The Heavy Vehicle Simulator in Accelerated Pavement Testing – a Historical Overview and New Developments

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ABSTRACT

The purpose of this paper is twofold. Firstly, 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 its conception in the late 1960's, to the current state-of-the art HVS Mk-IV$^+$, the HVS-A Mk-V, as well as the new HVS Mk VI.

Secondly, 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 experience in South Africa, the country in which 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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BACKGROUND

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 & Ebbs (2) listed significant findings from these for full-scale APT. The philosophies behind - and the approaches to - APT in the various programs 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. As APT appeared to have the capability of rapidly evaluating the performance of these developments, 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 The CSIR Built-Environment Unit) developed the Heavy Vehicle Simulator (HVS).

The start-up of the South African HVS program

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 led 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 resulting from the impact of aircraft landing gear. 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, in 1972 Van Vuuren (6) recommended that, owing to atypical construction of test sections at the Silverton site, a mobile loading facility 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 the 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 program 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). These 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 to those pertaining on the actual construction site. 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 and 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 the 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 DEVELOPMENTS 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 for approximately 18 000 bi-directional wheel load repetitions per day. At a test wheel load of 40 kN (half-axle) this produces 18 000 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 702 000 ESALs per day. The design allowed for simulation of up to 1 meter traffic wheel wander. Dimensions of the HVS 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 program, ensuring the earliest possible application of important findings.

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

In 1994, after a successful pilot project demonstrating the capabilities of the HVS, the California Department of Transportation (Caltrans) decided to establish the CAL/APT program 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 program. This program involved collaborative efforts between Caltrans, the University of California, Dynatest Consulting and the CSIR. This venture sparked international interest in HVS technology 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 modernized and re-designed from the ground up, resulting in an improved and more efficient machine. Fully computer controlled, many of the functions of the machine are monitored and automatic shutdown occurs if any of 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, thus allowing for approximately 26 000 bi-directional wheel loads per day. Other test specifications are similar to those of 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 (USACE), which 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) and weight (102 tonnes), the fundamental difference between the new HVS–A Mk V (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 a 200 kN load over 6m. The HVS–A is also designed to utilize 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 were 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. A HVS Mk IV^+ was delivered to Florida Department of Transport (FDOT) in 2000 and the Central Road Research Institute in India has ordered one for delivery in 2009.

The latest HVS is the Mk VI. The basic Mk VI costs about 25% less than the Mk IV^+. This was achieved by removing self propulsion and self powering features, which are now available as optional extras. The MK VI frame was re-designed and the hydraulic system simplified by using the Mk V carriage design. Loading and other functional capabilities are the same as those for the MK IV^+, but the MK VI has an optional beam extension which allows for a higher test wheel speed over a 6m test section or at the same test wheel speed as a Mk IV^+ over a 12m test section. The Mk VI can also be towed between sites and its reduced weight allows for easier towing. The MK VI wheels are turntable mounted, making it more maneuverable on site.

The first of these machines will be delivered to Chang'An University in Xi'an, China during the first half of 2008.

SIGNIFICANT OUTPUTS FROM THE HVS PROGRAM 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 behavior 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 and 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 been done. 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 labor-enhanced techniques

The application of labor-enhanced, or labor-intensive, construction techniques is of special relevance to South Africa. The HVS program for 1997 compared the behavior 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 characterization.

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

The SA flexible pavement design method and catalogue was developed over the years with major input from HVS data (CSRA, 1980; 1985, 19). It was revised to include certain additional refinements arising from the HVS program (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 modeling 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 modeling of in-depth deflection bowls

A back-calculation method for more realistically modeling 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).

Latest research

Long-Term Pavement Performance and HVS

Although accelerated pavement testing (APT) can, and does, provide significant data for analyzing and predicting the effects of traffic loading on the performance of various materials, it is not always capable of predicting environmental and other long-term effects. Only when comparisons of APT and long-term pavement performance (LTPP) are available will there be greater confidence in the interpretation and use of APT results.

During 2005 Gautrans conducted LTPP analyses of test sections adjacent to recently completed HVS experiments. The project started with the development of a protocol for the establishment and operation of LTPP sections, which includes:

- Details on linking LTPP to HVS data collection;
- Management and responsibilities;
- Site location and establishment;
- Data collection and storage, and
- Reporting of criteria.

To date, four LTPP sections have been established, three of which are adjacent to in-field HVS testing areas (23). All these LTPP sections are evaluated twice a year at the beginning (May) and end of the dry season (November) in South Africa. The first series of evaluations took place in December 2005, and is still ongoing. Current evaluations include:

- A visual assessment;
- Transverse and longitudinal profiles;
- DCP measurements;
- In situ density and moisture content determinations;
- Riding quality measurements, and
- Deflection measurements (Falling Weight Deflectometer (FWD) and Road Surface Deflectometer (RSD)).

Traffic volumes are determined from seven-day traffic counts and environmental conditions are determined from rainfall and temperature readings collected at nearby farms and by temperature sensors installed at the LTPP sections.

Because only 5 data points have been recorded (since December 2005) it is not possible to make realistic predictions on the success of HVS testing to simulate real life deterioration yet. An example of a comparison of rutting development of an HVS test (on the N7 near Cape Town) with the results from the adjacent LTPP section is shown in Figure 1. Promising results have been achieved although this investigation is still in its early stages.

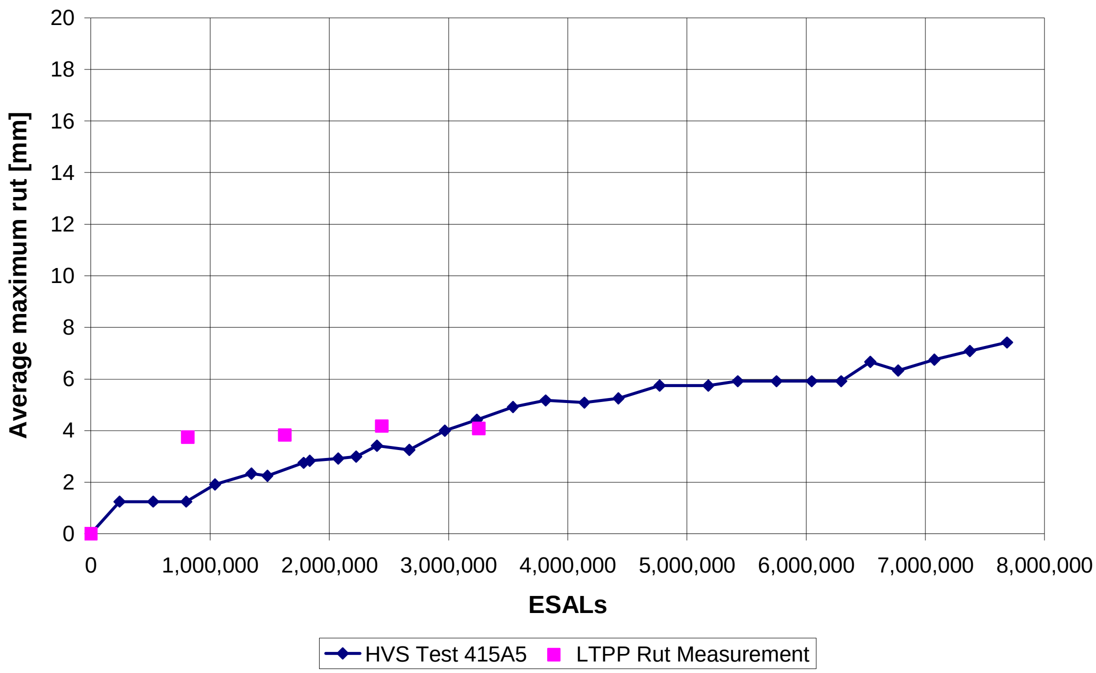

Figure 1: Comparison of the rut development of the HVS test section to the adjacent LTPP section

HVS testing of Concrete Pavement structures

The South African National Road Agency Ltd. (SANRAL), Gautrans, the Cement and Concrete Institute (C&CI) and the CSIR started a concrete research program in 2003 to address the current shortcomings in the South African mechanistically-based concrete pavement design manual.

In order to address especially the load transfer issue, two HVS experimental Portland cement concrete (PCC) sections were constructed. These sections were subjected to accelerated loading for a period of over 7 months starting in November 2003 (24, 25, and 26).

The specific objectives of these tests were to:

1. Investigate the influence of the environment and accelerated loading on joint deterioration of doweled and plain aggregate interlocking joints using quartzite and dolerite materials, and
2. Determine the remaining life of an in-service concrete inlay pavement section on the N3.

In a second study the structural capacity (remaining life) of an in-service Continuously Reinforced Concrete Pavement (CRCP) inlay which showed a significant amount of cracking (26) was investigated. The CRCP pavement was constructed in 1998 and up to December 2004 had carried about 7 million ESALs. It was originally designed for less traffic. At the time when the HVS testing was conducted only a few punch-outs had occurred on this section of the road, mainly at transverse construction joints and close to the inner longitudinal edge where the road is in a horizontal curve.

In order to obtain an indication of remaining life, a section was selected for testing with the HVS in a location where the existing crack pattern suggested the potential of a punch-out developing.

Using the 4.2 damage factor the pavement was subjected to 5.9 million ESALs in addition to the 6.5 million prior to the start of HVS testing and the pavement was not considered to have failed after completion of the test.

The benefit of HVS testing was clearly illustrated by this study. On account of the existence of a significant cracking pattern it was thought that the pavement had reached the end of its structural life. Through HVS testing it was discovered that the pavement had not yet failed and that a significant amount of traffic could still be carried before any major rehabilitation would be required.

In the most recent HVS study (April 2005 – April 2008) Ultra Thin Continuously Reinforced Concrete Pavement (UTCRCP) sections are being evaluated (27). This type of concrete (typically less than 50mm thick) is an ideal overlay rehabilitation method in areas where bridge clearance problems exist and limited time for full depth reconstruction is available. The HVS is used for the determination of the optimum mix design, structural strength and the applicability of UTCRCP to be placed on different pavement types in various states of distress.

The outcome of this research has been so successful that SANRAL has put out tenders for a full-scale rehabilitation project on a major freeway using this specialized rehabilitation method after the validation using the HVS

OTHER HVS PROGRAMS

The following is a brief summary 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 2007, these machines have applied about 81 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 those constructed with 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 AC pavements using foamed bitumen and warm AC is currently being tested. Details have been published elsewhere (28), 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 was used to test typical Finnish pavement structures. It was subsequently moved to Sweden where tests included the evaluation of three pavements with gradually increased bearing capacities, as well as evaluation of mill-and-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 has 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 cement-bound base layers of differing quality comprising semi-rigid pavements have been evaluated. Collaborative studies have also been undertaken with Iceland to evaluate Icelandic base and subbase performance, and a proposed warranty pavement structure for Poland was tested.

Current testing involves evaluation of potential pavement upgrade and reinforcing procedures in Slovenia and Poland under the Sustainable Pavements for European New member States (SPENS) project. Detailed reports are available at www.vti.se

Florida DOT

In the first 3.5 years after receiving its HVS Mk IV+ in 2000, FDOT has applied 8.5 million uni-directional passes of a 40kN wheel load. This would represent 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. Evaluation of the effects of aging on pavement cracking is on-going. The HVS has also been used to test the performance of raised pavement markers.

A study in which dual, wide based and new wide based tires are compared is planned. Details can be found at:
www.dot.state.fl.us/statematerialsoffice/pavementevaluation/peresearch/apt

USACE CRREL

This HVS Mk IV program specializes in APT at the USACE's 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 New York Department of Transport (NYDOT) and includes 18 other States. CRREL also performed a tire-pressure effect study on low-volume road pavements for the US Forrest Services (USFS) and a thaw-effect study for the US Air Force (USAF). CRREL evaluated the use of geogrids to reduce base thickness requirements, as well as reinforcement for high volume flexible pavements. It also evaluated the performance of repairs resulting from the provision of utility services. 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 passes of a

B727 aircraft landing 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 its 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. Current work includes testing to verify various revisions to the CBR procedure for flexible pavements, to verify minimum AC thickness requirements used in current AC pavement design procedures and to evaluate the use of marginal materials for airfield pavement base course construction. Details can be found at:
http://pavement.wes.army.mil/at.

CONCLUSIONS

The South African HVS program has had a significant impact on the development of pavement engineering in South Africa over the past 40 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, now deployed in four continents with 9 machines in operation and another on order, the next 40 years are likely to be equally successful.

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Bouzid Choubane (FDOT), Leif Wiman (VTI), Al Bush and Don Alexander (WES) and Edel Cortez (CRREL) for their generous input on their respective HVS program overviews.

REFERENCES

1. Metcalf, J.B. “Synthesis of Highway Practice 235: Application of Full-Scale Accelerated Pavement Testing”. NCHRP Synthesis 235, Transportation Research Board, Washington DC, 1996.
2. Hugo, F. and Ebbs, A. “NCHRP Synthesis 325: Significant Findings from Full-Scale Accelerated Pavement Testing”. NCHRP Synthesis 325, Transportation Research Board, Washington DC, 2004.
3. Walker, R.N., Paterson, W.D.O., Freeme, C.R. and Marais C.P. “The South African Mechanistic Pavement Design Procedure”. 4th International Conference on Asphalt Pavements, Vol. 2, Ann Arbor, USA, 1977.
4. Theyse, H.L., De Beer, M. and Rust, F.C. “Overview of the South African Mechanistic Pavement Design Analysis Method”. Paper #961294 Presented at the 75th Annual Transportation Research Board Meeting, Washington, D.C., January 7-11, 1996.
5. Van Vuuren, D.J. “Abnormally heavy vehicles on roads”. M.Sc Thesis, University of Pretoria, 1969.
6. Van Vuuren, D.J. “The allowable wheel and axle loads of heavy vehicles”. PhD Thesis, University of Pretoria, 1972.
7. Van Vuuren, D.J. “The Heavy Vehicle Simulator”. Shell Bitumen Review 41, London, UK, 1973.
8. 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.
9. Paterson, W.D.O. “An Evaluation of the Heavy Vehicle Simulator as a Tool for Measuring Pavement Behaviour". NIRR Technical Report RP5/76, CSIR, Pretoria, South Africa, 1977.
10. Clifford, J.M. “The Heavy Vehicle Simulators”. Technical Note TP/24/75, CSIR, Pretoria, South Africa, 1975.
11. Paterson, W.D.O. “Observations of Pavement Behaviour under Heavy Vehicle Simulator Testing during 1971-1976". NIRR Technical Report RP7/77, CSIR, Pretoria, South Africa, 1977(a).
12. Rust F.C., Grobler, J.E. and Myburgh, .P.A. “Towards analytical mix design for large stone asphalt mixes”. Proceedings of the 7th International Conference on Asphalt Pavements, Nottingham, UK, August 1992.
13. Sabita. “LAMBS - the Design and use of Large Aggregate Mixes for Bases”. Manual 13, Southern African Bitumen and Tar Association, Roggebaai, South Africa, September 1993.
14. De Beer, M. and Grobler, J.E. “ETBs: Heavy Vehicle Simulator (HVS) Evaluation of the Heilbron Sections”. Output report ETB/HVS, Southern African Bitumen and Tar Association, Roggebaai, South Africa, January 1993.
15. Sabita. “GEMS - the Design and Use of Granular Emulsion Mixes”. Manual 14, Southern African Bitumen and Tar Association, Roggebaai, South Africa, October 1993.
16. Steyn, W.J. vd M., de Beer, M. and Visser, A.T. “Thin Asphalt and Double Seal Rehabilitated Lightly Cemented Pavements: Evaluation of Structural Behaviour and Life Cycle Costs”. Paper submitted to the 8th International Conference on Asphalt Pavements, 1997.
17. Steyn, W.J. vd M. “Interim Progress Report on HVS Tests on Superlight Pavements: Road S702, Bultfontein, Gauteng”. Technical Note I/PA/17/95, CSIR, Pretoria, South Africa, August 1995.

18. Sabita. "Porous Asphalt Mixes: Design and Use". Manual 17, Southern African Bitumen and Tar Association, Roggebaai, South Africa, November, 1995.
19. CSRA. "Structural Design of InterUrban and Rural Road Pavements". TRH4, Committee of State Road Authorities, Department of Transport, Pretoria, South Africa, 1980, updated 1985.
20. CSRA. "Structural Design of Flexible Pavements for InterUrban and Rural Roads". Draft TRH4, Committee of State Road Authorities, Department of Transport, Pretoria, South Africa, 1996.
21. Theyse, H.L. "Mechanistic-Empirical Modelling of the Permanent Deformation of Unbound Pavement Layers". Paper submitted to the 8th International Conference on Asphalt Pavements, 1997.
22. Prozzi, J.A. "Backcalculation of Elastic Moduli: Towards a Unique Solution". Paper to be submitted to the XIIIth IRF World Meeting, Toronto, Canada, 1997.
23. Steyn, W.J. vd M.., Jones, D. and Fisher, C. "Technical Memorandum: 2006/2007 monitoring of four LTPP experiments in association with HVS tests in Gauteng" Report CSIR/BE/IE/IR/2007/0108/B, CSIR Built-Environment, Pretoria, South Africa, December 2007.
24 Brink, A.C. "Construction Report: HVS Testing of the Concrete Test Section on the N3 near Hilton." *Report CR-200/33*, CSIR Built-Environment, Pretoria, South Africa, July 2004.
25 Du Plessis, L. and Brink, A.C. "First Level Analysis Report: HVS Testing of the Concrete Test Section on the N3 Section on the N3 near Hilton: Tests 424A5" *Report CR-200/70*, CSIR Built-Environment, Pretoria, South Africa, September 2004.
26 Du Plessis, L. "First Level Analysis Report: HVS Testing of the Concrete Inlays on the N3 near Hilton" *Report CR-2004/59*, CSIR Built-Environment, Pretoria, South Africa, October 2004.
27 Kannemeyer L., Du Plessis, L. et.al. *''Ultra-Thin CRCP: Modeling, Testing Under Accelerated Pavement Testing and Field Application for Roads'*. Proceedings of the 2nd CROW workshop of the University of Delft, Belgium, Oct 2006.
28. Harvey, JT et al. "A perspective on accelerated pavement testing: The Caltrans partnered Pavement Research Program, Proceedings of the 8th Conference on Asphalt Pavements for Southern Africa, September, 2004.