

Three Decades of Development and Achievements: The Heavy Vehicle Simulator in Accelerated Pavement Testing

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ABSTRACT: Since the 1970s, the South African Heavy Vehicle Simulator (HVS) Programme has had a major technological and economic impact on the design, construction and maintenance of South African roads. It has impacted, for instance, on the development of national and regional pavement design standards and guidelines, the development of material specifications and guidelines, the development of human resources, capacity building in the road construction industry, the development of innovative products and designs, and the provision of cost-effective infrastructure engineering solutions.

A historical overview of technological developments associated with the HVS and related technologies/instrumentation is addressed. This covers the period from concept initiation in the late 1960s, to the current state-of-the art HVS Mk-IV Plus and HVS-A Mk-V. An overview of the research activities, outcomes and impacts of the various HVS programmes is also presented. Although this overview predominantly focuses on the South African experience, other international HVS research programmes are also discussed, including studies undertaken by the Partnered Pavement Research Center (California), the U.S. Army Corps of Engineers Engineering Research and Development Center (CRREL and WES), as well as the Swedish and Finnish HVS-Nordic programme and the Florida DOT HVS test programme, and the sharing of knowledge and experience amongst the HVS users.

The paper also provides an overview of the management of the HVS research programme, including the involvement of the road construction industry in the activities of the programme and the transfer of technology to practitioners. It concludes with an overview of benefits achieved from over thirty years of experience in accelerated pavement testing.

KEY WORDS: Accelerated pavement testing, Heavy vehicle simulator.

1 BACKGROUND AND OVERVIEW

The Heavy Vehicle Simulator (HVS) is a mobile machine that subjects road and airfield pavements to accelerated trafficking. In essence, it is a mobile laboratory taken to the road to evaluate the structural behaviour and capacity of the road under full-scale conditions. It is able to simulate the equivalent of 20 years of traffic in as little as three to six months, thus assisting engineers to understand the mechanisms of traffic-associated road failures. Accelerated Pavement Testing (APT) thus makes it possible to obtain quick results related to traffic, the mechanisms of failure and the influence of various environmental factors on the behaviour and performance of pavements.

For over 30 years, the HVS has been the dominant influence in development of South African pavement engineering capability. The extent of this influence has been well documented through contributions to various international conferences, on both direct HVS applications and the associated development of rational analysis/design methods and their practical implementation. Papers at the International Conferences on Asphalt Pavements (ICAPs), in particular, track these developments.

Although the use of monitored trial sections under actual traffic provides accurate prediction of the functional performance of pavements, they require monitoring over their total life span. In the day-to-day practice of pavement design and rehabilitation, existing knowledge and experience, backed up by short-term investigations such as field and laboratory materials testing, are typically used. However, most of the design methods are empirically based and were developed for specific conditions and specific materials. At present, with increasing traffic loading and decreasing availability of good quality road construction materials, these methods often do not provide optimum, cost-effective solutions. APT by means of instruments such as the HVS bridges the gap between laboratory testing and long-term monitoring of trial sections.

APT allows the prediction of the performance of new road materials and structural designs as well as the optimisation of road designs through the testing of trial sections well ahead of their implementation in practice, thus effecting cost savings and avoiding expensive failures. In addition, the technology can be used on in-service roads to determine their expected remaining life, as well as optimum rehabilitation and maintenance procedures to prolong their life. The above are generally short-term objectives which are often well-defined and aimed at solving specific problems over a relatively limited time period. These objectives would include aims such as optimization of material design, performance evaluation of a particular structure, or comparative testing of different pavement structures under similar conditions.

In contrast, long-term objectives of an APT programme may not always be readily apparent. In general, however, APT is geared towards evaluating the structural bearing capacity of pavements and any long-term objective will emanate from this. Over the long-term an APT programme must therefore contribute towards better structural design procedures for pavements. This is achieved primarily in two ways.

Firstly, if sufficient data of the correct type are collected for the full pavement system during each APT test, structural design models may be developed over the long-term. This can give a clearly defined long-term objective which has readily identifiable value in allowing optimisation of pavement designs, and therefore in achieving the laudable aim of more cost-effective pavements.

Secondly, APT testing adds to the development of the skills and understanding of pavement behaviour of those directly involved in the testing process. This knowledge gain must also be transferred to other practitioners, and in South Africa this has been generally successful through a

variety of mechanisms including courses, workshops and seminars, apart from direct input into documentation and guidelines.

Although the analysis and interpretation of data from specific APT tests are usually focussed on addressing short-term objectives, each test contributes directly to a data/knowledge base that becomes a platform from which structural design models may be developed. Ideally this should become public domain to enable accelerated development. In this way every APT test will contribute towards the longer-term objective of APT. It does, however, require that sufficient information should be collected and more importantly, stored for future use.

Embarking on an APT programme with the sole intention of only addressing the pressing problems that require immediate solutions may be reason enough to justify an APT programme, but realising the long-term objective of APT will maximize the return on investment. Consequently it is viewed as essential that a successful APT programme should have some longer-term objectives outlined from the beginning. This then provides focus for the programme, enables both researchers and funders to share a common vision, and forms the basis of the particular APT strategy.

Whereas APT is often conducted on purposely-designed trial sections, most of the advances in road engineering in South Africa have come from HVS testing on actual roads. The advantage of this type of road evaluation stems from the greatly reduced time needed to obtain meaningful indications of long-term (real life) performance, which allows the earliest possible appraisal of novel materials and techniques in seeking optimal, cost-effective, provision of roads.

The aim of this paper is to present the development, achievements and benefits of the South African HVS programme as an example as to how a coordinated research programme has major benefits. The paper first presents a historical perspective, then discusses the HVS programme, and finally show the extensive benefits derived from the programme.

2 HISTORICAL OVERVIEW

2.1 HVS Developments in South Africa

Prior to discussing specific aspects of the approach adopted in South Africa, it should be noted that the South African HVS programme used four machines from the late 1970s to about 1990, and three to about 1993. At present there are two HVSs in South Africa. While the ownership differed (and included the national Department of Transport, the Department of Public Transport, Roads and Works for Gauteng province, and the Council for Scientific and Industrial Research (CSIR)) all the machines have been operated by the CSIR throughout on behalf of the owners.

It was the impact of the AASHO road tests in the late 1950s that prompted local interest in APT. 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 research 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, which led to the development of an APT fixed facility on the CSIR campus in the 1960s. This fixed facility, referred to as Mark I, was manufactured from Bailey Bridge components and the reaction force (ballast) applied to the pavement utilised water tanks placed above the aircraft wheel supported by the Bailey Bridge structure. Although the facility produced useful results, particularly with respect to the

development of a better understanding of the impact of aircraft tyres on airport runways, it was not mobile. This led to the development of a mobile loading facility that could test real, in-service pavements.

The first fully mobile self-powered HVS (Mark II) was commissioned in October 1970 and by the end of 1975, 24 accelerated trafficking tests had been conducted with HVS Mark II. Data collected during these tests included surface deflections, radius of curvature, permanent deformation, visual distress data, such as cracks, material loss, shear failures, etc. Analysis of these data provided information on wheel load equivalency factors, rutting in untreated granular layers and load-associated cracking in cement-treated bases.

The encouraging outcomes produced by the HVS Mark II motivated the manufacturing of three additional improved HVS Mark III machines. From the late 1970s and throughout the 1980s, the South African HVS fleet was used almost continuously. The expanded HVS programme was then also able to underpin virtually all the advances and developments in South African pavement engineering. During this period, the most significant aims of the programme were to qualify:

- The behaviour of typical pavement structures as a system;
- The structural changes that take place in the system under trafficking;
- The failure / aging mechanisms of the different pavement types;
- The water sensitivity of different pavement types;
- The behaviour of different materials (as layers) within the various pavement types;
- The remedial measures for some typical pavement failure mechanisms;
- The typical load sensitivity / equivalency factors applicable;
- The cost efficiency of the different pavement types (cost / length / Million Std Axles);
- The typical life cycle strategies for different pavement types.

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, four additional new units had been sold internationally. The following provides a brief overview of the APT activities undertaken by the international owners of HVSs:

2.2 Partnered Pavement Research Center (University of California at Davis)

In the nine years between delivery of the two refurbished Mark III HVSs and the end of 2004, these machines have applied approximately 60 million actual load repetitions, or approximately 6 billion ESALS, if the fourth-power damage relationship is assumed. More than 70 pavement sections were tested, including pavement 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). Comparative testing of DGAC and RAC-G overlays on AC has been conducted, and long-life flexible overlays on 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.

2.3 Finland and Sweden (VTT and VTI)

The VTT/VTI Mark IV HVS was delivered to Finland in 1997 where it tested typical Finnish pavement structures. It was subsequently moved to Sweden where it was used to evaluate the performance of pavements with gradually increased bearing capacities, as well as mill & fill maintenance treatments for these sections. Innovative approaches, such as the use of steel mesh in bituminous pavements, have also been evaluated. Other studies included the evaluation of the performance of crushed rock compared to that of natural gravel, the effect of mica content in unbound base layers, the effect of gradation variations in crushed rock subbases, the performance of different base layer thicknesses on light fill material, and the performance of cement-bound base layers of varying quality. Collaborative studies have been conducted with Iceland to evaluate Icelandic base- and subbase performance, and with Poland to investigate a proposed warranty pavement structure.

2.4 Florida Department of Transportation (FDOT)

The FDOT HVS Mark IV+ was delivered in 2000. Since then, FDOT has evaluated the effects of polymer modification of Superpave mixtures, the rutting performance of coarse and fine-gained mixtures, early strength requirements for PCC slab replacement to minimize shrinkage and the feasibility of using composite pavements such as UTW and TWT in the State of Florida. The HVS has also been used to test the performance of raised pavement markers.

2.5 US Army Corps of Engineers (USACE) – Cold Region Research and Engineering Laboratory (CRREL)

The HVS Mark IV of CRREL is located at their frost-effect research facility which provides a moisture- and temperature-controlled environment for APT. A subgrade performance study evaluating moisture effects was initiated with FHWA and included collaboration with Denmark and Finland. This study continued as a pooled-fund approach led by NYDOT and involving 18 other States. CRREL also studied the effect of tire-pressures on low-volume road pavements for the USFS, and the effect of thawing for the USAF. They have also evaluated the use of geogrids to reduce base thickness requirements, as well as the performance of utility cut repairs.

2.6 USACE Engineer Research and Development Centre (ERDC)

The ERDC HVS-Airfield Mark V, located at the Waterways Experimental Station (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. ERDC 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.

Since 1994, The Gauteng Department of Public Transport, Roads and Works (Gautrans) kept the remaining South African HVS Mark III in operation. However, technological advances in the field of accelerated pavement testing motivated the Department to also purchase an HVS Mark

IV+ in 2002, which incorporates a number of improvements over the HVS Mark III including the capability to simulate full dynamic loading.

The remainder of the paper will deal with the aims and objectives of the South African HVS-associated technology development Programme (APT Programme), as well as the benefits achieved by this Programme since its inception.

3 THE SOUTH AFRICAN APT PROGRAMME

3.1 Purpose of the APT Programme

The APT Programme, managed by the Gauteng Department of Public Transport, Roads and Works (Gautrans), is aimed at:

- developing and promoting best practice for the management of a safe, sustainable and cost-effective road network with special focus on public transport routes and freight corridors;
- the ongoing assessment and development of performance-related standards for road construction, rehabilitation and maintenance;
- the ongoing development of human resources related to pavement engineering, and
- the coordination of APT throughout South Africa.

The APT Programme is supported by an APT Steering Committee, which consists of representatives from national and provincial road authorities, civil engineering consultants and contractors, tertiary education and the CSIR. The Steering Committee provides inputs into the research priorities, the research agenda, and assists in the evaluation of the progress on, and outcomes of, specific programme activities.

The transmission of outcomes of the APT Programme is typically effected through conference papers, presentations, seminars and workshops as well as through manuals and guidelines to aid road designers in the implementation of technologies that were tested and improved through the APT Programme. It has impacted on, for example:

- The development of pavement design standards and guidelines;
- The development of pavement material specifications and guidelines;
- The development of human resources (educational value);
- Implementation of labour intensive technologies;
- Development of innovative products and designs; and
- The provision of cost-effective, fit-for-purpose road infrastructure engineering solutions.

3.2 Strategic Focus of the APT Programme

The APT Programme is designed to be supportive of relevant key strategic areas of the overall transport goals on national and provincial levels. The diagram below shows how the APT programme contributes to these strategic areas.

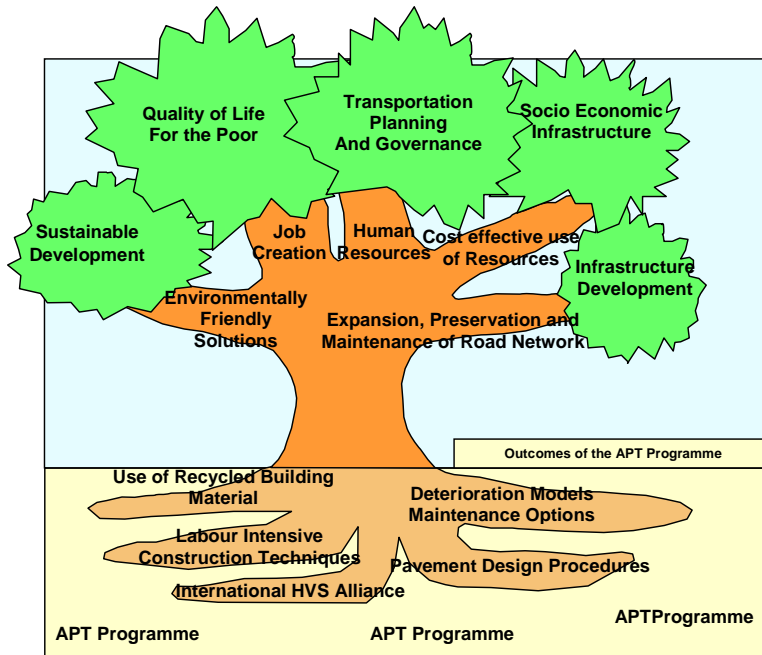


Figure 1: Relevance of the APT Programme to the Gautrans Strategic Plan and Agenda for Transport

In October 1995, in response to the radical changes in South Africa, a strategic document for the APT Programme was prepared by Gautrans. At that time, the following strategic objectives were identified in that the Gautrans HVS programme would aim to develop, improve understanding of, verify or evaluate:

- the design and performance of pavement structures suitable for basic access roads and collectors for rural road networks;
- labour intensive construction (LIC) friendly pavement composition and LIC techniques;
- techniques for upgrading and maintenance of existing gravel (and other) low volume pavement structures;
- the use of innovative, cost-effective materials and methods, optimising the use of in-situ materials (treated and untreated);
- technologies for the preservation of the existing road network in order to extend its service life, and
- technologies for optimisation of the use of scarce building materials (eg gravel roads).

The above strategic objectives were developed to support the broader national and provincial goals that were set to address the South African challenges for transport provision and socio-economic infrastructure developments.

The period from 2000 to 2003 saw a shift in the strategic focus for the APT Programme. The shift in focus was driven by the increase in traffic volumes on the heavier trafficked public transport routes and freight corridors, and the need to maintain and rehabilitate these roads quicker to reduce traffic delays. This was also compounded by stricter environmental legislation and the decline in availability of non-renewable aggregate sources. Hence there was a move towards the investigation and adoption of more sustainable and environmentally-friendly technologies that consume less energy, enable greater use to be made of waste or by-products in road construction and promote the re-use of existing road construction materials. An example of

the latter is cold in-place recycling of the existing base and wearing course material with stabilisation of the recycled material generally carried out using foamed bitumen or bitumen emulsion, both with or without cement. A series of HVS tests, coupled with an elaborate laboratory test programme, were conducted on cold in-place recycled mixes, which culminated into the development of guidelines for the appropriate design and use of cold in-place recycling with bitumen-emulsion and foamed-bitumen. These guidelines are currently being validated and further refined by means of Long-Term Pavement Performance (LTPP) studies.

The other major shift to the prevailing strategy occurred during the period 2004 to 2007, where the need was identified to investigate concrete and composite pavements for higher trafficked roads. The Gautrans HVS was used to test these pavements in a jointly sponsored programme with the South African National Road Agency Ltd (SANRAL) and the Cement and Concrete Institute (C&CI). HVS studies have also been undertaken to assess the performance of continuously-reinforced, ultra-thin concrete overlays (30-40 mm) and investigate whether they can be used as a cost-effective rehabilitation alternative for heavy trafficked roads.

Concurrently, the need was identified for improved (innovative) designs and materials for hot-mix asphalt, again targeted at optimising rehabilitation and improvement options for the major public transport routes and freight corridors of the Province of Gauteng in terms of providing more durable, longer-lasting materials requiring less frequent routine and periodic maintenance interventions, leading to reduced delays and disruption to traffic. These designs will be subjected to HVS trafficking, tested in the laboratory and integrated in LTPP studies with the ultimate aim to review and revise the current design guidelines for hot-mix asphalt.

3.3 Linkages with International APT Programmes

The South African APT Programme is very well connected with international APT user groups. One such a user group is the HVS International Alliance (HVSIA). This organisation, founded in 2003, consists of representatives of all HVS operators and owners worldwide.

HVSIA meets on an annual basis to discuss issues of common interest. Their objectives include the promotion and sharing of knowledge related to HVS technology, the optimisation of resources through the coordination of HVS related research, and the provision of expertise so that studies of interest can be expeditiously defined, managed and results reviewed. Typical topics that are dealt with by HVSIA include:

- Relationships between laboratory, HVS and true field performance;
- Analytical/performance prediction models;
- Pavement performance instrumentation, data collection methods, and
- Collaboration between the various HVS programmes.

4 QUANTIFYING THE BENEFITS OF THE APT PROGRAMME

In the face of increasing pressure on the roads budget, it became essential to proactively define and quantify the benefits arising from the APT Programme.

To this end, an independent, peer reviewed assessment (termed the “HVS Benefit Study”) was performed to identify and quantify benefits stemming from the APT Programme. The study focused specifically on those benefits that are relevant to the Gautrans mission and that are congruent with the South African National Research and Development strategy.

The study grouped benefits of the APT Programme into two categories. These are:

- Direct Benefits — benefits that rely primarily on the project outcomes. In the context of road technology development projects, these benefits arise because of improved technology which leads to more effective design and construction processes, which in turn reduces agency and road user costs. These benefits can to some extent be quantified in economic terms by means of indicators such as the benefit-cost ratio.
- Indirect Benefits — benefits that arise because of the development process. These benefits largely concern human resource development and the development of better understanding of the problems facing a particular development area. These benefits are not readily quantified in economic terms, and are best monitored and evaluated through indicators and trend analysis.

4.1 Direct Economic Benefits of the APT Programme

The HVS Benefit Study has shown that the technical impact of HVS development work can be generalised into the following three categories: (1) optimised materials and pavement design, which lead to reduced construction costs; (2) more reliable design and maintenance practices, which reduce the likelihood of costly early failures, and (3) more cost-effective materials and pavement design, which optimises the time between maintenance interventions and reduces pavement life cycle costs. Examples of HVS findings that have influenced national practice include:

- The dramatic effect of water influencing designs and maintenance procedures;
- Bearing capacity of the road authority's light pavement catalogue increased;
- A deformed pavement has not necessarily failed structurally (traffic moulding);
- Concept of deep versus shallow pavement composition accepted and applied;
- Pavement designs must strive for strength-balance;
- Load equivalency exponent (n) normally lower than "4" for local pavements;
- Cemented-base-only pavements used only for very light traffic by road authorities;
- High-quality crushed stone base (G1) proven top-performer in national specification document;
- Inverted pavement design philosophy proven sound and used by all road authorities;
- HVS findings incorporated into pavement mechanistic modelling.

These benefits stemming from specific HVS projects were quantified in relation to the costs of the projects. Figure 2 shows an estimated benefit-cost-ratio for different discount rates. The range is based on economic calculations compiled with feedback received from road agency personnel and practitioners during formal, documented interviews.

The quantifiable benefits of the APT Programme were found to be significant: for a discount rate of 8%, between \$3 and \$5 is returned for every \$1 invested in the APT Programme.

4.2 Indirect Benefits of the APT Programme

Three main benefit streams identified by the South African National R&D strategy objectives are: (1) contribution to better business performance (including performance of public service departments such as Gautrans); (2) contribution to technical progress, and (3) contribution to the development of Science, Engineering and Technology (SET) human capital.

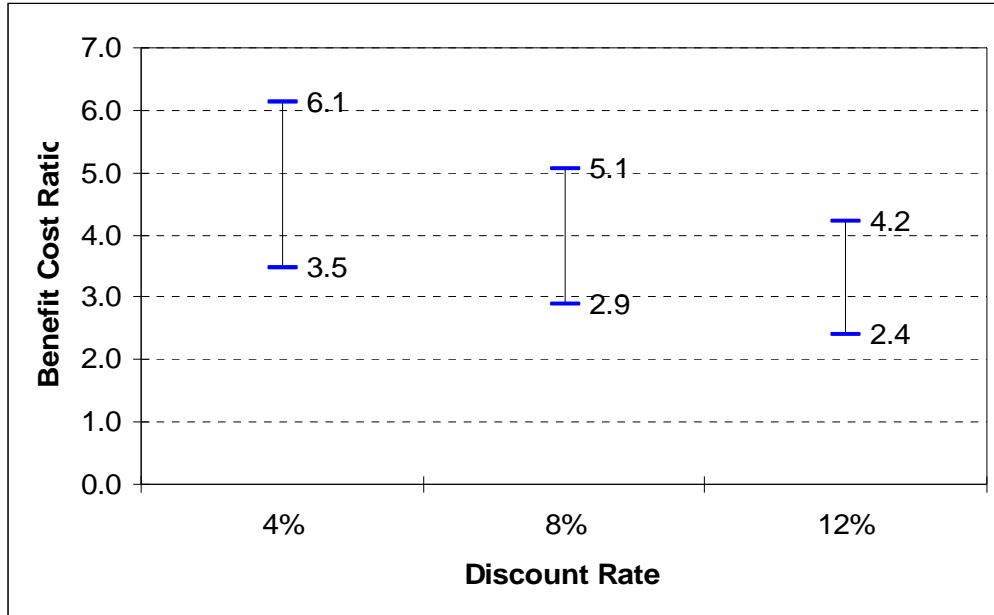


Figure 2: Estimated benefit-cost ratios for specific HVS projects

Benefits arising from better business performance are generally those that are directly quantifiable in economic terms, while the other two main benefit streams result in benefits that are more intangible and indirect in nature (i.e. the so-called “Indirect Benefits”).

Over many years, HVS investigations and their associated development of human resources, new technologies and international alliances have impacted significantly on the people of South Africa. For instance, the APT Programme provides a stable training ground for individuals wishing to specialise in technologies related to road design, construction, maintenance and rehabilitation. Although difficult to quantify in economic terms, there is little doubt that this contribution of the APT programme to technical progress and human capital development has huge economic benefits over the long term.

5 CONCLUSIONS

The paper has endeavoured to provide a concise overview of the history, management and benefits of the South African APT Programme, whilst also describing the activities of other international HVS Programmes. The South African APT Programme has demonstrably benefited pavement engineering in South Africa, and has had both direct and indirect impact on the philosophy and approach to material selection and pavement structural design.

There can be no doubt that every road design undertaken in South Africa, at present and in future, will be influenced by results that were generated by the APT Programme over the past three decades.