Three decades of development and achievements: The Heavy Vehicle Simulator in accelerated pavement testing.

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Abstract

The purpose of this paper is two fold. First, it will provide a brief description of the technological developments involved in the Heavy Vehicle Simulator (HVS) accelerated pavement testing equipment. This covers the period from concept in the late 1960's, to the current state-of-the art HVS Mk-IV Plus and HVS-A Mk-V. Second, an overview of the research performed by the various accelerated testing programs currently using the HVS as their accelerated testing tool will be provided. The overview will focus on the South African experience, where the HVS was developed. Brief descriptions of HVS research and summaries from other programs worldwide are also provided. These include the Partnered Pavement Research Center (California), the U.S Army Corps of Engineers Engineering Research and Development Center (CRREL and WES), the Swedish and Finnish HVS-Nordic program and the Florida DOT HVS test programs.

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Introduction

The need for accelerated testing of pavements arose from the uncertainty of design models and analysis techniques that could only be verified with performance observed under normal traffic in real time. Accelerated Pavement testing (APT) was developed to fill the important gap between empirical design models and real, long-term pavement performance monitoring and analysis.

APT came to the fore in the late 1950s with the AASHO road test in the USA and since then has played an important role in the elevation of road construction to a largely rational process Metcalf (1) reported 28 active APT programs worldwide, and Hugo (2) lists significant findings from these for full-scale APT. The philosophies behind - and the approaches to - APT in the various programmes vary considerably, imparting some degree of uniqueness to several of these experimental set-ups. In the case of the South African Heavy Vehicle Simulator (HVS), this uniqueness results primarily from the fact that it was designed to be used on real, in-service pavements.

Motivation for an HVS program in South Africa

Although empirical design procedures developed from the AASHO road test were originally incorporated in the South African design methods in use at that time, a great deal of effort was devoted to the development of design procedures to suit the local environment. APT appeared to have the capability of rapidly evaluating the performance of these developments and South Africa decided to pursue this approach.

Fixed-facility APT devices, and in some cases loop facilities, have the disadvantage that specially designed experimental pavement sections built at these facilities may not be typical of in-service pavements. In order to address the shortcomings of all the available APT technologies at that time, the then National Institute of Road Research (NIRR) of the Council for Scientific and Industrial Research (CSIR) (now CSIR-Built Environment Unit) developed the Heavy Vehicle Simulator (HVS).

The start-up of the South African HVS programme

The South African pavement design approach during the 1960s was to develop an analytical design procedure in which the engineering characteristics of pavement materials could be used together with a mathematical model to predict or analyze pavement performance (Walker *et al.*, 3). This led to the South African Mechanistic Design method (4). Confidence in these models could however, only be established by verifying their predictions against the performance of real pavements. In 1967 van Vuuren (5) reported that there was no satisfactory procedure for the determination of the effects of abnormal vehicles on roads and he recommended that full-scale experimental test roads be built and trafficked with abnormal heavy vehicles. This lead to the construction of full-scale test section loops at the Silverton test site of the then NIRR. Heavy vehicles were used to apply the loads on these test sections. The low rate of load applications by using this approach became the motivation for the development of an accelerated loading testing facility.

The first HVS was designed to simulate the damage done to airport runways due to aircraft landing gear impact. This fixed facility was manufactured from Bailey Bridge components and subsequently became known as the HVS Mk I. The reaction force (ballast) applied to the pavement utilized water tanks placed above the aircraft wheel supported by the Bailey Bridge structure. The facility produced useful results but was not mobile. As a result, Van Vuuren in 1972 (6) recommended that, due to atypical construction of test sections at the Silverton site, a mobile loading facility should be developed that could test real, in-service pavements.

The first fully mobile self-powered HVS (Mk II) was commissioned in October 1970 (7). The 30 ton machine could apply up to 800 repetitions per hour over a 6.2 m long test section. The initial maximum load applied to the pavement was 35 kN (1/2 axle), which was later increased to 75 kN (1 axle). By the end of 1972, 10 accelerated trafficking tests had been conducted with HVS Mk II. Data collected during the initial 10 tests included surface deflections, radius of curvature, permanent deformation, Visual distress data, such as cracks, material loss, shear failures, etc.

Analysis of this data provided information on wheel load equivalency factors, rutting in untreated granular layers and load-associated cracking in cement-treated bases. By the end of 1975, 24 tests had been completed with HVS Mk II, but the main success and focus of the

HVS programme began in 1972. A new coal delivery road, had been built between Witbank and Johannesburg between 1966 and 1969. Severe failures occurred on a 48 km section of this road within the first year of operation and major rehabilitation was necessary on certain sections. As a result 18 HVS tests were conducted on this road to investigate these problems (8).

The test results were so promising that in 1972 NIRR motivated for the manufacture of 3 additional improved HVS Mk III machines, which were designated HVS 2, 3 and 4 (9). The machines were financed by NIRR, the National Department of Transport (NDoT) and the Transvaal (now Gauteng) Department of Transport. The motivations for expansion of the HVS fleet are briefly summarized below:

- The desire was expressed by some road authorities to verify new pavement designs in the field before the start of any major construction, by constructing trial sections in the same area so that environmental and subgrade conditions would be similar. The objective would be to determine the mechanism of distress and life (in terms of the number of load repetitions) to "failure" of the proposed pavement. To improve the South African new Pavement and Rehabilitation design procedures. The specific aims were:
    - To determine wheel load equivalencies;
    - To establish the effect of Bi-directional trafficking;
    - To verify new designs proposed in the pavement design method;
    - To extend the data from above to four climatic regions in South Africa;
    - To verify the theoretical predictions of distress in cemented base pavements;
    - To evaluate the prediction of fatigue cracking in bituminous pavements, and
    - To evaluate stress-dependent response and deformation of existing pavement for overlay design purposes.

Further development of the HVS

Fundamentally similar to the Mk II, the Mk III machines had significant differences beyond simple cosmetic improvements: the test wheel carriage was now designed to take normal dual truck wheels (only single wheels were used in the Mk II model), as well as aircraft wheels. Road transportation was changed to use a truck tractor for towing the HVS between remote locations at about 45 kph. It was self-powered for on-site mobility. The design also allowed for both uni- and bi-directional trafficking (Clifford, 1975, 10; Paterson, 1977, 11). The test section length remained at approx. 6m and loads of up to 200 kN were possible. Test wheel speed was about 8 kph, allowing approx. 18000 bi-directional wheel load repetitions per day. At a test wheel load of 40 kN (half-axle) this produces 18000 ESALs per day. Further acceleration is achieved by increasing the test wheel load. For instance, if a wheel load of 100 kN is applied the fourth power damage relationship suggests that each pass of the wheel produces 39 ESALs, for a total of about 702000 ESALs per day. The design allowed for simulation of up to 1 meter traffic wheel wander. Dimensions were 23m L x 3.7m W x 4.2 H. The Mk III weighed about 57 tonnes

In contrast to the Mk II, the three new production machines went into continuous use on public roads throughout South Africa from the outset. They were funded from grants received from the NDoT (for two machines) and from the Transvaal Provincial Administration (TPA) (for its machine) and were all operated and maintained by NIRR staff. This was done in close collaboration with the road authorities involved, and representative advisory committees were formed from the beginning. This relationship has been a significant factor in the undoubted success of the programme, ensuring the earliest possible application of important findings.

From the late 1970s and throughout the 1980s, the expanded HVS programme was able to underpin virtually all the advances and developments in South African pavement engineering, some of which are highlighted later. While South Africa's political status at that time undoubtedly restricted direct exposure of the HVS' work there were, nevertheless, significant numbers of overseas visitors during this time, notably from the United States, United Kingdom and Australia.

In 1994, after a successful pilot project demonstrating the HVS capabilities, the California Department of Transportation (Caltrans) decided to establish the CAL/APT programme and purchased two of the HVS Mk III machines. Both machines were refurbished in South Africa before being shipped to the USA. The machines were delivered in 1995 and immediately began testing pavements for the CAL/APT programme. This programme involved collaborative efforts between Caltrans, the University of California, Dynatest Consulting and the CSIR. This venture sparked international interest and by 2003, 4 additional new units had been sold internationally.

The rising interest in APT internationally has boosted further development in HVS technology and a new generation of HVSs, the HVS Mk IV was developed by Dynatest Consulting under license from the CSIR. The HVS Mk IV remains closely aligned to its forerunners, but was modernised and re-designed from the ground up, resulting in an improved and more efficient machine. Fully computer controlled, many machine functions are monitored and automatic shutdown occurs if these functions deviate beyond pre-set limits. Use of off-the-shelf running gear components and other improvements resulted in a weight reduction to approx. 46 tonnes. Height was reduced to 3.9m. Test wheel speed was increased to about 12 kph allowing approx. 26000 bi-directional wheel loads per day. Other test specifications are similar to the Mk III. The first HVS Mk IV was purchased by the Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers, who took delivery in early 1997. A second HVS Mk IV, was sold jointly to the national Road Research Laboratories of Finland and Sweden (VTT and VTI respectively), and was delivered in June 1997.

In a parallel development, a HVS for the testing of airport pavements was designed for the Waterways Experiment Station (WES) of the US Army Corps of Engineers. Apart from its physical size (36.3m x 4.23m x 4.99m , 102 tonnes), the fundamental difference between the new HVS–A (dubbed "Bigfoot") and the HVS Mk IV lies in the loading capability of the former - it can load the test wheel up to 440 kN over a 12m test section whereas the HVS Mk IV can only apply 200 kN over 6m. The HVS–A is also designed to utilise dual aircraft wheels. This machine was delivered to WES in 1998.

An improved version of the Mk IV, the HVS Mk IV + was also designed for CSIR and was delivered in March 1999. The HVS Mk IV+ is based on the HVS Mk IV, but the frame and loading beam have been strengthened in order to allow the simulation of full dynamic loading. The hydraulic systems of the HVS Mk IV+ and the strengthened frame will allow for a future hydraulic and systems upgrade to simulate dynamic loading at a frequency of 10 Hz.

Significant outputs from the HVS programme in South Africa

Some of the most significant developments in the South African pavement design engineering field resulting from the use of the HVS are briefly mentioned.

Materials-based development.

Large aggregate mix bases (LAMBs)

Preliminary results are reported elsewhere (Rust *et al.*, 1992, 12), which highlighted the promising behaviour and the technical benefits of this type of base course. Following an extensive laboratory study, the HVS was utilized to validate laboratory findings. The development work has since been completed and resulted in a design method (Sabita, 1993, 13).

Granular emulsion mixes (GEMs)

The use of emulsion-treated bases, primarily for rehabilitation and improvement of existing roads, remains a particular area for development in SA. The main objective was to compare GEMs using marginal parent in-situ material with imported aggregate crushed stone base materials. More recent HVS results (de Beer & Grobler, 1993, 14) have provided additional input for the development of an appropriate design method (Sabita, 1993, 15).

Rehabilitation measures for cemented-base pavements

A long-term HVS investigation into the selection of rehabilitation measures for lightly cemented-base pavements has recently concluded. The main findings of this investigation are reported elsewhere (Steyn *et al.*, 1997, 16).

Treatments for phased upgrading of unpaved roads

HVS work in South Africa is closely aligned with the need for cost-effective improvements to unpaved roads, as part of a phased upgrading. Details of an HVS comparison of several bitumen- and tar-based treatment types were investigated during the 1990s (Steyn, 1996, 17).

Comparison of bases constructed by labour-enhanced techniques

The application of labour-enhanced, or labour-intensive, construction techniques is of special relevance to South Africa. The HVS programme for 1997 compared the behaviour of different base types constructed in this way. These include penetration macadam, emulsion treated natural gravel and slurry bound macadam.

Porous asphalt

The performance of porous asphalt, with void contents in excess of 20 per cent, under accelerated traffic was investigated. The deformation characteristics of a porous asphalt with a bitumen-rubber binder were investigated with the HVS. This work has been incorporated into a porous asphalt design manual (Sabita, 1996, 18). .

Developments in design, analysis and performance characterisation.

South African pavement structural design method (Technical Recommendations for Highways, TRH4)

The SA flexible pavement design method and catalogue has been developed over the years with major input from HVS data (CSRA, 1980; 1985, 19). It has been revised to include certain additional refinements arising from the HVS programme (CSRA, 1996, 20). Details of the underlying changes in the analytical evaluation (the SA mechanistic design method, SAMDM) were given by Theyse *et al.* 1996, 4).

Improvements in the modelling of permanent deformation in pavements

HVS performance data have been used in the investigation into the individual contributions of the various pavement layers to the overall deformation of the structure. A new approach to the estimation of these permanent deformations has been proposed, details of which are reported elsewhere (Theyse, 1997, 21).

Improved modelling of in-depth deflection bowls

A back-calculation method for more realistically modelling in-depth and surface deflection bowls, based on actual responses measured during HVS testing, has been developed. Extremely good correlations were obtained using linear elastic layer theory to derive appropriate stiffness values (Prozzi, 1997, 22).

Other HVS programmes

The following is a brief indication of APT efforts undertaken with the HVS outside South Africa.

California

In the nine years between delivery of the two refurbished Mk III HVS's and the end of 2004, these machines have applied about 60 million actual load repetitions, or approximately 6 billion ESALS if the fourth-power damage relationship is assumed. More than 70 pavement sections have been tested, including materials such as dense graded asphalt concrete (DGAC), asphalt-rubber (RAC-G), aggregate base (AB), and subbase (ASB), asphalt treated permeable base (ATPB), PCC, fast-setting hydraulic cement concrete (FSHCC), modified binders and cement treated bases (CTB). Performance of DGAC and RAC-G overlays on AC has been compared, and long-life flexible overlays of existing PCC have been developed and tested. Dowel bar retrofit (DBR) of PCC for potential performance of this approach has been evaluated, as has deep in-situ recycling (DISR) of AC pavements using foamed bitumen. Details have been published elsewhere (23), or can be found at www.its.berkeley.edu/pavementresearch.

Finland and Sweden (VTT & VTI)

The VTT / VTI Mk IV HVS was delivered to Finland in 1997 where it tested typical Finnish pavement structures. It was subsequently moved to Sweden where testes have included the evaluation of three pavements with gradually increased bearing capacities, as well as evaluation of mill & fill maintenance treatments for these sections. Innovative approaches such as the use of steel mesh in bituminous pavements have been evaluated. The performance of crushed rock compared to natural gravel have been studied, as well the effect of mica content in unbound base layers, and the effect of gradation variations in crushed rock subbases. Different base layer thicknesses on light fill material have been tested, and different quality cement-bound base layers comprising semi-rigid pavements have been evaluated. Collaborative studies have been performed with Iceland to evaluate Icelandic base- and subbase performance, and a proposed warranty pavement structure for Poland was tested. Detailed reports are available at www.vti.se

Florida DOT

In the first 3.5 years after receiving the HVS Mk IV+ in 2000, FDOT has applied 8.5 million uni-directional passes of a 40kN wheel load. This would be 17 million passes if a bi-directional approach had been used. FDOT has evaluated the effects of polymer modification of Superpave mixtures, as well as the rutting performance of coarse and fine-gained mixtures. The early strength requirements for PCC slab replacement to minimize shrinkage have been studied and the feasibility of using composite pavements such as UTW and TWT in Florida has been investigated. The HVS has also been used to test the performance of raised pavement markers. Details can be found at:
www.dot.state.fl.us/statematerialsoffice/pavementevaluation/peresearch/apt

USACE CRREL

This HVS Mk IV programme specializes in APT at their frost-effect research facility which allows moisture and temperature control. A subgrade performance study evaluating moisture effects was initiated with FHWA and included collaboration with Denmark and Finland. This study continues as a pooled-fund approach led by NYDOT and includes 18 other States. CRREL also performed a tire-pressure effect study on low-volume road pavements for the USFS, and a thaw-effect study for the USAF. They have evaluated the use of geogrids to reduce base thickness requirements, and have evaluated utility cut repair performance. Details can be found at www.crrel.usace.army.mil/cerd/hvs

USACE WES

The HVS-Airfield Mk V at WES is typically used for high wheel load short duration APT studies. For instance, the first test at WES was planned to involve 100 000 coverages of a B727 aircraft gear. Work has been performed on evaluating pavement structures for the new C-17 cargo aircraft including rapid repair strategies. Short term research has focused on wheel load interaction for new aircraft gear configurations. WES is unique in it's evaluation of expedient airfield pavements for military use over very short periods, with durations of 4 weeks, 6 months or 2 years. The long-term efforts focus on pavement performance relationships. Details can be found at: http://pavement.wes.army.mil/at.

Conclusions

The South African HVS programme had a significant impact on the development of pavement engineering in South Africa the past 30 years. The use of this technology has resulted in significant savings in road building and rehabilitation costs to the country. Given the international acceptance of HVS technology, the next 30 years are likely to be equally successful.

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