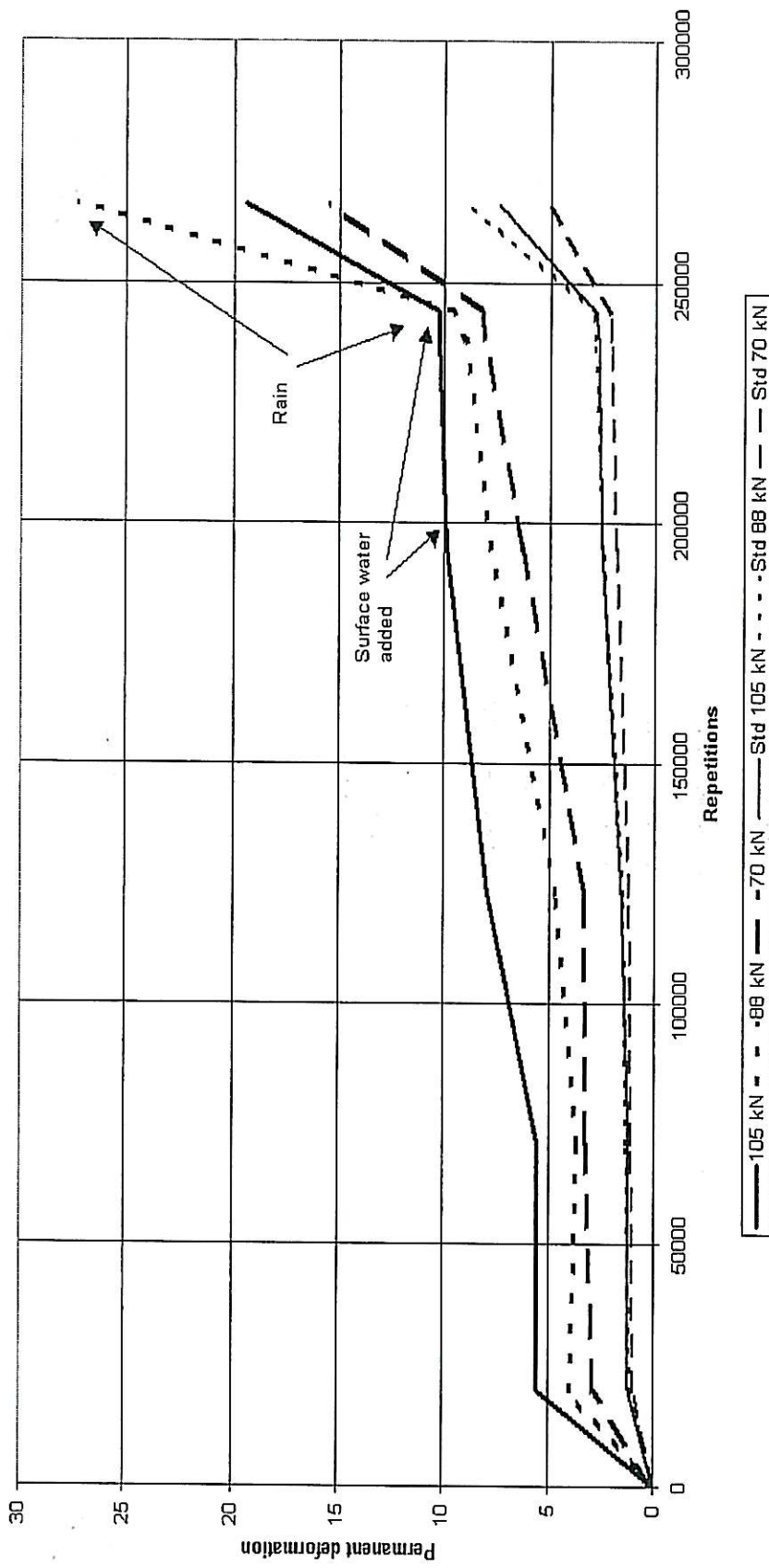


Figure 8 : Permanent surface deformation growth for HVS test section loaded using a Moving Dynamic Load of 88 kN \pm 20 per cent variation and a spatial frequency of 3 cycles per section length.

In Figure 9 the diurnal change in tyre inflation pressure and tyre temperature are shown together with the diurnal ambient temperature during the HVS test for a 24 hour period. It indicates that a relationship exists between the ambient temperature and the tyre temperature, and therefore also between the ambient temperature and the tyre inflation pressure. For the specific conditions under which the HVS test was performed, a diurnal tyre inflation pressure change of approximately 45 kPa was observed. This relates to a diurnal tyre-pavement maximum vertical contact stress change of approximately 60 kPa. Although it is too early to speculate regarding the effect of such changes on pavement behaviour and response, it is now possible to monitor these changes using HVS Mark IV⁺. As it shows that ambient temperature affects tyre inflation pressure directly, the possibilities of analysing differences in diurnal vehicular loading and pavement behaviour should be investigated. The effect of diurnal changes in ambient temperature on asphalt temperature and behaviour combined with diurnal contact stress changes also appears to be a new area of investigation. More analysis of this data together with the pavement response data is currently planned.

3.5.2 VRSPTA Tests

Full three dimensional VRSPTA measurements are planned of all the tyres to be used on the HVS, under a range of loading conditions (i.e. Stress-In-Motion database of HVS tyres). This is to serve as a reference for later HVS and tyre-pavement contact stress work.

3.5.3 Load History Tests

A set of load-history measurements for all the load modes of the HVS is also planned. These results will be compared with simulated vehicle load histories to determine the actual simulation potential (in terms of speeds and pavement roughnesses) of the HVS Mark IV⁺.

It is intended that the results of this project would serve as the basis for a thorough understanding of the physical and operational capabilities of HVS Mark IV⁺.

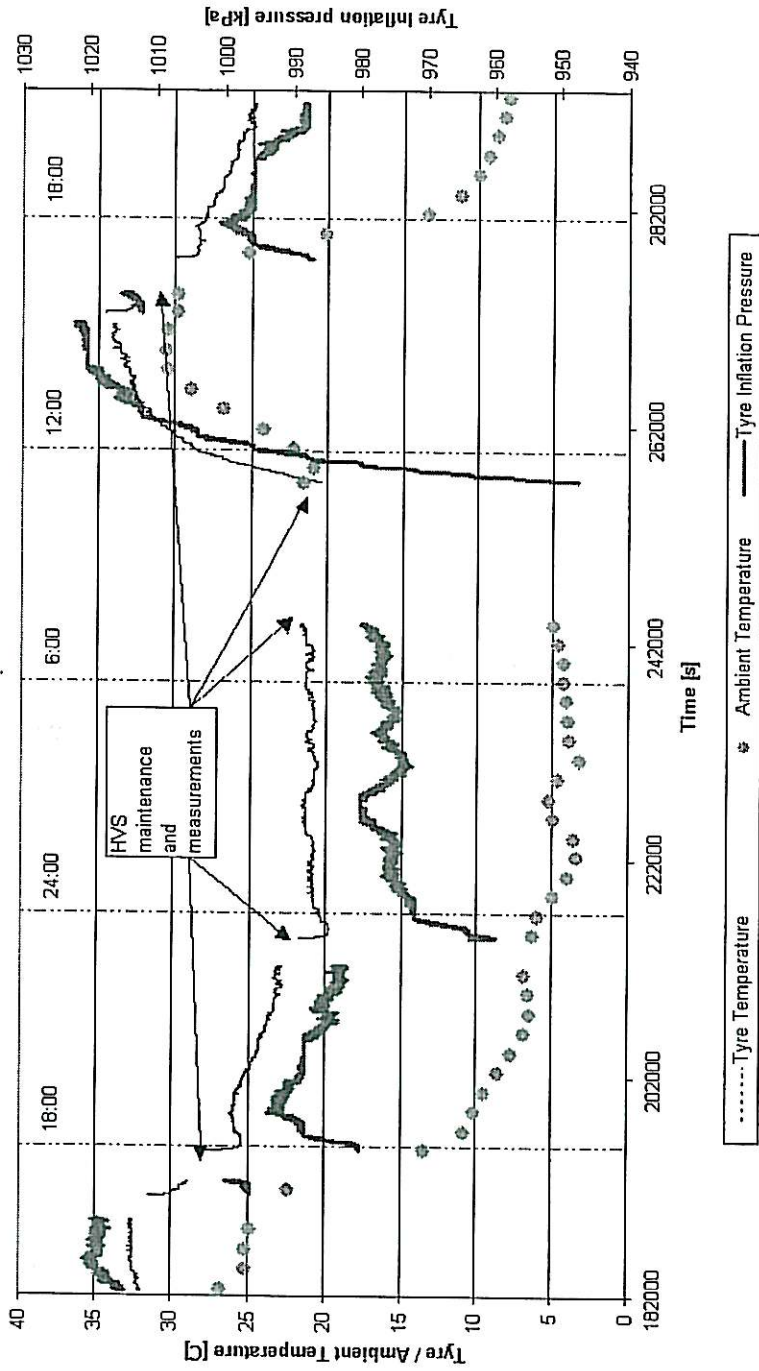


Figure 9: Tyre inflation pressure, tyre temperature and ambient temperature over a 24 hour period of HVS operation.

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4. CONCLUSIONS

The objective of this paper is to introduce the newly developed HVS Mark IV⁺ and some of its capabilities. The history and development of the HVS fleet and some HVS instrumentation have been discussed. The specifications of the HVS Mark III and the HVS Mark IV⁺ were shown to indicate the main differences. Detailed information regarding some of the load function capabilities of the HVS Mark IV⁺ were provided.

It was indicated that the primary innovations in the capabilities of the HVS Mark IV⁺ lie in the simulation of dynamic traffic loading and random load distribution patterns. Further, the automation of the HVS ensures better repeatability of tests and control over applied parameters. Definitions were proposed for a description of the newly acquired dynamic load capabilities both from a loading and a pavement response viewpoint.

Initial results from the first pilot study where the Moving Dynamic Load option was used were shown. It was shown that the effect of the varying load can be observed on the permanent deformation behaviour of the pavement. Data regarding the HVS and tyre behaviour during a long-term test were also monitored. Further investigation and data reduction is ongoing.

The intention of the HVS Mark IV⁺ is to be used in studies concerning tyre-pavement contact stresses and the dynamic response of pavements to static, moving constant, dynamic and moving dynamic vehicular loading conditions. It is foreseen that the application of this technology can increase the effectiveness of pavement analysis and design to ensure more mileage for the same money for longer lifetimes.

5. ACKNOWLEDGEMENT

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6. REFERENCES

1. Van Vuuren, D.J. *Pavement performance in the S12 road experiment, an AASHO satellite test road in South Africa*. 3rd International Conference on Asphalt Pavements, London, UK, 1972.
2. Van Vuuren, D.J. *The Heavy Vehicle Simulator*. Shell Bitumen Review 41, London, UK, 1973.
3. Steyn, W.J.vdM. *Guideline to the use and operation of the Heavy Vehicle Simulator (HVS)*. Internal Report I/PA/3/95, Division for Roads and Transport Technology, CSIR, Pretoria, South Africa, 1995.
4. Gass, G. *The HVS text database*. Technical Note: I/PA/18/95, Division for Roads and Transport Technology, CSIR, Pretoria, South Africa, 1995.
5. Rust, F.C., Kekwick, S.V., Kleyn, E.G. and Sadzik, E.S. *The impact of the Heavy Vehicle Simulator (HVS) test programme on road pavement technology and management*. Proceedings of the 8th International Conference on Asphalt Pavements, Seattle, USA, 1997.
6. National Instruments. *Data Acquisition Catalogue*, 1998.
7. Herr, W.J., et al *Deflection basin measurements and backcalculation under a rolling wheel load*. Transportation Congress Proceedings.1995.1:600-611. San Diego, CA.
8. Herr, W.J. and Johnson, W.G. *Rolling-wheel deflection measurement with Scanning Lidar*. North American Symposium on Non-destructive Evaluation of Ageing Infrastructure.1995.2455:342-353. Oakland, CA.
9. Jost, S. and Palmer, C. *Prism 2.4 Ghz "Antenna-to-Bits" 802.11 DSSS Radio Chipset Solution*. Harris Semiconductor Application note, 1998.
10. Hewlett-Packard. *IrDA Data Link Design Guide*. 1997.
11. Brignell, J.E. and White, N.M. *Intelligent Sensor Systems*. ISBN 0 7503 0297 6, IOPP,Bristol,1994.
12. Nokes, W.A., Harvey, J.T., Du Plessis, L., Long, F. and Stolarski, P.J. *CALTRANS accelerated pavement testing (CAL/APT) program - test results: 1993-1996*. In: Proceedings of the 8th International Conference on Asphalt Pavements; University of Washington, Seattle, Washington, 1997.
13. Eloff, J.P. *HVS MK IV⁺ User's manual*. Confidential Report R0009700-0795. Ermetek Reumech, Elandsfontein, South Africa 1999.
14. Blab, R. and Litzka, J. *Measurements of the lateral distribution of heavy vehicles and its effects on the design of road pavements*. In: Road Transport Technology - 4, Proceedings of the Fourth International Symposium on Heavy Vehicles and Dimensions; edited by C.B. Winkler, Ann Arbor: University of Michigan Transportation Research Institute, pp 389-395, 1995.
15. Steyn, W.J.vdM. and Fisher, C. *Report of survey on truck suspension and tyre characteristics: Beitbridge - 2/3 December 1997*. (Technical Report TR-97/048), Pretoria: Division for Roads and Transport Technology, CSIR, 1997.
16. De Beer, M., Fisher, C. and Jooste, F.J. *Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers*. Proceedings of the 8th International Conference on Asphalt Pavements, August 10-14, 1997, Washington, Seattle, USA, 1997.

17. HRB, *The AASHO road test*. Highway Research Board, Special Report 73, Washington, DC, USA, 1962.
18. Horak, E., Kleyn, E.G., Du Plessis, J.A., De Villiers, E.M. and Thompson, A.L. *The impact and management of the Heavy Vehicle Simulator (HVS) fleet in South Africa*. Proceedings of the 7th International Conference on Asphalt Pavements, Nottingham, UK, 1992.
19. *Dynamic Interaction of Vehicle & Infrastructure Experiment: Asia-Pacific Concluding Conference*. Melbourne, Australia: ARRB-TR, 1997.
20. *Structural design of flexible pavements for interurban and rural roads*. Technical Recommendations for Highways; TRH4, Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport, 1996.