Evaluating the benefits of accelerated pavement testing

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Thesis submitted for the degree *Doctor Philosophiae* in Engineering Development and Management at the Potchefstroom Campus of the North-West University

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April 2016

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ACKNOWLEDGEMENT

I wish to express my sincere gratitude to the following persons and institutions:

The North-West University, in particular the individuals at the Hazeldean Satellite Campus in Pretoria: Professor Johann van Rensburg for his undivided attention and assistance, and Liza Lotter for efficient and reliable administrative support.

My original promoter, Prof. Leon Liebenberg, substituted by Dr Johann Krüger for their leadership and technical guidance.

My employer, the CSIR of South Africa, for financial support and allowing me the time complete this study.

Mr Bill Nokes at the California Department of Transportation (Caltrans), Division of Research, Innovation and System Information for his support and constructive input. Mr Nokes has been with the HVS programme in California since its inception in 1992. This thesis would not have been possible without his technical guidance, original ideas and the financial assistance from Caltrans through the Partnered Pavement Research Centre.

Prof. John Harvey, principle investigator of the HVS programme at the University of California (Davis) for his support, technical review and guidance on this project stretching over 10 years.

My colleague, Dr Chris Rust, at the CSIR and my long-time mentors, Dr Nick Coetzee, Dr Emile Horak and Prof. Carl Monismith for career guidance, advice and valuable lessons learnt from their experience.

My loving wife, Christine, for language editing, quality assurance and correlation, encouragement and overall support!

My Heavenly Father, for giving me the talent and patience to complete this body of work.

ABSTRACT

South Africa, like many other countries, is facing challenges regarding the optimal utilisation of taxpayers' money to the benefit of the country. Research, transportation infrastructure research in particular, has its unique challenges as it competes with very sensitive public spending needs such as health, education and safety. Very often research does not receive its rightful share in government's investment in public services. The downstream effects of neglecting the upkeep and maintenance of our road infrastructure is rising logistics costs and social disbenefits due to a lack of acceptable access to facilities such as hospitals, schools and shops.

Due to the pressure on the available funding for research, it is increasingly more important to justify research spending and the success of continued governmental support depends on the impact of the research. The development of the first South African electric passenger vehicle, the Joule, is an example of a product that was never commercially available and investment in its development was ceased in 2012. Research utilising Accelerated Pavement Testing (APT) machines are expensive in comparison with mere laboratory testing. However, they are reliable tools to assess the durability of full-scale road structures in a short period of time and to avoid costly early failures. The ability to measure the impact of implementable research stemming from APT-related research is becoming more important given the backdrop above.

This thesis is centred around the development of a robust methodology to measure the success and impact of research from a particular type of APT device, the South African designed Heavy Vehicle Simulator (HVS). Research with the HVS started in the 1960s and is still continuing in South Africa and in many other countries.

With the use of well-established tools and models the author developed a methodology to measure the impact and benefits of APT. This methodology was tested on a case study of a sizable pavement rehabilitation project in California.

Realistic and defendable results were derived and were within industry acceptable norms. It is also realised that the quantification of benefits through the deterministic analyses done in this thesis is narrative and does not capture the true value of implemented research. Non-quantifiable, qualitative, indirect or downstream benefits should also be recognised for their positive societal contribution.

It must be stressed that, although the methodology developed as described in this thesis mainly focused on benefit determination of APT-related research in California, it is generic by nature and can easily be adopted in South Africa across various spheres of research impact measurement.

PREFACE

An article-based format was selected for this PhD submission. All articles have been published in peer reviewed journals. All journals are accredited with the flagship Science Citation Index Expanded™ (SCIE) citation indexes as published by Thomson Reuter/ISI Web of Science List (January 2016).

The thesis comprises the following four articles in fulfilment of the minimum required publications as prescribed by the Development and Management PhD in Engineering programme of the North-West University.

i) Nokes, W.A., Du Plessis, L., Mahdavi, M., Burmas, N., "*Evaluating the Benefits of Accelerated Pavement Testing: Techniques and Case Studies*", Transportation Research Record: Journal of the Transportation Research Board. No. 2225, pages 147–154. Transportation Research Board of the National Academies, Washington, D.C., 2011. DOI: 10.3141/2225-16. ISSN: 0361-1981.

ii) Du Plessis, L., Nokes, W.A., Mahdavi, M., Burmas, N., Holland, J., Lee, E.B., "*Economic Benefits Assessment of Accelerated Pavement Testing Research in California: Case Study*", Transportation Research Record: Journal of the Transportation Research Board. No. 2225, pages 137–146. Transportation Research Board of the National Academies, Washington, D.C., 2011.
DOI: 10.3141/2225-16. ISSN: 0361-1981.

iii) Du Plessis, L., Nokes, W.A., Mahdavi, M., Burmas, N., Harvey, J., Liebenberg, L., "*Case Study for Evaluating Benefits of Pavement Research: Final Results*", Transportation Research Record: Journal of the Transportation Research Board. No. 2367, pages 63–75. Transportation Research Board of the National Academies, Washington, D.C., 2014. DOI: 10.3141/2367-07. ISSN: 0361-1981.

iv) Du Plessis, L., Krüger, J.J., *"Methods, Measures and Indicators for Evaluating Benefits of Transportation Research*", The International Journal of Pavement Engineering, Volume 7, Issue 8. April 2016.
DOI: 10.1080/10298436.2016.1172713. ISSN: 1029-8436

The author was responsible for all the technical content of every article. Co-authors are recognised for financial assistance and client recognition. As per requirements, two of the four articles were published under the name of the North-West University with university-appointed promoters as co-authors.

SHORT BIOGRAPHY OF LOUW DU PLESSIS

Louw du Plessis is a Principle Engineer and Research Group Leader at the CSIR, South Africa. He started his career at the CSIR in 1990.

He has four degrees: BSc degree in Mathematics and Applied Mathematics from the University of the Free State, a Civil Engineering degree and a Honores degree (Transportation) from the University of Pretoria, and a degree of Master in Science in Transportation Engineering from the University of California in Berkeley.

He is currently the manager of the Accelerated Pavement Testing programme (APT) at the CSIR where he conducts pavement performance evaluations and APT-related research. He has over 25 years' experience conducting research with the Heavy Vehicle Simulator (HVS) nationally and internationally. He is a member of the international committee on Full-scale Accelerated Pavement Testing (AFD 40) of the Transportation Research Board (TRB), USA, the co-chair of a sub-committee on Accelerated Pavement Testing at TRB and is a member of the executive committee of the International HVS Alliance (HVSIA).

He is currently serving and has served on numerous technical committees at international conferences. He has published more than 85 conference papers, project reports and journal articles, and regularly acts as a technical reviewer for international conferences and journals.

He is a registered professional engineer. Since 2006 he has been involved in the development of a methodology to measure the impact of research through the quantitative determination of the economic benefits stemming from transportation-related research. Other fields of interest include the refinement of the ultra-thin concrete technology at the CSIR. Currently, he is developing the first structural design guideline for ultra-thin reinforced concrete (UTCRP) in South Africa.

GLOSSARY OF TERMS

The following list defines the most common terms used in this thesis:

Accelerated Pavement Testing (APT): APT is a technique used to evaluate the performance of full-scale constructed pavements in an accelerated manner as opposed to long-term pavement performance monitoring. To study the negative impacts of the environment and traffic on the condition and performance of pavement structures can take years under true field conditions. APT utilises special full-scale mobile or fixed testing apparatus to simulate these effects in a shorter time period.

Heavy Vehicle Simulator (HVS): The HVS is a mobile full-scale APT device designed by the CSIR, South Africa. This device accelerates pavement failure by simulating many years of traffic loading in a few months.

Benefit-Cost Analysis (BCA): BCA is a methodology developed for evaluating investment in projects/programmes. BCA is a process by which business decisions are analysed. The benefits of a given situation or business-related action are added and then compared with the costs associated with taking that action. It utilises the concepts of the reducing value of money over time to compare economic benefits in the future of a project with the direct costs related to the project.

Benefit-Cost Ratio (BCR): BCR is an indicator, used in the formal discipline of benefit-cost analysis that attempts to summarise the overall value for money of a project or proposal. The BCR is the quotient of total discounted benefits divided by total discounted costs. Projects with a BCR higher than 1 have greater benefits than costs, i.e. positive net benefits. The higher the ratio, the greater the benefits relative to the costs. All benefits and costs should be expressed in discounted present values. Using the benefit-cost ratio allows businesses and governments to decide on the negatives and positives of investing in different projects.

Basic Research: An activity of which the outputs are also new knowledge, but knowledge of which the nature and use are explicitly needed to achieve a specific useful outcome.

Applied Research: Exploration of nature of which the only required output is new knowledge and of which the outcomes are not known in advance.

Benefits (Direct and Indirect): “Benefit” is a specific indicator such as economic, environmental and social. Benefits are measureable and have economic value. Examples include transportation cost reduction, travel time reduction, accident reduction and vehicle operating cost reduction. Direct benefits (and costs) are the immediate or first-order impacts of the project on users and non-users, including changes in agency capital and maintenance costs as well as user costs for vehicle operation and travel time. Indirect benefits include effects on the economy, land use and environment.

Contribution Ratio: The contribution of a specific APT test to a benefit, expressed as a percentage of total benefit.

Economic Impact Analysis: The study of all the indirect economic impacts of a project on the economy, including jobs and other impacts of construction. Benefit-cost analysis is part of this larger analysis.

Life Cycle Cost (LCC): LCC is the total cost over the service life of infrastructure (i.e. roads, bridges, dams, buildings), discounted to a reference year.

Present Value or Present Worth (PV or PW): PV is the value today of a future cost or benefit, discounted to the present date.

Net Present Value (NPV): NPV is the total discounted costs that are subtracted from the total discounted benefits.

Discount rate: Discount rate is the interest rate used in discounted cash flow analyses to determine the present value of future cash flows in this study. The discount rate takes into account the time value of money (the idea that money available now is worth more than the same amount of money available in the future because it could be earning interest). The discount rate represents the required rate of return to make a business acquisition worthwhile.

Internal rate of return (IRR): IRR is the discount rate at which the present value of future cash flows equals the cost of the project.

Process: Process is a course of action taken to achieve a goal.

Input: Input is tangible quantities put into a process to achieve a goal.

Output: Output is products and services delivered.

Outcome: Outcome is results that stem from the use of the outputs. Unlike output measures, outcomes refer to an event or condition that is external to the programme and are of direct importance to the intended beneficiaries (e.g., scientists, agency managers, policy makers, other stakeholders).

Impact: Impact is the effect that an outcome has on something else. Impact metrics are outcomes that focus on long-term societal, economic or environmental consequences.

1. INTRODUCTION

The complete study as it evolved, was developed and finalised, is detailed in the four published journal articles (in Appendices A to D). Apart from the published journals, numerous output reports, conference papers and technical memoranda have been generated since the inception of the study in California. For clarity the following is a brief summary of the content of the four published journal articles indicating the progression of knowledge from the first to the final journal publication. The information contained in this thesis goes beyond the published information presented in Appendices A to D; however, the author feels that it is important to put the content of the four articles in context with the complete research study from its inception in 2006 to the final delivery of this thesis.

Appendices A and B detail the fundamental work done in the initial stages of the study. Both publications appeared in the same year (2011) and detail the literature survey on the techniques to evaluate the benefits of transportation-related research and a case study used in the initial pilot study done in California.

Appendix A contains the initial literature study done on possible qualitative and quantitative methods to evaluate the benefits stemming from transportation-related research. It also introduces a methodology originally developed in Australia and adopted in South Africa, and formed the basis of the development work done by the author in this thesis.

Appendix B details the preliminary improvements and enhancements by the author to the method developed in South Africa to suit Californian conditions. It contains details of a case study: testing the application of the developed methodology on a real rehabilitation project on a major freeway in California, the Interstate I-710. As it presents the first round of calculations, numerous assumptions were made. The results presented in this publication were preliminary and were only published as proof of concept. Although it was accepted that the results would be fairly inaccurate (due to inaccuracies in assumptions), confidence in the method was established as the results were in the same range as reported by the previous two studies (in Australia and South Africa) and passed the test of reasonableness.

Appendix C contains the final analysis and results using the methodology developed by the author. It details the rehabilitation project on the I-710 in greater detail and contains the true costs of the rehabilitation done on the freeway. The calculations done on the effects of road-user costs were refined as determined through the use of the specially developed software using realistic calibrated input values. The LCC calculations were refined and the NPV determinations of the various scenarios and alternatives were calculated using the RealCost software. In addition to the calculations, the article also reports on a retrospective analysis done on the I-710 in which the measured performance after five years of traffic is compared to the predicted performance done by HVS testing on the innovative pavement mixes constructed on the I-710. It concludes that the HVS predictions were valid and the true performance measured in all lanes was in fact slightly better than predicted through APT testing.

Appendix D was published in 2016. The purpose of this article is to provide updated information by identifying and discussing methods, measures and indicators for evaluating benefits appropriate for transportation-related research facilities/programmes. The information was drawn from within and outside transportation research. The article discusses the sources driving the need for evaluating benefits and describes the challenges confronting the evaluation process. It reviews and compares qualitative and quantitative techniques and highlights previous published work, investigations and case studies.

The motivation for this investigation and publication stems from the realisation by the author that to quantify the benefits of implementable research using only one technique (benefit-cost analysis) is very narrative as this method does not account for the indirect societal and qualitative benefits. Apart from the direct quantifiable methods, there are also challenges in the ability to identify non-technical benefits of research, and there is a growing need to demonstrate such benefits.

This thesis aims to stimulate dialogue and investigations to advance the development of appropriate methods to determine the complete range of quantitative and qualitative, direct and indirect benefits stemming from specifically APT-type transportation research. The two main goals of this thesis are to: 1) help better understand, demonstrate and communicate the benefits of APT research and 2) to develop a robust methodology to measure at least one aspect, the quantification of direct benefits of APT testing.

All this knowledge was consolidated in the four published articles with the supplementary information contained in the body of this thesis.

Appendices E and F contains supplementary information and includes journal guidelines and photos, figures and additional information.

For simplicity and clarity the articles in this thesis are referred to as follows:

1) The article in Appendix A is referred to as “*The initial literature study*”.
2) The article in Appendix B is referred to as “*The initial case study*”.
3) The article in Appendix C is referred to as “*The final case study*”.
4) The article in Appendix D is referred to as “*The final synthesis on the evaluation of benefits*”.

For additional clarity a road map (Figure 1) was developed showing the complete research study and how the different journal articles presented in this thesis fit into the research study from its inception in December 2006 to completion in April 2016. The road map shows a timeline of the Partnered Pavement Research Centre (PPRC) HVS programme in California. The green blocks indicate the periods in which journal articles were published in relation with what was achieved by the publication date. The orange blocks indicate the activities and details that the author was involved with during the indicated time periods.

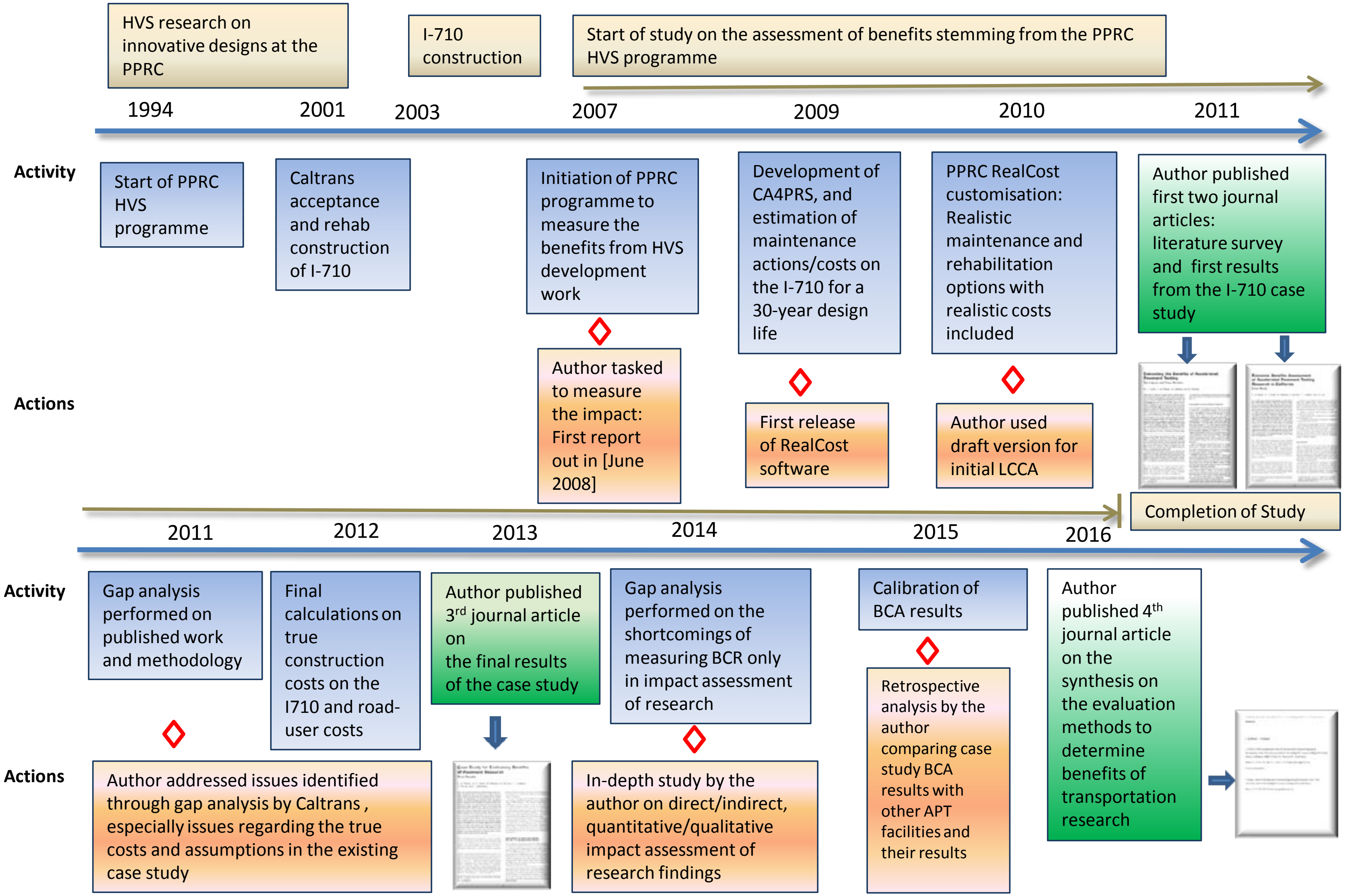


Figure 1: Road map showing the various journal publications in relation to the complete research study

2. HISTORY AND BACKGROUND

The Californian Department of Transportation (Caltrans) developed an interest in APT in 1989, and after evaluation of the South African Heavy Vehicle Simulator (HVS) through a pilot study, decided to purchase two HVS units from the CSIR in South Africa in 1993 (1). The APT programme in California started at the University of California at Berkeley (UCB) and was initially called CAL/APT. The research work was conducted for Caltrans by UCB under the leadership of Professor Carl Monismith from UCB with support from Dynatest USA and the CSIR in South Africa. The initial role of the CSIR was technology transfer in the operation, use and analysis of HVS data.

In 2003 the research programme became a partnership between two universities: the University of California at Davis and UCB, supported by Dynatest and the CSIR. Since the creation of this partnership the name of the programme changed from CAL/APT to the PPRC under the leadership of Prof. John Harvey.

Since its inception of the CAL/APT programme in 1993 and during the following 14 years, significant technical breakthroughs were made by the PPRC programme. However, the following questions remain:

- What is the potential impact of the research results?
- To what extent were results implemented?
- What are the practical benefits from the research programme?

The aim of this thesis is to address these issues through the evaluation of selected HVS tests and implementation projects done in California. In order to accomplish this, an investigation was required and the development of a robust methodology suited for Californian conditions followed, using historical published, existing and new information.

2.1 The purpose of the PPRC programme and the importance of assessing impact

The PPRC programme aims at developing innovative and cost-effective solutions to identified problem areas related to road design and construction. Although the PPRC research programme is centred around the HVS units, a significant part of the effort is expended on laboratory testing and data analysis as well as on the transfer of research findings to Caltrans, consultants and contractors in California and the implementation thereof. Typically, the transfer of findings is done through research reports, conference papers, presentations, seminars and workshops, and through manuals and guidelines that aid designers in the implementation of technologies that were tested and improved through HVS projects.

The overall HVS programme aims at achieving inter alia the following main objectives:

- To identify and highlight deficiencies in current practices to avoid costly early rehabilitation work;
- To evaluate new material and design methods before full-scale implementation, and
- To do comparative studies to determine the most cost-effective solutions to problems.

This thesis reviews the experience gained over more than 35 years with the assessment of the impact of the South African Heavy Vehicle Simulator (SA HVS) programme and its potential applicability to the Californian situation. It also summarises and describes methodologies used by other international researchers to quantify benefits from research work of APT technology development. The benefit-cost calculation flowing from the development work of the SA HVS is summarised in this thesis and acts as the departure point of the methodology developed by the author in terms of its applicability to the situation in California. The study compares the differences between approaches and the assumptions used in the Californian and the SA-derived methods. The applicability of these methods to assess the benefit derived from HVS testing in the PPRC programme is discussed. An analysis method developed by the author was tested through a pilot study in California.

2.2 Lessons from previous evaluations in South Africa

From the beginning of the SA HVS programme, various authors published information on the outcomes of the HVS programme and the impact thereof on South African pavement design and construction practices. A fleet of three HVS units was used over two decades (1970–1990) to evaluate in-service road and airport pavements, to test new design concepts, to develop new design methodologies and to evaluate rehabilitation options for problem roads.

The first attempt to quantify benefits stemming from HVS testing in South Africa was done in 1979 by Freeme in an internal unpublished CSIR report, “The Heavy Vehicle Simulator System: Objectives, Cost and Potential Savings”.

The report identifies five areas in which HVS testing results can be used to save money:

- Reduction in pavement thickness;
- Utilisation of substandard (or marginal) materials;
- Avoiding future problems;
- Improving state-of-the-art knowledge regarding pavement behaviour, and
- Optimising rehabilitation.

The Freeme report discussed the direct financial benefit derived from using pavement designs that were thinner than the standard designs of the time and that had been tested by HVS units and proven to be adequate. Over a range of pavement structures, including asphalt-treated bases, granular bases, cement-treated bases and jointed concrete pavements, an average saving in construction costs of 22.4% was calculated.

In 1982, Marais (2) investigated HVS testing projects conducted on road pavements from 1977 to 1981 with five different base layer types in the then Transvaal province in South Africa. The initial objective was to confirm the ability of unbound crushed stone base pavements to carry very heavy traffic. The report concluded that pavements with granular bases and good quality subbase layers are “deep” structures (adequate strength with depth) and were less sensitive to overloading than “shallow” structures (strong top layer and little strength with depth). The report suggests that an exponential damage factor (n) of 3 should be used to calculate equivalent traffic for such deep structures (instead of the generally accepted value of 4.2 derived from the original American Association of Highway and Transport Officials (AASHTO) Road Test).

Marais also stated that the improved understanding of pavement functioning, effects of traffic, influence of subgrade design moisture content and the importance of maintenance would lead to considerable savings, which were not easy to quantify. However, he calculated that the proven ability of crushed stone base pavements to carry the heaviest class of traffic may result in a saving of at least R100 000 per km of dual carriageway, compared with more expensive designs such as concrete or asphalt base pavements. The HVS studies were therefore instrumental in validating the use of more cost-effective pavement structural designs.

Freeme (3) discussed the use of the HVS to improve the mechanistic pavement design method that was used at the time (late 1970s up to early 1980s). Several improvements on the South African pavement design method were made as a result of HVS testing on pavements throughout South Africa. During that time the CSIR operated three HVS units and these units tested a wide variety of designs, materials, traffic and environmental conditions throughout South Africa. One of the main aims was the determination of distress and failure criteria for the different types of pavement layers used in South Africa. Ane example of this is the determination of permanent deformation limits of the surface (also called “rut”). Freeme (3) concluded that:

> “*The large volume of data on the behaviour of different pavement types has led to a high degree of confidence in the use of the mechanistic design method in South Africa. It has also been possible to modify designs in practice and to reduce pavement costs without a loss of confidence that the pavement will carry the expected traffic. In this way many millions of Rands have been saved in South Africa, thus justifying many years of research into mechanistic design through HVS testing.*”

2.3 Direct quantifiable benefit investigations

In 1992 Horak (4) conducted a comprehensive investigation into the benefits stemming from HVS testing. He compiled a comprehensive list of specific technical impacts from the HVS programme at the time. These included the improved use of new, innovative construction materials and methods, improved design and analysis procedures and specific rehabilitation investigations. An overall BCR of 12.8 was estimated through his analysis. Horak states that "*It should be appreciated that such economic quantification, in this instance attempting realistically to compare the 'with HVS' and 'without HVS' scenarios, is invariably both imprecise and conservative (the latter to minimize potential contention).*" The subjective nature of some of the determinations of the benefits, even though admittedly conservative, and the lack of benchmarking with other expert opinions make this a difficult study to update. Nevertheless, the quantum of the range of BCRs thus determined created additional interest in the value of HVS research and technology development implementation.

Rust, Kekwick, Kleyn and Sadzik (5) reported on the HVS programme in the period 1987 to 1998. This report provided a detailed commentary on the work undertaken by the Gautrans' Heavy Vehicle Simulator (HVS), from its commissioning in 1978 to 1996 (updated to 1998 during the report revision in 1999). The report provided details of the background of each significant HVS project, the underlying motivations and the most significant findings. The report summarised the experience of the Gauteng province in APT up to 1999, provided primarily by the insights of one of the key provincial team members who were involved in the HVS programme. It was not intended to measure the impact of the benefits quantitatively, but rather to provide a perspective on the work and a basis from which future Gautrans HVS work could be assessed. Their work focused on the calculation of direct benefits and also elaborated on the work done earlier by Horak by means of anecdotal descriptions of cost savings or benefits. It used granular emulsion mixes (GEMs) developed through HVS testing as an example of a direct calculation of cost savings. The HVS was used to assess the bearing capacity of a marginal, in-situ material upgraded to base standard with an asphalt emulsion additive. It was found that the performance of the material was comparable with that of an imported crushed aggregate base. Due to the savings in material and the transportation cost, this resulted in a saving of R32 000 per km (in 1992). Currently, this technology is used extensively in parts of South Africa where good aggregate sources are scarce.

The overall benefit of the HVS programme in South Africa was assessed by Rust, Mahoney and Sorenson (6) in 1998. The study, among other things, compared the costs of pavement designs in South Africa with those commonly found in California and Washington State. Validated through years of HVS testing in South Africa, the commonly accepted pavement structure in South Africa consisted of high-quality granular bases supported by a cemented subbase and covered with a relatively thin wearing course. The South African design philosophy yielded more cost-effective designs than those utilising relatively thick asphalt layers on weaker granular layers. It was evident that, should one be able to construct with these materials in the USA cost-effectively, a significant saving on initial cost should be effected. The saving on initial cost could be 30–45 per cent, depending on the traffic class and the quality of the subgrade support. It is concluded in their work that the lower cost in pavement structure construction found in South Africa was mainly due to the results produced by the HVS programme in its efforts to determine the most cost-effective design for a particular pavement type and traffic class.

2.4 Benefit-cost calculation methodology development and application

Two studies were investigated by the author, one in Australia and the other in South Africa.

2.4.1 South Africa

In 2005, Jooste and Sampson (7) calculated the benefit-cost ratio of the HVS work done in South Africa to develop the high-quality crushed aggregate base pavement design (called G1 base). The basis of their analysis rested on the development of benefits flowing from research with the HVS and is illustrated by the conceptual diagram shown in Figure 2.

The diagram shows that technology development goes through various stages in terms of process and information available from blue skies type discrete research to ever increasing technology maturity concepts before reaching a technology transfer and implementation stage.

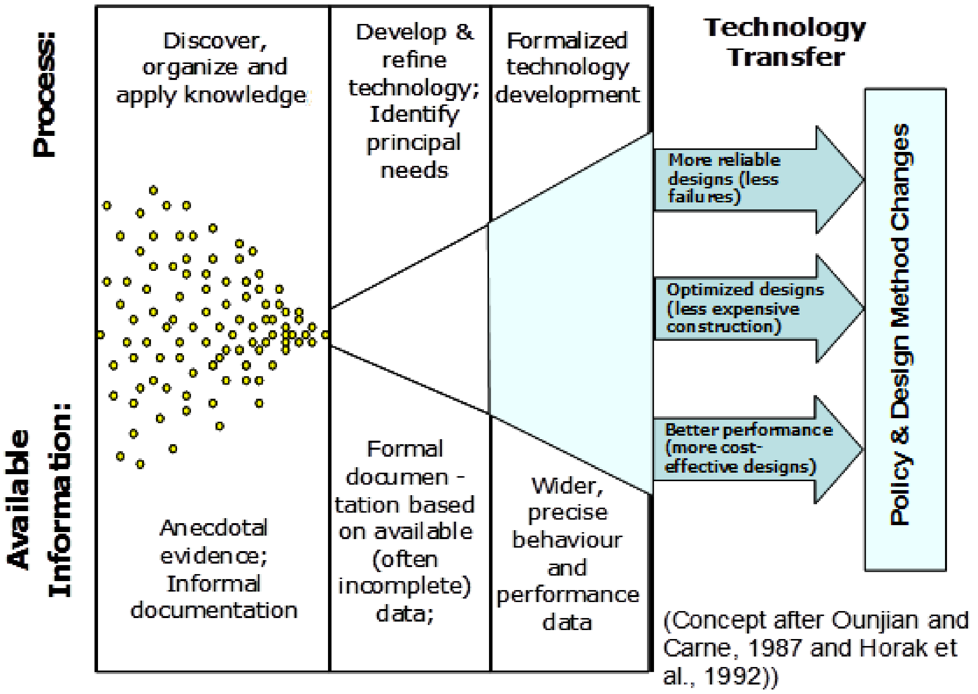


Figure 2: Conceptual diagram showing technology development (Source: Jooste and Sampson)

Technology development projects (such as those involved with APT and HVS testing) often refine and complete technology that was "ripened" by earlier (often informal, anecdotal, philosophised or conceptually visualised) evidence. The value and contribution of prior developments during the preceding phases therefore also need to be recognised in order to place the contributions made by the HVS testing and development in perspective.

In Figure 3 the specific timeframes and development processes of the high-quality G1 crushed stone base pavement technology originated by the previous Transvaal Roads Department (TRD) are illustrated. It is clear that the HVS testing made a significant contribution towards the final technology transfer by building on initial development work by the TRD and research done by Maree on G1 material characterisation in the laboratory.

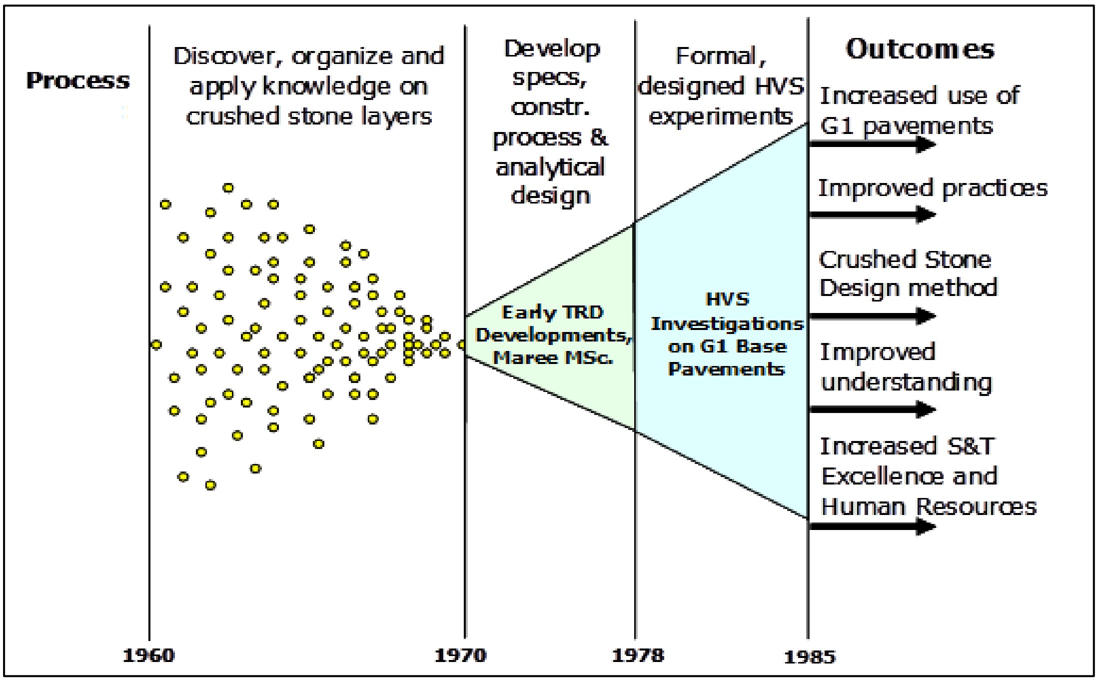


Figure 3: Illustration of timeframes and development of the G1 crushed stone base pavement technology (Source: Jooste and Sampson)

These outcomes were translated into main benefits of G1 crushed stone base construction and were used in the further analysis. The benefits identified are summarised as follows:

1) Increased use of G1 base pavements for higher design classes and wet regions;
2) Use of 150 mm maximum thickness for G1 base layers, and
3) Improved construction and maintenance strategies (reduced risk of earlier failure).

Jooste and Sampson (7) adopted a methodology for the evaluation of economic benefits which is based on the framework established by Australian investigators (8, 9) concerned with the assessment of the benefits of their APT facility. The methodology has been applied to the analysis of the use in G1 base materials in South Africa, verified through HVS testing.

Jooste and Sampson (7) only investigated benefits which they could convert to economic savings with reasonable confidence and assumptions. Their study admits that it failed to take into account the further downstream benefits and the impact of these benefits on the population at large. These were not calculated due to the difficulties in the determination of the indirect benefits. Road-user costs were also not taken into account in their analysis. This means that the benefit assessment done by Jooste and Sampson (7) probably greatly underestimated the true benefits stemming from the HVS investigations done in South Africa.

2.4.2 International best practice in benefit quantification

The Australian Accelerated Loading Facility (ALF) also conducted a study to evaluate the benefit-cost ratio of their APT programme (8, 9). The methodology they used determined economic benefits which took uncertainty into account in the assessment of the benefits of technology development work. The methodology formed the basis of the one later developed by Jooste and which was applied to the analysis of the G1 economic benefit determination. The range of estimated benefit-cost ratios reported by them varied between 3.8 and 9.4, depending on various factors and assumptions. The similarity in the ranges of BCR found by the Australian and South African researchers provides confidence in this methodology.

However, the selection of best performing projects for benefit quantification is also important according to Zilberman and Heiman (10). They found that benefits from research programmes comprising several separate projects were skewed. This means that a form of the Pareto principle applies as a small number of projects may account for most of the benefits of a research programme. Parker, Zilberman and Castillo (11) found that out of several hundred royalty-generating research projects at the University of California, the top two generated 70 per cent of the technology transferred in 1994. This effect suggested that it might be more effective to identify the best performing projects within a research programme and then to focus on those, as opposed to trying to evaluate the entire research programme over a long time.

3. LIMITATIONS IN EXISTING KNOWLEDGE AND MOTIVATION FOR DEVELOPING A ROBUST METHODOLOGY

The author studied the published methodologies on direct benefit determination of APT research in South Africa and worldwide, and identified a number of limitations which made the direct implementation of existing methodologies in California difficult. Two of the most critical limitations are detailed below.

1) Public participation and acceptance of results

   The suggested methodology in South African allowed for a single “contribution ratio” parameter. This parameter assigned a percentage contribution of a successful implemented technology development to the HVS and this contribution ratio was tested through an interview process with industry experts.

   In the case of California, public participation and acceptance are very important as many research outcomes are criticised for being biased towards a certain outcome. To address this need, the final methodology developed for Caltrans by the author allowed for the sensitivities in differences of opinion during an extensive interview process. No single “contribution ratio” was used; however, the South African method was enhanced to cater for the range of opinions regarding the use of the HVS and its value for the Californian road user. Unlike in South Africa, where the majority of the road infrastructure is constructed using asphalt, California’s road network consists of over 30 per cent concrete roads. This complicated the matter as many pavement district engineers, academia and roads authorities had distinct different opinions of what type of pavement structures were the best (asphalt vs concrete) for long-life low-maintenance pavement structures. For this purpose the method was enhanced by introducing a sensitivity analysis to cater for the wide ranges of public opinions and perceptions. Sensitivity analysis is a method of testing how much influence a single parameter may have on the results.

2) Road-user costs

   The Australian and South African methods investigated the direct benefits of APT from an agency point of view only and not from the road-user point of view. In California, where road-user delay (due to congestion, construction or accidents) is a significant cost component, this reality had to be addressed in the current suggested methods developed in South Africa and Australia. The author expanded the work done in South Africa by introducing road-user costs as a cost centre into the methodology. This called for the accurate determination of the quantum of road-user costs when pavement construction was causing road-user delay.

> For the purpose of determining road-user costs, a software tool CA4PRS was specifically developed as a planning tool for rehabilitation projects. CA4PRS calculates the maximum length of highway pavement that can be rehabilitated or reconstructed under a given set of project constraints such as a limited time window. CA4PRS is used to optimise construction activities and traffic management plans for rehabilitation projects. Optimal scheduling for traffic accommodation, user delay and construction time is calculated to minimise road-user costs during construction disruptions. This tool was used to incorporate the benefits of APT testing from a road-user perspective and was incorporated into the final methodology developed for the determination of benefits from the APT programme in California.

The final development regarding the methodology developed by the author for the California study was the incorporation of RealCost (12). RealCost is a manual and computer software program developed by the Federal Highway Administration (FHWA) in the USA in 2003 for the evaluation of the cost-effectiveness of alternative pavement designs. It was chosen as software for evaluating the cost-effectiveness of alternative pavement designs for new roadways and for existing roadways requiring Capital Preventative Maintenance (CAPM) rehabilitation or reconstruction. The software does a life cycle cost analysis (LCCA) to be used on pavement projects on the State Highway System in the USA.

LCCA is an analytical technique that consists of well-founded economic principles to evaluate long-term alternative investment options. The analysis enables total cost comparison over the service life of design alternatives with equivalent benefits. LCCA accounts for three cost centres: the initial costs of the agency or owner, the total road maintenance and rehabilitation required over the lifespan of the facility, and the road-user costs (carried by the users) which will occur throughout the life of an alternative. Relevant costs include initial construction, future maintenance and rehabilitation, and road-user costs. Discount rates are used to account for the declining value of money over time.

This analytical process helps to identify the lowest cost option in the selection of project alternatives and provides other critical information for the overall decision-making process of projects.

The author further investigated the limitations in the existing methodology in order to do a complete economic impact analysis where BCA was only a part of the larger analysis. The impact (benefits) of research goes beyond the measurement of direct first-order impacts (such as BCR) and also covers social and environmental impacts and indirect qualitative benefits not measured through BCA. Perhaps these other impacts have a bigger influence on society at large than the political short-term gains in saving costs on infrastructure development. This investigation (The final synthesis on the evaluation of benefits – Appendix D) was included as the author increasingly became aware of the limitations of the methodology he had developed through this thesis and the growing need to put this narrative view into perspective regarding what is required to complete a total economic impact analysis on the benefits of APT testing.

4. PROBLEM STATEMENT AND MOTIVATION FOR THE STUDY

South Africa is not unique when it comes to the challenges of investing into research for the future benefit of the county. Currently, a number of countries are cutting on their research funding due to slow economic growth and other pressing needs on the fiscus. Although not directly related to investment in research Rust (13) reported in the Journal of the South African Institution of Civil Engineering (2011) that:

> *"In many countries infrastructure is ageing or inadequate, particularly in developing countries where economic growth over the past decade has been significantly higher than the long-term average. The World Bank estimates that the projected funding gap for infrastructure in the USA is a significant US$ 1,6 trillion over a five-year period, while Asia will need an estimated US$ 1 trillion over the same period. In South Africa there are also significant needs for infrastructure development, as is reflected in the Medium Term Strategic Framework (MTSF, 2009) that refers to a massive programme to build economic and social infrastructure."*

The lack of infrastructure spending directly cascades down to research funding expenditure by government. According to the Organisation for Economic Co-operation and Development (OECD) (14, 15), South Africa rates low in its research and development (R&D) spending as a percentage of the Gross Domestic Product (GDP) in comparison with countries with comparable economies. The latest data (prior to 2013) indicated that South Africa had spent 0.760% of its GDP on R&D in comparison with countries such as Korea (4.2% of GDP), Belgium (2.28% of GDP) and France (2.23% of GDP).

In the infrastructure domain in South Africa R&D expenditure is as low as 0.3% (14). In a recent addition of the South African Journal of Industrial Engineering (2015) Rust indicated that, although SET (science, engineering and technology) has a major impact on the social development and economic growth of a country, South Africa's capability to deliver R&D outputs is under threat due to a lack of investment in the South African research core (16). South Africa ranks 32 out of 84 measured countries and spends only US$ 92.25 on R&D per capita in comparison with the Czech Republic (ranked 31) with a spending of US$ 600 on R&D per capita (15).

Human resource development is also an important part of the whole R&D process. This is highlighted in the South African National R&D Strategy document (17), which states that R&D investment is a significant contributor to human resource development. Rust (16) reported in a study of Japan (a developed country), Korea (a newly-industrialised country) and South Africa (a developing country) that Korea has nine times more researchers per capita than South Africa. This is a clear indication of the low levels of research and development funding in South Africa. These findings are in agreement with the OECD finding that South Africa only has 1.48 researchers per thousand employment (FTE) in comparison with Korea (FTE = 12.84), Belgium (FTE = 9.83) and France (FTE = 9.81) (14).

With this low level of investment in research it is increasingly important that research funding should be invested wisely with a measurable degree of certainty that it will benefit South Africa in future.

Transportation infrastructure investment has its unique challenges as it competes with very sensitive public spending needs such as health, education and safety. Very often it does not receive its rightful share of government's investment in public services. The downstream effects of neglecting the upkeep and maintenance of the road infrastructure in South Africa is rising logistics costs (the price of moving goods and people from origin to destination) and social disbenefits due to a lack of acceptable access to facilities such as hospitals, schools and shops.

The South African National Roads Agency SOC Ltd (SANRAL) measures the condition of South Africa's road network and classifies it from "Very Good" to "Very Poor". Its 2013 data (18) is shown in Figure 4. It is clear that on average, more than 60% of the quality of the South African surfaced road network is in the bottom three categories of "Fair" to "Very Poor". In response to this reality, the latest figures (2015) on logistics costs published by the University of Stellenbosch (19) indicate that:

> "*Logistics costs make up just over half of the landed cost of agriculture, mining and manufactured goods and rising input costs are expected to increase logistics costs as % of GDP by 0.6 percentage points from 2013 to 2015. South Africa's logistics costs as a percentage of GDP in 2013 were 11.1% which is higher than developed countries (Europe: 9.2%, North America 8.8%).*"

Given these facts it is clear that research organisations such as Universities and the CSIR should direct its research funding towards projects and programmes where the most benefits will be realised.

The Gauteng Department of Roads and Transport (GDRT) maintains the Gauteng Technology Development Programme, which is centred on the HVS machine and related technologies. A key objective of this programme is to develop innovative and cost-effective pavement designs, including the identification of possible weaknesses and limitations in materials, design and construction practices. The development of a system or method to measure the impact of the GDRT programme should not be limited to the investigation of the direct (engineering) impacts, but should also consider the impacts from the funding agency side. To a large extent, this means that the needs of the funding agency should be understood at the political level, and then the way in which to include these needs in the whole analysis system should be considered.

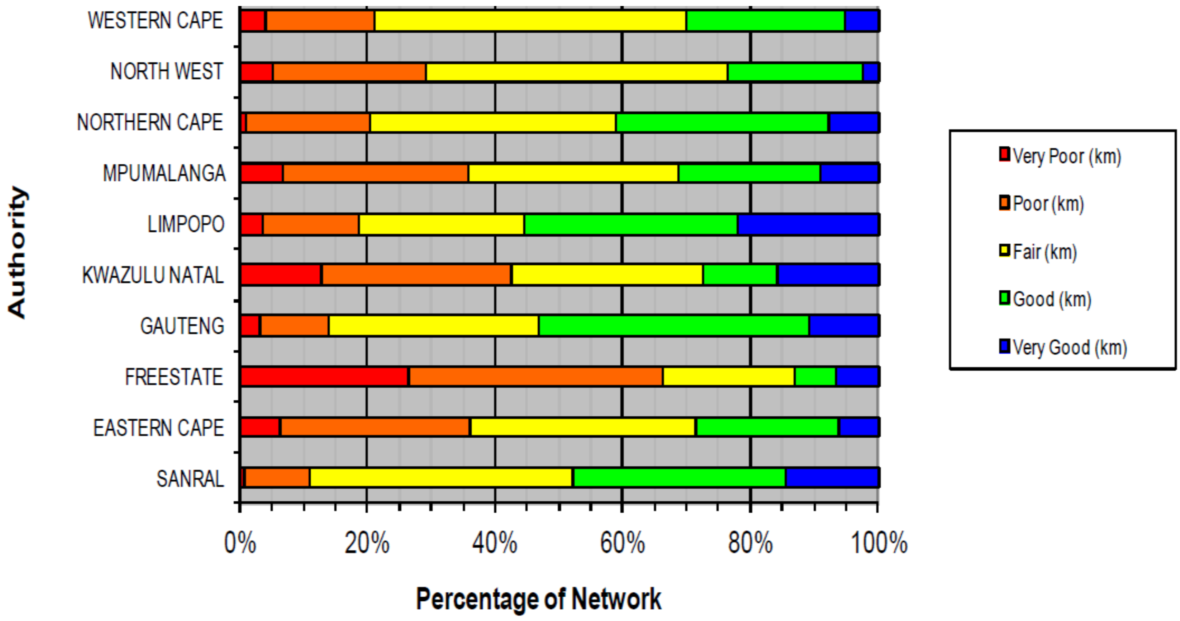


Figure 4: Condition of the South African surfaced road network in 2013 (Source: Kannemeyer 2016)

A key aspect here is to understand that some benefits arising from technology development work are direct. That is, they have direct economic benefits. Other benefits, however, are indirect and intangible, but they are no less important to the mission of the funding agency, and perhaps these indirect benefits are even more important to the funding agency.

Research done here should also be aligned with the South Africa National R&D Strategy (17). This document clearly explains the objectives and general benefits of research and development work. It specifically highlights the two high-level goals of research and technology development, namely to improve quality of life and wealth creation. For GDRT specifically, focus areas are accelerated infrastructure development, job creation and better social service delivery. These goals are clearly political in nature. The first challenge is to clarify the links between highly technical development work and the political objectives.

As the title of this thesis suggests, it is a narrative investigation of benefit determination of the impact of research. The author acknowledges that indirect qualitative benefits such as the following are also important indicators of the success of research:

1) Human capital development by contributing to post-graduate research qualifications and in improving science, engineering and technology (SET) excellence through guidelines, workshops and seminars, and
2) Technical progress, by ensuring that the South African pavement engineering technology is aligned with international best practice.

These types of qualitative indicators are investigated and reported during the final synthesis on the evaluation of benefits as detailed in Appendix D.

The author was involved in the HVS programme in California since its inception in 1993. Thirteen years later, in 2006, Caltrans faced similar challenges in the motivation of their APT programme and tasked the author with measuring the effectiveness of the California HVS programme. The first step in assessing benefits from APT in California was to conduct a literature review on the subject and identify limitations with current practices (the initial literature study). The second step was to develop a methodology suited for the Californian environment. The last step was to test the methodology through a pilot project that included a case study.

The need to assess benefits from APT in California comes from many sources, including Caltrans' commitment to its strategic goal of effective stewardship of California's resources and assets (very similar to the case in South Africa). In managing HVS tests and pavement research overall, the Caltrans Division of Research and Innovation supports their department's vision, mission and strategic goals through processes that include the following:

- Feedback, to ensure that sound investments are made in the pavement research programme;
- Continuous improvement, to identify and overcome barriers in the research process, and
- Accountability and performance measurement, to identify and communicate benefits of research.

It must be stressed that, although the methodology developed as described in this thesis mainly focused on benefit determination of APT-related research in California, it is generic by nature and can easily be adopted in South Africa across various spheres of research impact measurement. As service delivery is becoming a main driver in government spending, this imperative will also impact on research institutions (such as universities and the CSIR).

The development of the first South African electric passenger vehicle, the Joule, is an example of a product which was never commercially available and investment in its development was ceased in 2012. Scrutiny of the value of research in South Africa is a reality and research organisations should develop the right tools and methods to assist in the justification of governmental grants and funding for research.

5. LITERATURE REVIEW ON CURRENT PRACTICES

Many traditional challenges of determining benefits persist, contributing to the gap between the ability to identify non-technical benefits of research and the growing need to demonstrate such benefits. The initial literature survey article in Appendix A aims to stimulate dialogue and investigations to advance the development of an appropriate robust method of determining quantitative benefits stemming from specifically APT-type transportation research.

The methods, measures and indicators discussed in this thesis show substantial variability in approaches used worldwide to evaluate benefits of research in and outside of transportation research. No universal approach is recommended because there is no one-size-fits-all technique. Despite the recurring observation that no country appears to have a totally satisfactory technique, many approaches have been proposed, applied and reported. Developments during the past decade appear promising.

In the case of APT-related research, there are qualitative and quantitative, direct and indirect benefits. The growing global interest and awareness of efforts to quantify the economic benefits of APT research was the main theme at the 2008 International APT Conference in Madrid, Spain (20). Conference discussions explicitly associated technical activities with their relative costs and benefits, which are suitable for BCA. In the case of calculating cost savings (better pavement designs, construction processes and materials due to APT results), BCA was identified as the ideal method to measure the impacts and benefits of APT-related research. The key component of this method is obviously market uptake and the acceptance of new technologies. Case studies were suggested to prove a concept and the real benefits can be measured only after implementation on a larger scale.

It is suggested that all measurable parameters mentioned in the summary of evaluation techniques in Table 1 (The initial literature survey, Appendix A) should be captured during APT experiments. Retrospective analyses of both qualitative and quantitative benefits would only be possible if quality information were gathered and kept for all APT experiments, including information on implementation projects. BCA and positive benefit-cost ratios are powerful convincing tools to justify expensive research programmes (such as APT), while bibliometrics, the number of PhDs, peer-reviewed articles, patents, etc. highlight the importance of APT in academia and political circles.

Table 1: Summary of Evaluation Techniques (References appear in parentheses)

	Transportation		Non-Transportation	
	USA (FHWA, 21)	USA (NCHRP, 22)	Europe 2009 (RAND, 23)	Europe 2007 (RAND, 24)
Methods – Qualitative:				
Peer and Expert Review	✓		✓	✓
Survey	✓	✓		✓
Case Study – Descriptive			✓	
Training and Education		✓		
Tracing and Logic Modelling			✓	✓
Benchmarking				✓
Sociometric Analysis			✓	
Methods – Quantitative:				
Benefit-cost/Savings analysis	✓	✓	✓	✓
Bibliometrics	✓			✓
Safety (Less Crashes/Fatalities)		✓		
Econometrics			✓	
Outputs (Products and Reports)		✓		
Performance	✓	✓		

The summary in Table 1 leads to several observations, including:

- Qualitative and quantitative techniques are both well represented;
- Many techniques are cited in at least two publications;
- The most common methods are benefit-cost/savings analyses, peer reviews and surveys, and
- These common methods are used in transportation research as well as non-transportation research.

Evidently, a wide variety of methods are in use. The choice of approach is driven by the purpose and conditions of the study as well as time, resources and other constraints. Each technique offers advantages and disadvantages.

6. ECONOMIC BENEFIT ASSESSMENT OF ACCELERATED PAVEMENT TESTING IN CALIFORNIA

The method developed by the author is based on decision analysis, the concept of Expected Value for Perfect Information (EVPI) and expected values, which are the product of probabilities of outcomes multiplied by the cost of each outcome (25, 26). The method is based on Bayesian statistics and is suitable for events in non-repeatable random experiments or when the process of sampling is suggested by circumstances (oil-well drilling is a typical example in the literature). Unlike the frequentist approach that emphasises underlying population and sample distributions, their statistical measures (e.g. central tendency and dispersion) and associated confidence intervals for hypothesis testing, the Bayesian approach relies on states of knowledge and the beliefs (including probabilities) aired by knowledgeable individuals.

In the case of this thesis, Californian pavement experts who had first-hand knowledge and experience of rehabilitation projects and associated HVS testing provided input. The Bayesian approach is suitable for characterising and analysing non-repeatable decisions and counterfactual scenarios, such as assessing what design alternative would have been constructed in the absence of HVS testing/validation. To examine and understand the range of potential impacts from reliance on subjectivity, the use of sensitivity analysis is strongly recommended.

A payoff table or decision tree (as used in this case study of this thesis) is a framework for calculating expected costs for a decision. Each decision, such as not conducting a test, results in its associated expected cost. The generic decision tree adopted for the analysis of the case study is shown in Figure 5.

Conducting a test may provide more information that might reduce the expected cost. Depending on the cost of conducting a test, the difference in expected costs may show a cost saving (i.e. benefit). If savings exceed the cost of testing, then the benefits are worth the cost of the test. The BCR of conducting a test can then be calculated. Details of the method and its application in the case study are given on the next page.

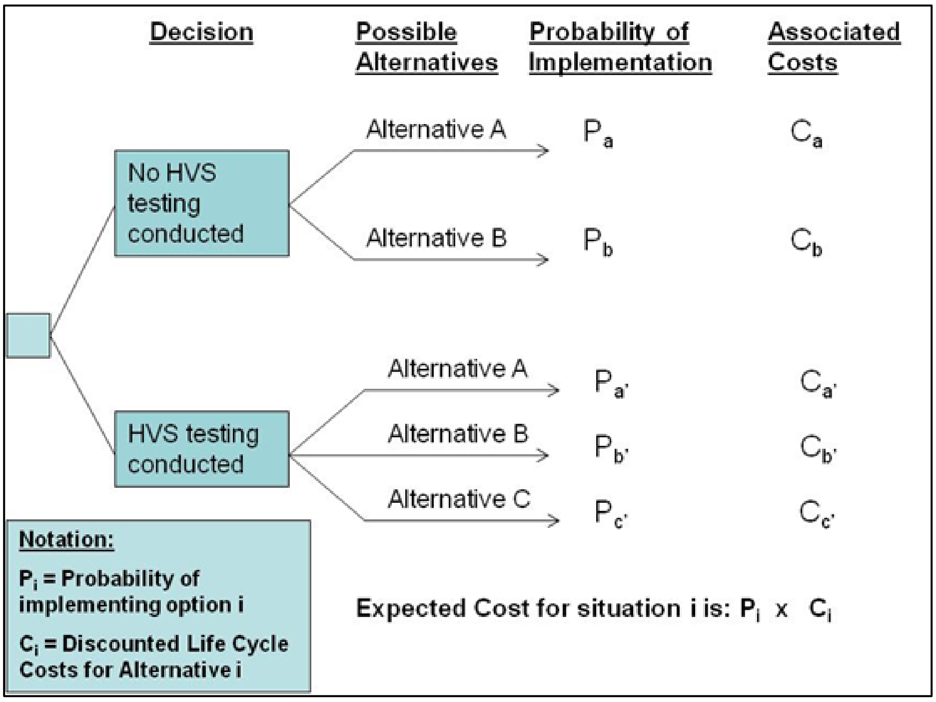


Figure 5: Decision tree showing the approach for assessing the benefits of APT-testing based on EVPI principles

For benchmark objectivity and credibility, each of the alternatives identified were validated through formal interviews with pavement engineers from within and outside of Caltrans. These engineers have first-hand knowledge of the HVS test and rehabilitation projects of the case study used in this thesis. During the interviews the various rehabilitation alternatives, probabilities for implementation, costs and perceived impacts and benefits were discussed. Interviews provided a wide range of opinions as well as the inputs needed for analysis such as the probability for each alternative and the extent to which the HVS test contributed to benefits. To accommodate the variability in the perceptions of the interviewees, a sensitivity analysis was conducted to examine how the range of their inputs affected BCA results.

It is also important to take into consideration the fact that benefits (e.g. from a less expensive design) cannot be realised over the whole road network where an innovation is applicable and certainly not immediately after validation. The potential benefit would be phased in based on the needs of the road network, budgets and other priorities.

As was noted earlier, apart from many indirect benefits, the assessment of economic benefits may stem from technology development projects, and is based primarily on the assumption of new and freely available information. This information is assumed to impact positively on policies, which in turn lead to measurable economic benefits. The use of the EVPI approach aims to establish a rational method for evaluating the value of information that can assist in directing and clarifying policy decisions.

The consequences linked to the alternatives of implementing new technology are illustrated in Table 2. It helps to put the situation and possible consequences in perspective and helps to assign probabilities to the situations. This table can, therefore, be used in an interview situation with Caltrans officials to help verify the assumptions made, the extent of new technology implementation and their perceived impact.

It is necessary to achieve this calibration effect as it has been shown that the benefits can be relatively large. The large scale of the implementation of relatively large road networks has a significant economy-of-scale effect and this in itself can lead to significant benefit quantification. Therefore, this needs proper benchmarking and verification by those who can give reality checks for the EPVI used and the assumptions made.

Table 2: Consequences linked to the alternatives of implementing new technology

Option	Situation	Consequences
Implement new technology for all appropriate projects	New technology is significantly more cost-effective.	Network-wide savings are realised due to more cost-effective technology.
	New technology is not more cost-effective.	Cost is higher but ineffective. New technology is wasted.
Disregard new technology	New technology is significantly more cost-effective.	Potential network-wide savings are not realised.
	New technology is not more cost-effective.	Cost is higher but ineffective. New technology is prevented but cost avoidance results in savings.

As in the case with the demonstration of BCR calculation in South African, the initial calculations by the author were used to partly inform the potential interviewees and then to guide them to make subjective value judgements on the extent and impact of the technology development and transfer in California. The initial case study (Appendix B), therefore, acted as departure point for the revision after the intended interviews with Caltrans officials, academia and the industry.

6.1 Case Study

The methodology developed by the author was tested in a case study conducted on an HVS test on hot-mix asphalt pavement associated with the Long-Life Pavement Rehabilitation Strategy (LLPRS) programme of Caltrans that began in 1998.

Criteria for the LLPRS programme were:

- Construction had to be fast (within a limited number of 55-hour weekends), and
- Rehabilitated pavements had to have at least a 30-year service life with minimal maintenance.

The project selected was a rehabilitated section of the Interstate 710 (I-710) in Long Beach, California. The details of the project can be found in the two publications, The initial case study and The final case study, as presented in Appendices B and C. The details are briefly explained below.

The I-710 was opened in 1952. It is a major freeway running north-south connecting the city of Los Angeles with two major ports, the port of Long Beach and the port of Los Angeles as shown in Figure 6. These are two of the busiest ports in the United States of America. In 2002, on weekdays, the I-710 carried more than 164 000 vehicles per day, 13 per cent of which were heavy trucks. A section of this freeway was in poor condition and various rehabilitation techniques were considered. Caltrans was concerned about traffic disruption during the rehabilitation of such a busy freeway and decided on a 55-hour weekend closure, which was typical for LLPRS closures.

The existing pavement consisted of 200 mm portland cement concrete (PCC) on top of 100 mm of cement-treated base (CTB), which was Caltrans' most commonly used rigid pavement type in the 1960s and 1970s. Beneath the highway overcrossings (OCs), which did not meet current federal bridge clearance requirements, the existing concrete pavement structure was removed with an additional 150 mm to improve bridge-height clearance.

The possible rehabilitation alternatives included the standard Caltrans rehabilitation options and innovative alternatives which have been tested and verified through extensive HVS testing. The alternatives were:

1) Standard Caltrans crack, seat and asphalt concrete overlay (CSOL);
2) Innovative CSOL overlay;
3) Standard Caltrans full-depth asphalt concrete (FDAC) replacement;
4) Innovative FDAC replacement, and
5) Long-life PCC lane and slab replacement.

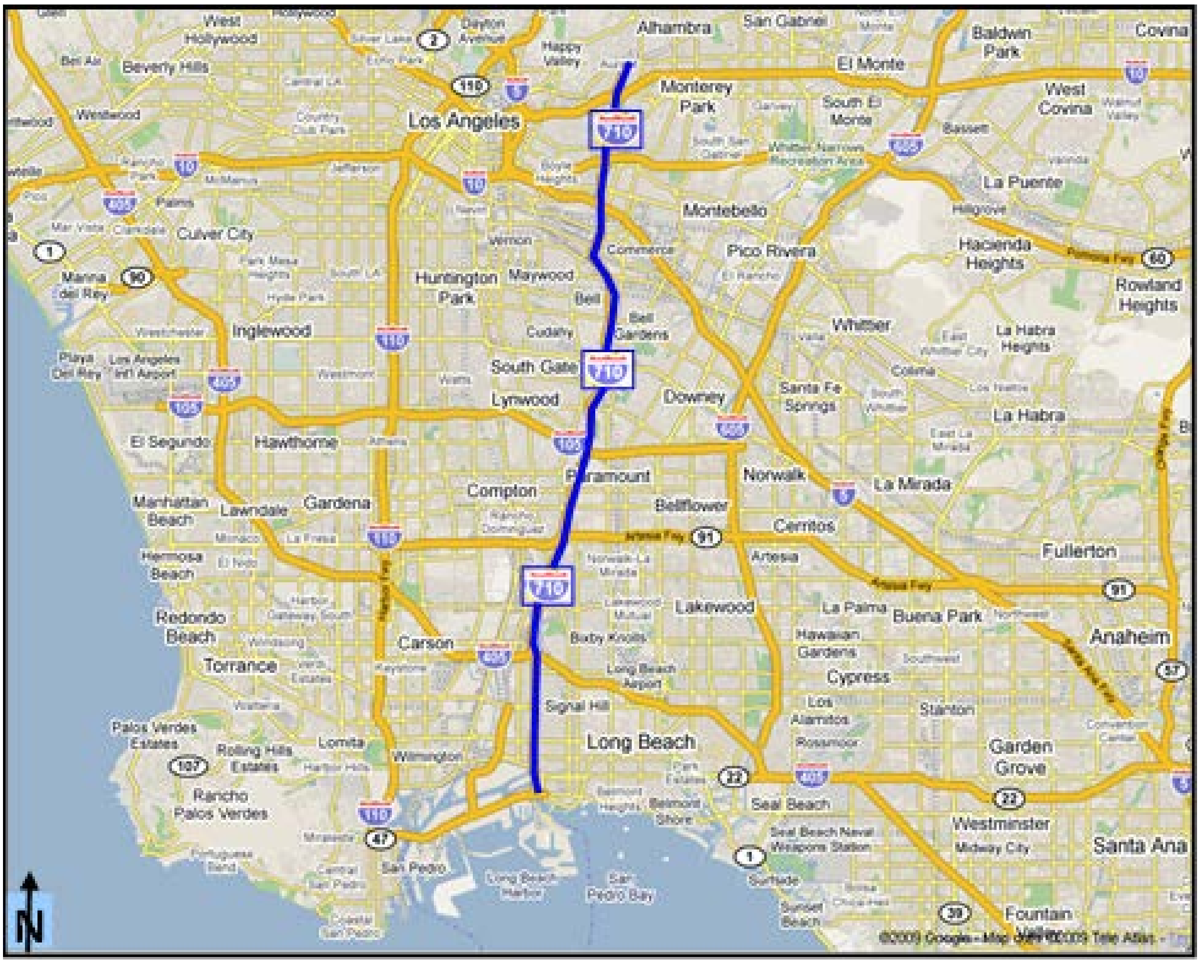


Figure 6: The I-710 corridor in Los Angeles (Source: Google Maps 2009)

The null hypothesis (i.e. not doing anything) was not an option as the existing freeway was in urgent need of rehabilitation and was, therefore, not included in this analysis.

A technology road map (Figure 7) was generated and it detailed the various phases of the evaluation of the innovative materials research and design prior to the full-scale implementation on the I-710. Due to the high traffic volumes and possible road-user delays in case of early failures, Caltrans was strict in the testing and evaluation requirements of new products and methods on such an important freeway. Thorough laboratory and HVS testing were required to verify the use of these unconventional rehabilitation alternatives.

The road map shows that the knowledge base supplied information to meet Caltrans' needs. The sources of knowledge included Caltrans research funds as well as other sources. The HVS tests conducted specifically for the Phase 1 mixes are indicated by shaded boxes in Figure 7. The figure indicates that the HVS tests (referred to as "Goal 6") and the validation knowledge base resulted in meeting Caltrans' need for validation. Figure 7 also shows other activities that contributed to the knowledge base indirectly and that were funded by Caltrans as well as others. An important fact is that the HVS played a big part in the evaluation and validation; however, HVS testing was not solely responsible for the development and implementation of these innovative designs.

These circumstances proved to be ideal for the case study to test the methodology developed by the author in California for the determination of the benefits of APT testing. This was a sizable project where HVS-tested innovative designs were constructed and the true costs of the various designs (standard and innovative) could be compared within the context of Life Cycle Cost Analysis (LCCA) techniques, including road-user delay. The project allowed for the evaluation of two possible benefits reflecting the two different designs (one on the open road and one under overcrossings (bridges) where vertical clearance problems prevented an overlay design).

The identified benefits are:

Benefit 1: Innovative mixes enabled the improvement of vertical clearance under overcrossings while meeting LLPRS criteria.

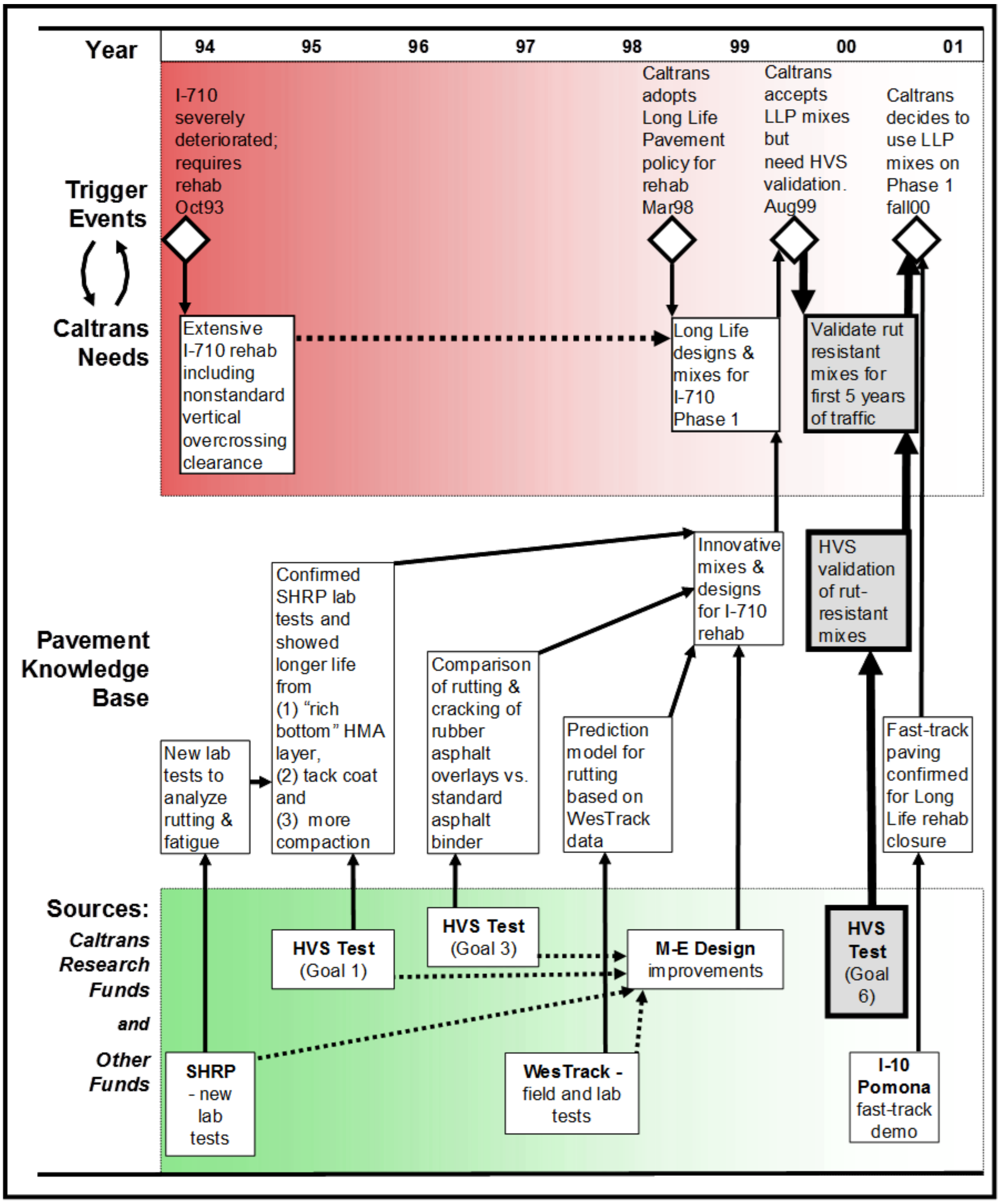
Benefit 2: Innovative mixes enabled meeting the LLPRS criteria where no vertical clearance constraints existed.

6.2 Key elements of the methodology

The steps in applying the developed methodology are as follows:

1) Situations with and without the benefit of HVS testing are identified;
2) Uncertainty in assumptions and outcomes is accommodated by assigning a probability (on the basis of input from interviews) to each alternative outcome;
3) Life cycle cost of each alternative outcome is calculated;
4) Expected value (cost) of each alternative outcome is calculated by multiplying its probability by its cost;
5) Total expected for value of each decision (with HVS testing and without HVS testing) is calculated as the sum of expected costs of alternatives;
6) Benefit (expressed as NPV of cost savings) of the information from the HVS test is determined by subtracting the total expected cost without the HVS test from the total expected cost with the HVS test, and
7) BCR is derived by dividing the benefit by the total costs of the HVS testing.

A key part of the assessment and validation effort is estimating the likelihood of technical advances that would have occurred if HVS testing had not been performed. To address alternative scenarios of technology development explicitly, decision-tree analyses were performed as shown in Figure 8 for the five selected alternatives. The expected cost of each design alternative is determined by multiplying the life cycle cost for each alternative by its assigned probability. The sum of all probabilities must equal 1 in each decision branch.



KEY: M-E Design – Mechanistic Empirical Design
SHRP – Strategic Highway Research Programme

Figure 7: Technology roadmap developed for the evaluation of innovative technologies for the I-710 rehabilitation

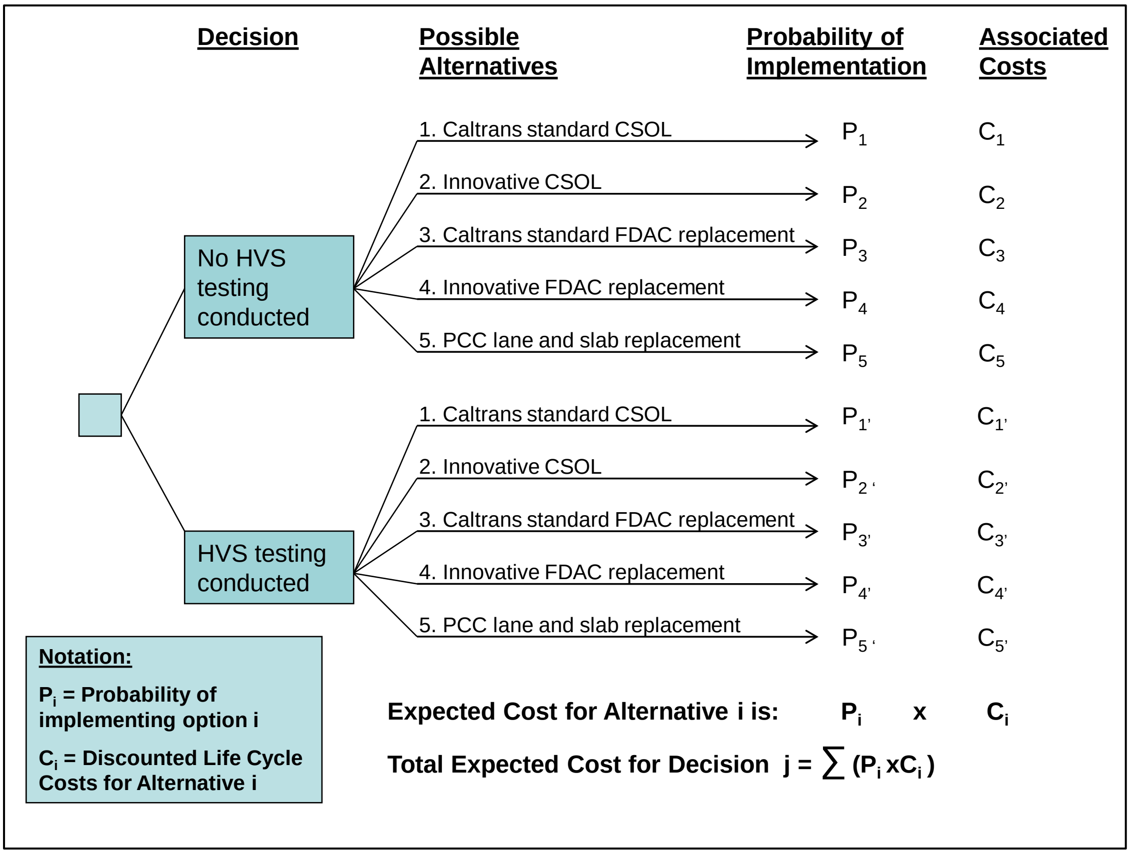


Figure 8: The decision tree developed for the I-710 rehabilitation alternatives

6.3 Benefit-Cost Analysis

In order to determine the savings and BCR, a number of different analysis steps were followed. These steps are outlined below. The decision-tree diagram for the I-710 case study is shown in Figure 8 above.

1) Validation interviews were conducted with pavement engineers from within and outside of Caltrans who had first-hand knowledge of the HVS testing and I-710 rehabilitation project. They identified likely alternative designs (with and without HVS testing), probabilities of construction of each alternative, maintenance and rehabilitation schedules for the design life and the percentage contribution of HVS testing to innovative designs. Their input was part of the selection of the final five alternatives as shown in Section 6.1;
2) The costs (NPV) of each alternative were calculated using the Caltrans Life-Cycle Cost Analysis Procedures Manual (2007) and RealCost software (27, 28). Along with CA4PRS software, estimates were calculated for construction schedules, work zone user costs and agency cost for initial and future maintenance and rehabilitation as presented in the final case study (Appendix C). Costs were discounted to determine the NPV of agency and road-user costs for each alternative;

3) Applying the costs from above and the probabilities as determined through the interview processes, the total expected cost (discounted NPV) was determined for the two decisions, with and without HVS testing. Sensitivity analysis was conducted to take reconnaissance of the range of probabilities from the interviewees' perceptions. (Note that $\sum(P_1...P_5) = 1.0$ and similarly for $P_{1'}$ to $P_{5'}$ as shown in Figure 8);
4) The maximum expected payoff (i.e. cost savings in this case) is the greater total expected cost of the two decisions;
5) The benefit (cost saving) is the difference in the total expected cost of the two decisions and is determined by subtracting the total expected costs of the "with HVS decision" from the "without HVS decision". A positive value indicates a positive net benefit;
6) Scaling up the benefit is based on the projected number of lane miles where the innovation may be implemented. Projecting the likely number of lane miles required inputs from interviews, programmed roadway improvements and judgement. The total benefit was then calculated by scaling up the benefit to the correct expected lane miles suitable for these rehabilitation strategies;
7) Determining the development costs required identifying historical records along with judgement about the costs of operations, testing and analysis in developing the I-710 innovative mixes and designs, and
8) The BCR is determined by dividing the total scaled-up benefits by total development costs.

The base year for all cost comparisons is 2000, using Caltrans' standard 4% discount rate. For step 2 numerous assumptions were required. The initial construction costs were known, and various maintenance and rehabilitation strategies were planned following the initial construction of the I-710 to keep the facility in a serviceable condition for a 60-year analysis period. The costs of all maintenance and rehabilitation interventions, including road-user costs, were reported in the final results (Appendix C). The maintenance and rehabilitation interventions developed for the innovative designs were based on input from pavement engineers who had had experience with the I-710 project. For the standard mixes the analysis period and discount rate recommendations in the Caltrans Life-Cycle Cost Analysis Procedures Manual were followed (27). A sensitivity analysis on the discount rate was performed. Although the standard Caltrans-approved discount rate was 4%, the analysis was also repeated for 3% and 5%, although it was not reported in the final analysis (Appendix C). Analyses were also performed for the undiscounted case (0% discount rate).

The total expected costs (NPV) were calculated for three cost centres: 1) agency initial construction cost, 2) agency annual maintenance and rehabilitation costs (over an analysis period of 60 years), and 3) road-user cost. These costs were divided into the lane-mile length of the project to produce a comparable unit cost of US$ per lane mile of construction.

The benefits of using innovative designs (verified by HVS testing) were calculated by comparing the total expected costs of the innovative designs with those alternatives of standard practice (as shown in Figure 8). In the cases where the total expected costs of the innovative designs were lower than standard construction practice, a positive benefit was realised, and vice versa (if the total expected costs of the innovative designs were higher than standard construction practice, then there was no benefit using the innovative designs as these designs were more expensive than standard construction practice).

After potential unit costs savings (US$ saving per lane mile) had been calculated, the next step was scaling up. This was done through the determination of the degree of market penetration, i.e. the degree to which this technology was accepted and could be applied over the entire road network in California. According to a report by the UC Pavement Research Center (29), the condition of the total road network in California in 2000 was as follows (Table 3):

Table 3: Summary of the total road network condition in California in 2000 (Source: UC Pavement Research Center)

Area in California	Percentage in Poor or Mediocre Condition	Percentage in Fair Condition	Total Percentage: Not in a Good Condition	Average Cost per Car over Lifespan of Car (US$)
California	13%	63%	75%	857
San Diego	11%	71%	82%	1004
L.A. Area	13%	64%	78%	1325
S.F. Bay Area	14%	60%	74%	837
Sacramento	7%	55%	62%	877

The highway network maintained by Caltrans consists of 49 000 lane miles, of which 68%, or 33 320 lane miles, are flexible asphalt concrete pavements. Given the different climatic regions and traffic volumes in California it can be assumed that at least 25% of the flexible pavement network can benefit from the newly developed rehabilitation strategy. This suggests that approximately 8 330 lane miles of flexible pavement can potentially be rehabilitated with a design similar than what was developed for the I-710 project. One can appreciate that massive potential benefits would be realised if unit savings were to be scaled up, for example to 8 330 lane miles.

For example, for the 4% discount case (including road-user costs) the total mean unit savings are as follows: Benefit 1 = US$ 377 147 and Benefit 2 = US$ 278 270 per lane mile of rehabilitation, which results in total savings of US$ 655 417.00 for every lane mile. Multiplying that with 8 330 lane miles resulted in savings of over US$ 5.46 billion if the innovative designs were to be used during rehabilitation instead of standard practice.

Due to possible critique in the publication of such huge savings (and high BCRs), the author decided to scale up the potential benefit by only the number of lane miles which would definitely be rehabilitated using the innovative designs. Since early 2011, a minimum of 115 lane miles were selected for rehabilitation using the innovative mixes and designs, including subsequent rehabilitation phases on the I-710. Using this conservative degree of immediate market penetration (only 115 lane miles), the total mean cost savings were over US$ 43 million for the 4% discount rate case (including road-user costs).

6.3.1 Determination of development costs of the innovative designs

The total costs of developing the technology must be calculated and compared with the benefits. This is complex because the PPRC has devoted its research efforts to more than just the technologies developed for the I-710 rehabilitation. Certain reasonable assumptions are, therefore, required before a calculated guess can be made regarding the total development cost.

The PPRC has two HVS machines and for nine years (1998–2007), the one HVS has exclusively been used for rigid pavement studies and the other HVS for flexible pavement studies for Caltrans in line with the strategic objectives of the PPRC. The main focus areas of the UCPRC during that period (1998–2007) were:

1) Asphaltic Concrete (AC) (flexible) pavement studies;
2) PCC and Hydraulic Cement Concrete (HCC) (rigid) pavement studies;
3) Analytical developments related to both asphalt and concrete pavements;
4) Construction issues for both asphalt and concrete pavements;
5) Database considerations, including the development of the CAL/APT programme database and evaluation of Caltrans pavement management system (PMS) database for performance information;
6) Development and interpretation of in-situ measurements for stiffness properties of pavement components and water content of untreated base and subgrade materials using ground penetrating radar (GPR), and
7) Economic analysis demonstrating potential benefits that might have accrued with the implementation of some of the initial results obtained from the asphalt pavement studies. Both the flexible and rigid pavement studies included laboratory test programmes, HVS tests, pavement analyses and design considerations.

It was, therefore, not a trivial task to isolate the proportion of research that had been dedicated to the I-710 rehabilitation study as the I-710 rehabilitation strategy evolved through research done across the areas mentioned above. The road map developed in Figure 7 was used to guide the author to make realistic estimations on the true costs of developing the innovative designs constructed at the I-710.

In summary, the bulk of the implementable research used for the I-710 rehabilitation project took place during a 5-year period, 1997-2000. The total research budget of the UCPRC during that time amounted to US$ 5 million per year.

Costs of the HVS and associated laboratory testing and analyses are estimated at US$ 2 113 200, as follows:

- US$ 1.011 million for HVS tests (operations, equipment, measurements, analyses and reports);
- US$ 250 000 for the mechanistic-empirical design of two pavement rehabilitation designs, modelling;
- US$ 250 000 for the laboratory studies to characterise materials, and
- 20% of all preceding costs for managerial, reporting and administrative activities.

6.3.2 Final calculation of the BCR of implementing HVS-verified designs

The final step in determining the quantifiable benefits of the HVS project is the comparison of the total costs of the research in comparison with the benefits derived after implementation, as shown in Section 6.3. Tables 4 and 5 show results of the final calculations. All results are presented in the final case study (Appendix C) and only a summary is presented below.

Tables 4 and 5 contain the total NPV benefits from HVS research and BCR calculated at an undicounted rate (0%) and a 4% discount rate, including all cost centres: 1) agency (initial construction), 2) agency (yearly maintenance and rehabilitation over a 60-year analysis period), and 3) road-user costs.

The influence of the 4% discount rate is clear. Because of discounting, the calculated NPV (and BCR values) are lower in the 4% discounted case than in the undiscounted case, especially when road-user costs are included. BCR values are between 9.4 and 57.5 for the undiscounted case and between 2.8 and 17.1 for the 4% discounted case. The reasons for this stem from the influence of the reducing value of money over time as determined through economic impact analysis.

Inclusion of road-user costs in the calculations favours low-maintenance roads that have substantial road-user benefits over roads that require regular maintenance and closures (and a subsequent higher degree of road-user delay). One can also appreciate the big ranges in reported results due to significant differences in the perceptions of Caltrans officials in the use of asphalt as opposed to the use of concrete for LLPS.

Table 4: NPV benefits and BCR undiscounted due to the implementation of HVS-derived innovative pavement designs

Summary of benefits (in US$) for Caltrans Investment in HVS technology development and implementation (undiscounted)								
Benefit	Contribution Ratio	Range of Probabilities			Contribution Ratio	Range of Probabilities		
		Mean	Low	High		Mean	Low	High
Benefit 1: Innovative mixes enabled the improvement of vertical clearance under overcrossings while meeting the LLPRS criteria.	20%	$ 8 340 201	$ 7 162 691	$ 9 517 711	85%	$ 35 445 854	$ 30 441 435	$ 40 450 274
Benefit 2: Innovative mixes enabled meeting the LLPRS criteria where no vertical clearance constraints existed.		$ 15 886 302	$ 12 685 591	$ 19 087 014		$ 67 516 785	$ 53 913 760	$ 81 119 810
Total Benefit (2000 base year):		$ 24 226 503	$ 19 848 281	$ 28 604 726		$102 962 640	$84 355 195	$ 121 570 084
Total HVS Testing Cost (2000 base year)		$ 2 113 200	$ 2 113 200	$ 2 113 200		$ 2 113 200	$ 2 113 200	$ 2 113 200
Benefit:Cost Ratio		**11.5**	**9.4**	**13.5**		**48.7**	**39.9**	**57.5**

Table 5: NPV benefits and BCR at 4% discount rate due to the implementation of HVS-derived innovative pavement designs

Summary of benefits (in US $) for Caltrans Investment in HVS technology development and implementation (at 4% discount rate)								
Benefit	Contribution Ratio	Range of Probabilities			Contribution Ratio	Range of Probabilities		
		Mean	Low	High		Mean	Low	High
Benefit 1: Innovative mixes enabled the improvement of vertical clearance under overcrossings while meeting the LLPRS criteria.	20%	$ 3 157 477	$ 2 533 056	$ 3 781 899	85%	$ 13 419 278	$ 10 765 486	$ 16 073 070
Benefit 2: Innovative mixes enabled meeting the LLPRS criteria where no vertical clearance constraints existed.		$ 4 070 540	$ 3 423 168	$ 4 717 912		$ 17 299 796	$ 14 548 464	$ 20 051 128
Total Benefit (2000 base year):		$ 7 228 017	$ 5 956 224	$ 8 499 811		$ 30 719 074	$ 25 313 950	$ 36 124 197
Total HVS Testing Cost (2000 base year)		$ 2 113 200	$ 2 113 200	$ 2 113 200		$ 2 113 200	$ 2 113 200	$ 2 113 200
Benefit:Cost Ratio		**3.4**	**2.8**	**4.0**		**14.5**	**12.0**	**17.1**

7. CALIBRATION WITH OTHER REPORTED STUDIES

Although not reported in any of the four articles, the author did a retrospective comparison between what was revealed through the results reported in Tables 4 and 5 in comparison with BCR values reported by similar institutions. The investigated studies were all done on the evaluation of direct economic benefits.

There are many publications on quantifying the benefits of transportation improvement projects (capital as well as maintenance/rehabilitation). In contrast, similar to findings reported more than three decades ago by McFarland (30), information on quantifying benefits of transportation research projects (especially economic benefits) remains much scarcer.

Approaches proposed for measuring economic returns on research investments have been categorised into three groups: macroeconomic, microeconomic and direct outputs (31). Direct economic benefits are immediate, first-order impacts often expressed in terms of savings in agency costs (e.g. lower capital and maintenance costs) and user costs (e.g. less travel delay and lower vehicle operating costs).

7.1 The Strategic Highway Research Programme (SHRP)

Case study evaluations of direct economic benefits (in terms of agency- and user-cost savings) were calculated for the various products developed in the SHRP (32, 33, 34). The evaluation was a partially-retrospective assessment (similar to that by McFarland (30)) that focused on specific research products in case studies. Expected future benefits were calculated as an assumed percentage of expected costs projected over a long time period. The SHRP research assessment was conducted and completed by 1997, at the same time that the SHRP results were communicated and product implementation was getting underway. Due to the timing of the assessment, the evaluation required the use of the best available information as well as assumptions on which to base projections of expected benefits.

The SHRP evaluations relied on a deterministic approach and were based on benefits projected to occur over a time horizon of up to 20 years. In addition to qualitative benefits over this period, quantitative cost savings for agencies and users were calculated based on assumed values using the MicroBENCOST software model to calculate future projections (35). MicroBENCOST is one of many software models and tools to calculate user benefits. Similar to other software, it is more often used in the planning phase in which various alternative transportation improvement projects are evaluated. The approach to projecting future benefits contrasts with the focus of the author’s current PhD study, which is a retrospective evaluation of benefits accrued after research products have been implemented. It is noteworthy that the SHRP evaluations also relied heavily on case studies.

The TRB Special Report 260 (36) reviewed the results of the SHRP evaluation case studies, which it identified as providing estimates of potential benefits from SHRP based on various implementation scenarios (detailed in (33)). Estimated benefits (in US$) projected for transportation agencies and for users from implementing SHRP products are presented in the report as summarised in Table 6. The values represent "US dollars of benefit for each US dollar invested in research, development and implementation" (36). Economic benefits are projected to far exceed the costs for each SHRP product.

Table 6: Estimated US$ benefits from implementing SHRP products (based on TRB Special Report 260)

SHRP Products	BCR (US$ benefit for each US$ spent)
Asphalt products (Superpave)	26 to 43 for agencies 72 to 116 for users
Snow and ice control	15 to 29 for agencies 62 to 124 for users
Concrete (six selected products)	1 to 3 for agencies No estimate for users
Portland cement concrete pavements	3 to 11 for agencies 9 to 33 for users
Pavement maintenance	36 to 131 for agencies 47 to 173 for users
Work-zone safety	1 to 2 for agencies 6 to 12 for users

7.2 APT-focused NCHRP projects

APT activities and outputs have been the focus of several National Cooperative Highway Research Programme (NCHRP) projects. In 2004 NCHRP Synthesis 325 (37) reported results from a review of APT programmes around the world. This report included direct economic benefits in terms of benefit-cost ratio and net savings. Responses to a questionnaire from APT owners/operators found that monetary benefits, in terms of cost savings, exceeded US$ 2M for six of the seven agencies that responded. BCRs reported by respondents varied from 1 to greater than 20. No upper limit for savings and BCR was set in the questionnaire. Savings and BCRs were presented in the report as respondents provided them with no additional analysis. Unfortunately, few details of procedures and assumptions on which savings and BCRs were based were given in the NCHRP Synthesis 325 report. The report provided anecdotal highlights of economic assessments prepared for various APT programmes. This was in accordance with the project's goal.

The report presented results of assessments; however, there were no descriptions and discussions of the methods from which they resulted. The report identified over 40 APT programmes worldwide, described the diverse APT technologies in use and reviewed the state-of-the-practice. The study found that “few formal evaluations” of benefit-cost had been published and that “evaluation of APT benefit-cost is historically limited and had only rarely been rigorously quantified”. However, it concluded that “shrinking budgets and privatisation of facilities may result in more frequent, formal and quantitative assessments in the future” (38).

When comparing the case study results with what was published in the NCHRP Synthesis 325, it should be noted that the NCHRP investigated APT programme-wide benefits, whereas the study reported in this thesis investigated the quantifiable benefits stemming from project-specific HVS testing. It is realised that the results stemming from programme-wide investigations will be different from project-specific investigations; it is nevertheless important to gauge the results of this study with what has been reported on a worldwide scale.

NCHRP Synthesis 325 reported “overall estimated savings/benefits in monetary terms” from survey respondents (37). No maximum value for savings/benefits was set. Information about the discounting of costs and savings/benefits is not available. Reported results include:

- Savings/benefits ranging from US$ 500k to US$ 1M for one APT programme (ISETH, in Switzerland), and
- Savings/benefits greater than US$ 2M for eight programmes including WesTrack, HVS-Corps of Engineers (Vicksburg, MS), NCAT, MnROAD, FAA, CAPTIF, PPRC and ARRB.

BCR values were reported at three different levels by seven APT programmes. No maximum BCR value was defined in the questionnaire.

- BCR of 10 for three APT programmes, including ISETH, SA-HVS;
- BCR of 20 for one programme (Indiana APT), and
- BCR greater than 20 for three programmes including NCAT, FAA and CAPTIF.

Cost savings from this investigation are consistent with the highest level of savings (greater than US$ 2M) reported in the NCHRP Synthesis 325 (37). BCR values from the case study span the range of values reported in NCHRP Synthesis 325. Values for an assumed low contribution ratio are lower than the lower end (10:1 and below) reported in the NCHRP Synthesis 325. For an assumed high contribution ratio, BCRs from this case study are at the high end (higher than 20:1) of the range reported in the NCHRP Synthesis 325.

At the Second International Conference on APT in 2004, King and Rasoulian (39) presented results from BCAs of the Louisiana Accelerated Loading Facility (ALF). BCAs were performed on research projects of the Pavement Research Facility (PRF) sponsored by the

Louisiana Department of Transportation and Development (LADOTD). The BCAs evaluated ALF-validated pavement design sections that were recommended for implementation in the LADOTD's construction programme. The new pavement designs were cement-treated bases (for low-volume roads) and stone interlayer (for high-volume roads).

Based on the extended service life expected (from ALF test results), benefits were calculated for a design service life ranging from 15 to 40 years, assumed traditional maintenance activities and evaluated for an analysis period of 30 to 40 years. The discount rate used in the analysis was not given. Cost savings were calculated based on the number of lane miles for each of the new pavement designs for the time period 2001-2003. Life cycle cost analysis used LADOTD's construction cost data from 2003 as a base year.

Total benefits amounted to approximately US$ 8.17M. Costs that led to the validated designs included operations and research activities as well as test section construction and amounted to about US$ 1.55M. A BCR of 5.3 was reported based on the three-year period evaluated (38).

7.3 Comparisons with previous studies at 4% discount rate

Comparing BCR values at a discount rate of 4% that was used in the I-710 case study and also reported in the Australian and South African BCA studies revealed the following:

- The Australian ALF programme reported a BCR of 4.9 for the overall APT programme and BCRs of between 1.4 and 11.6 for individual ALF tests (8, 9);
- The South African HVS study involved BCR calculations on provincial and national levels managed by SANRAL. On provincial level the use of the G1 base course technology was measured by Gautrans (now called the Gauteng Provincial Department of Roads and Transport). BCR values of between 2.2 to 5.6 (low contribution ratio) and 3.6 to 10.2 (high contribution ratio) were reported (7), and
- The California I-710 HVS tests calculated BCR values from 2.8 to 4.0 (low contribution ratio) and 12.0 to 17.1 (high contribution ratio), including road-user costs as detailed in this thesis in the final results of the case study (Appendix C).

8. CONCLUSIONS AND RECOMMENDATIONS

Before commenting on the results and conclusions drawn from the analytical sections of this thesis, emphasis is required on what was not analysed, investigated and reported in this study. It is realised that the quantification of benefits through the deterministic analyses done in this thesis is very narrative and does not capture the true value of implemented research. The content of the fourth published article, the final synthesis on the evaluation of benefits (Appendix D) goes into great detail to highlight the deficiencies of only studying the direct economic benefits.

Two main categories of benefits are identified:

- Direct benefits, and
- Indirect benefits

In the BCA reported in this thesis only direct quantifiable benefits are investigated and presented. These are resource savings and a benefit for which a beneficiary (road agency) is willing to pay for. This is highlighted in the flow diagram presented in Figure 9.

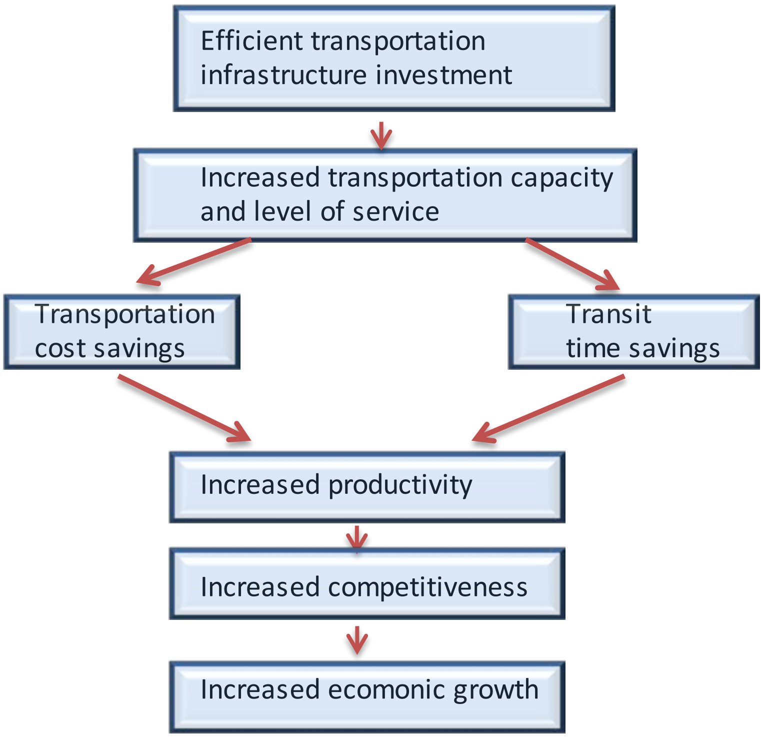


Figure 9: Flow diagram illustrating the direct quantifiable benefits of transportation research

Apart from quantifiable benefits, there are also non-quantifiable benefits (also called process benefits). The fact that Caltrans has now gained the knowledge to reconstruct heavy-duty pavements more cost-effectively is an example of a process benefit. In broader terms, process benefits are concerned with the development of better understanding a challenge and are best evaluated through indicators and trend analysis. This realisation prompted the author to investigate this in greater detail as presented in the final synthesis on the evaluation of benefits (Appendix D).

Lastly there are indirect (or downstream) benefits. These benefits are not just focused on the funding agency, but benefit society at large and include the following:

- Human capital development;
- High-tech spin-offs (such as advances in pavement performance monitoring instrumentation);
- International alliances, user groups and the sharing of knowledge on an international level;
- Improvement in science and technology excellence, and
- Creation of employment and career growth opportunities.

To truly measure the impact of implementable APT research, all these benefits should be included in the analysis. As this thesis does not focus on these important domains of benefit assessment, it is not included here; however, the importance of these types of benefits is recognised. It is perhaps best illustrated in Figure 10 which shows links between implementable research and political objectives in broad terms.

One way to clarify the links between political objectives and engineering implementation outcomes (such as APT research implementation) is to consider how technology development outcomes feed into the broader society. When one looks at the South African society as a tree, one can consider the political objectives such as wealth creation and quality of life as the leaves of the tree. The main pillar, or trunk, that sustains the tree is economic growth. There are three main benefit streams that result from research and technology work: technical progress, the development of SET human capital and improved business performance. The infrastructure, or roots, that anchor and sustain the tree are the cluster strategies, the country's infrastructure and the so-called key enablers.

As shown, the APT research contributes by benefiting the infrastructure (roads), and by stimulating innovation and developing human resources.

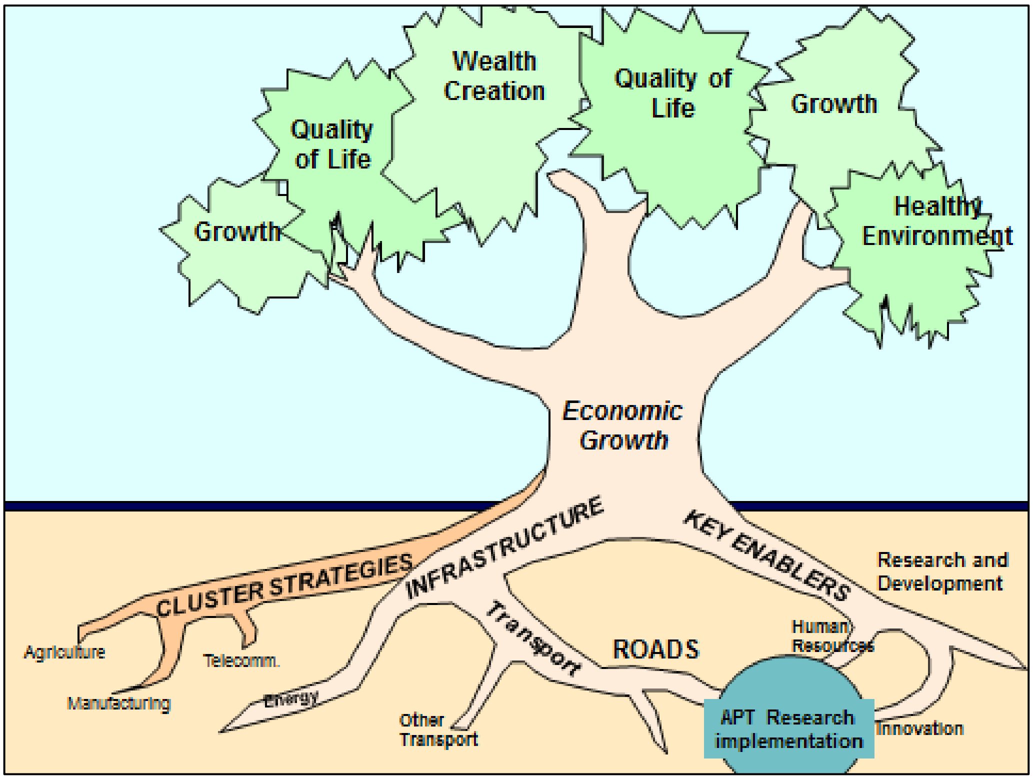


Figure 10: Links between implementable APT research and political objectives (adopted from Jooste and Sampson)

Regarding the use of BCA, critique was identified against the use of BCA and includes the following:

- It was necessary to predict consequences of alternatives and their rehabilitation needs over long time periods. In the case of this thesis, it was over 30 years. The degree of uncertainty increases when predictions stretching so far into the future are required;
- The morality of reducing everything to a monetary value: Not everything can be measured in monetary value including gaining knowledge;
- BCA is usually conducted by economists who tend to be more aware of monetary impacts than the true benefits and value for society at large;
- The analysis method is not concerned about equity. How benefits and costs are distributed among different income groups, regions, generations, etc. are not taken into account, and
- Similar than the critique listed in the 1st bullet: for the method to work it is necessary to predict values of all inputs of the BCA over extended time periods. For example, it is difficult, if not impossible, to estimate road-user costs in 30 years' time.

As highlighted in this thesis, direct benefit determination is not trivial. Some of the key challenges in direct benefit quantification include:

1) Conceptual and time-related separation between project impacts and realised benefits. As shown in Figure 11 of the initial literature survey (Appendix A) there is a substantial time difference between active research and the successful implementation thereof.

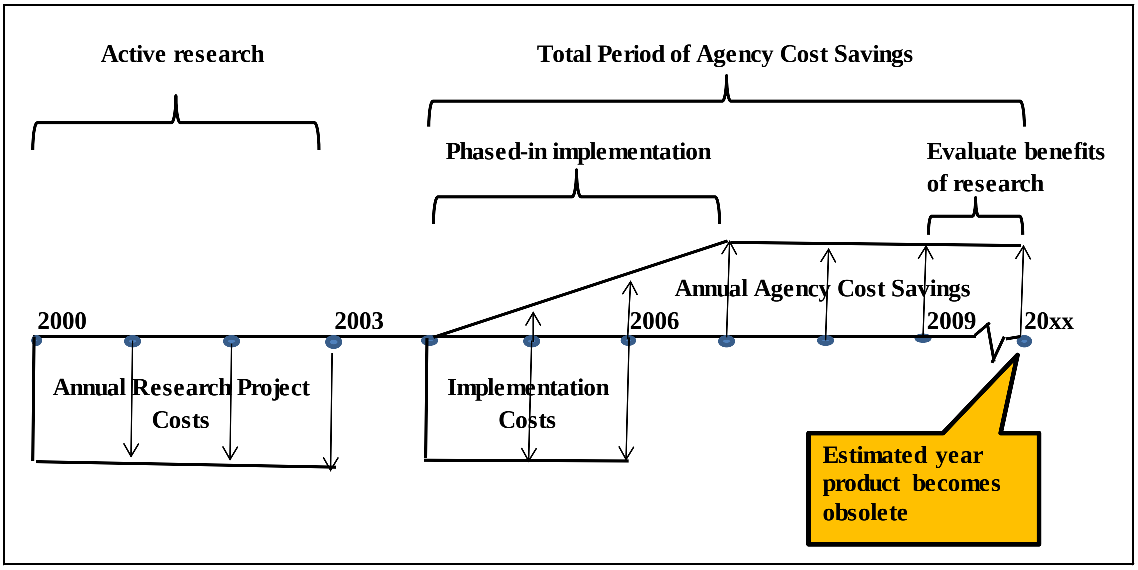


Figure 11: Timeline and cash flow of publicly funded research (Adapted from Kruger)

2) Several projects and processes contribute to realised benefits. It is rare that one single process can be credited for being 100% responsible for the success of an implementable finding. The contribution of impacts linking outcomes to specific research and separating them from preceding research projects should be recognised.
3) Setting boundaries and identifying the starting and ending points are important as no research can continually be credited for contributing research in retrospective studies. The challenge lies in estimating the useful service life of a research product before becoming obsolete or being superseded by subsequent research projects or other changes in technology, policies, practices and specifications.
4) Not all research avenues lead to realised benefits. As this thesis tests a methodology on a specific case study with a high certainty of direct benefits, it is important to note that on programme level, this may not always be the case. In certain cases research outcomes can result in “what not to do/implement/etc.”. In these cases cost avoidance can also be considered a benefit (no implementation due to proper research).
5) Subjective estimates are needed to quantify benefits. This is perhaps the most challenging part as human perception of the quality of the research output must be accounted for. In-depth testing of the success of APT findings was necessary in this thesis to gain confidence in the subjective assumptions and the importance of the

contribution of the HVS in the development and verification of implemented alternative pavement design.

The wide ranges of BCR values reported in this thesis reflect the wide range of perceptions of independent engineers/academia and Caltrans officials not directly related to the PPRC or the HVS research work. Although it can be criticised that BCR ranges of between 10:1 and over 55:1 are unrealistic (as reported in the final results in Appendix C), the importance of sensitivity analysis is highlighted in this investigation. This is a better presentation of the true perceptions than presenting an average value that does not cater for the wide range of public perceptions on the true value of the implemented HVS-research findings.

Given the above, it is realised that the quantification of benefits is not a simple analytical exercise. One main conclusion is that it is not really possible to state benefits as if they were a fact. What is possible, however, is to evaluate benefits according to a specific "best practice" framework, and then be as transparent as possible regarding the manner in which one documents findings.

In this thesis the author formalised this process into a framework which was tested on a case study of a sizable project on one of the busiest corridors in California (the I-710). Realistic and defendable results were derived and are within industry acceptable norms as published by other similar research agencies.

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10. APPENDIX A: Published Journal Article 1

“Evaluating the Benefits of Accelerated Pavement Testing Techniques and Case Studies”

For simplicity and clarity, this article is referred to as “*The initial literature survey*” throughout the body of the thesis.

Evaluating the Benefits of Accelerated Pavement Testing

Techniques and Case Studies

W. A. Nokes, L. du Plessis, M. Mahdavi, and N. Burmas

A pilot study was conducted to determine the direct economic benefits of accelerated pavement testing with heavy vehicle simulators in California. The study discusses the identification and comparison of methods used in various countries to determine the benefits from the research. The study highlights approaches in use since the 1990s, compares alternative methods in a global context, and describes the attributes of an economic evaluation methodology applied to benefits from accelerated pavement testing that was initially developed and used in Australia and subsequently enhanced in South Africa. Promising developments include a toolbox created recently in the United States, consisting of more than 30 measures, in which European and Asian transportation research agencies have expressed substantial interest. The pilot study identified a wide variety of methods at state, national, and international levels and found an emphasis on qualitative benefits. Case studies found that the Australian and South African methodology provided advantages such as quantitative, direct economic benefits (a benefit–cost ratio of around 10:1); an analysis of alternative outcomes; accounting for uncertainty; and validation interviews with implementers of research findings. Challenges identified in using this methodology included intensive cost, labor, and time requirements; sensitivity to assumptions; and subjective input.

What are the qualitative and quantitative benefits of accelerated pavement testing (APT)? How do the direct economic benefits of APT compare with the typically high costs of conducting APT? What are the possible future directions and next steps toward improving and applying techniques for evaluating the benefits of APT? This paper provides APT researchers, owners, and operators with information to help answer questions and to stimulate further dialogue and advances in determining the benefits of APT.

The main objective of this paper is to provide APT researchers with descriptions of techniques and measures and to discuss recent developments and case studies. Most of the techniques and measures were identified during a pilot study done to evaluate the direct economic benefits in a retrospective evaluation of APT performed in California (*1*). This paper also describes the pilot study, which focuses on a cost–benefit analysis methodology first reported in Australia and later enhanced and applied in South Africa for retrospective assessment of APT (*2–4*).

CHALLENGES IN EVALUATION OF BENEFITS

A basic challenge in evaluating research benefits is that many view it as unnecessary. In answering the question, "Why invest in road research?" Lay commented that an "impediment in valuing research projects is the difficulty of convincing the researchers to take the valuation process seriously" and that it is "as if the researchers' livelihoods did not depend on the value of their research output" (*5*).

The importance of evaluating the benefits of research is growing for many reasons. Recent studies in the United States suggest that clear justifications of costs and benefits may increase public confidence in decision makers (*6*). The current economic downturn has led to increased calls for accountability and greater transparency, which increase the scrutiny of processes and the pressure to use state-of-the-practice techniques. Regarding APT research, the COST 347 study suggested that transparency and the use of evaluation methods (such as cost–benefit analysis) may help increase funding by enhancing the marketing of research activities and results (*7*). Wider global collaboration in transportation research is likely to require the establishment of evaluation techniques that are acceptable to all participating agencies (*8*).

Another challenge to assessing the benefits of research is the scale on which such evaluations should be performed: test specific, project specific, or program level. Each level presents challenges. A one-size-fits-all approach does not exist. However, developments in recent years, such as reported by Krugler et al., provide tools that may be customized for the level of evaluation needed (*9*).

Unfamiliarity with this topic is a major challenge. Techniques and measures for evaluating research benefits have been reported extensively in the literature since the 1950s. A decade ago, analysts observed that evaluations had less influence in the literature than deserved in part because reports on the best work were difficult to obtain (*10*). This observation stands despite online publications and increasing demands for accountability about public expenditures.

Complexity is another challenge. Like research itself, the evaluation of research benefits is complex. The evaluation process is context-sensitive, reflecting the unique attributes and constraints of the research products as well as those of evaluators, organizations, and users—who often are decision makers. Varying contexts explain in part why no universal technique has been recommended.

The time domain also presents challenges. Figure 1 is an example of activities as well as cash flow (costs and benefits) for a research

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Transportation Research Record: Journal of the Transportation Research Board, No. 2225, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 147–154.
DOI: 10.3141/2225-16

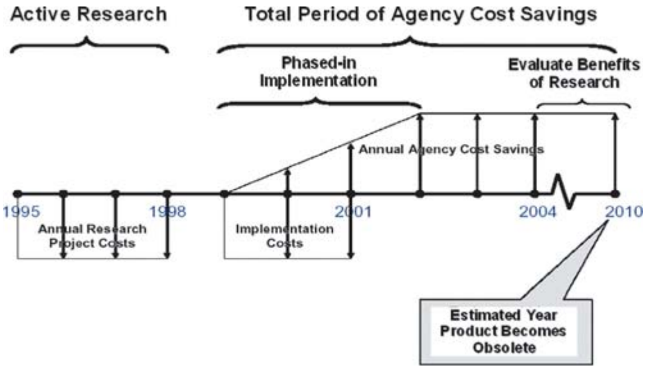

FIGURE 1 Timeline and cash flow of publicly funded research [adapted from Krugler et al. (*9*)].

project. Omitted from the figure are the processes and costs of identifying a problem, defining and scoping a project, incorporating it into an overall research program, obtaining funding, and securing resources (in-house or contract). There are two aspects of this preresearch phase to keep in mind. First is the time required, which could add one or more years (on the left in Figure 1). Second is that the responsibility for preresearch activity typically is led by staff dedicated to managerial activities. They often do not perform research or implement the results.

After the project starts, the focus shifts to active research and then later to implementation. Researchers take responsibility for the research, and implementers (typically in operational functions such as design and construction) take the lead on implementation. Successful research outputs and phased-in implementation begin to produce benefits, which appear as agency cost savings above the time line in Figure 1. Safety projects lead to immediate benefits in lives saved and fewer accidents, but this paper focuses on monetary benefits of research.

It is clear that (*a*) the life cycle is long, (*b*) monetary benefits accumulate very late in the process, and (*c*) lead responsibilities change in successive project phases. The eventual accumulation of benefits—which typically will take longer than any preceding phase—requires actions by implementers often not associated with the research. Figure 1 shows fairly constant agency cost savings that would most likely diminish gradually over a time horizon such as 5 to 10 years. For the best results, retrospective assessment of the benefits of research must wait until most or all cost savings have accumulated. But as the research product heads toward obsolescence, attention shifts to new problems and new projects and the research cycle continues.

Analysts who evaluate research benefits must decide what is significant and should be measured, how and when to measure, and how to interpret the results. Many impacts are difficult to quantify. Whether quantitative or qualitative methods are used, recurring challenges to the evaluation of benefits have been observed (*11*):

- Attribution of impacts, linking outcomes to specific research and separating them from preceding research projects that influenced it (as well as other research influenced by it);
- Setting of boundaries, identifying the starting and ending points of contributing research in retrospective studies, and identifying the time frame and end point for analysis in prospective studies;
- Exhibition of bias in selecting research projects for case studies, for example, low- versus high-payback projects;
- Nonuniform definition of terms and concepts, for example, basic versus applied research; and
- Unclear descriptions of techniques in data collection and analysis.

SYNTHESIS OF TECHNIQUES

Advantages and Disadvantages

Techniques for evaluating benefits generally are categorized as quantitative or qualitative. Quantitative measures have numerical value, such as savings in dollars and lives, that are viewed as objective. Qualitative measures are descriptive indicators without numerical value and hierarchy but instead reflect subjective attributes such as satisfaction and quality.

Each technique has advantages and disadvantages that present various trade-offs. For example, a clear linkage of research outputs to benefits can be identified in a case study but difficult to determine with econometrics, whereas a broader assessment by econometric modeling can be difficult to do in a case study (*12*). Choosing a technique is context sensitive, reflecting specific needs such as determining whether a line of research should be terminated, whether results are within accepted quality standards, or whether there are direct economic benefits. Techniques to evaluate the indirect and larger-scale economic impacts of a project on the economy, such as jobs and construction, are described in the literature but not in this paper.

The advantages and disadvantages of various techniques, based on a 1999 report by the National Academies of Science Committee on Science, Engineering, and Public Policy (COSEPUP), are summarized in Table 1 (*13*). COSEPUP conducted studies and workshops with federal agencies, the research community, industry, states, and agencies in other nations. The goal was to identify and analyze the most-effective ways to assess research results. Like other, more recent studies, the COSEPUP findings suggest that a multifaceted approach, combining various techniques and measures in a complementary manner, should enable the analysis of outcomes and impacts from many types of research.

Qualitative and Quantitative Approaches

Two years after the COSEPUP report, NCHRP Synthesis 300 reported a review of approaches for measuring performance and effectiveness of transportation research and development (*14*). Results from a survey of state departments of transportation (DOTs) in the United States showed that 25% used performance measures after implementing research outputs. All measures relied on qualitative information, but DOT respondents described them as quantitative. The literature and survey showed substantive differences between public, private, and academic sectors in approaches to and concerns about determining the benefits of research. The study found that quantitative assessment was a desirable priority but faced many challenges, including the need for better quality cost data, more clearly identified benefits, and clearer links of research outputs to benefits. For qualitative assessment, the study concluded that peer review was the standard. Most DOTs were not satisfied with their cost–benefit techniques and said many issues would need to be resolved to produce useful and reliable information in a long-term assessment. Quantifying benefits in the private sector also was problematic but was aided by better cost data and a more customer-driven environment. Less quantifica-

TABLE 1 Advantages and Disadvantages of Various Techniques

Technique	Advantage	Disadvantage
Peer review	Well-understood method and practices Provides evaluation of quality of research and sometimes other factors Already an existing part of most federal agency programs in evaluating the quality of research projects	Focuses mainly on research quality Other elements are secondary Evaluation usually of research projects, not programs Great variance across agencies Concerns regarding bias Results depend on involvement of high-quality people in process
Case study (descriptive and quantitative)	Provides understanding effects of institutional, organizational, and technical factors that influence the research process so that the process can be improved Illustrates all types of benefits of research process	Individual cases are not comparable across programs Focus on cases that might involve many programs or fields, making it difficult to assess federal-program benefit
Economic rate of return	Quantitative Shows economic benefits of research	Measures only financial benefits, not social benefits (such as health-quality improvements) Time separating research from economic benefits is often long Not useful across all programs and fields
Bibliometrics	Quantitative Useful on aggregate basis to evaluate quality for some programs and fields	At best, measures only quantity Not useful across all programs and fields Comparisons across fields or countries is difficult Can be artificially influenced
Retrospective analysis	Useful for identifying linkages between federal programs and innovations over long intervals of research investment	Not useful as a short-term evaluation tool because of long interval between research and practical outcomes
Benchmarking	Provides a tool for comparison across programs and countries	Focused on fields, not federal research programs

NOTE: Adapted from NAS (*13*).

tion of benefits appeared in the academic sector, where neither faculty nor administrators routinely discussed cost–benefits of academic research.

The report noted that many DOTs had efforts under way to improve and resolve gaps in the performance measurement of research. A decade after that report was published, many gaps persist, such as “no standardized, commonly accepted methods for establishing either the costs or, more dramatically, the benefits from research projects” (*14*). DOTs cited concerns about establishing direct economic benefits and needing a measure for payoff from implementation. The study found that (then) existing measures of payoff varied substantially and were neither rigorous nor robust. No existing technique was clearly superior. Benefits compatible with cost–benefit analysis were preferred. Guidance was needed on the use of cost–benefit analysis.

A 2002 review of the state of the art in measuring outcomes of nontransportation research in the United States describes peer review as the standard against which other methods are judged for both retrospective and prospective evaluation (*15*). The review recommends developing methods that better capture the noneconomic benefits of research. In discussing the usefulness of conducting surveys, it cautions against potential bias from surveying individuals who benefit from research. Furthermore, the review recommends more emphasis on long-term qualitative benefits but also suggests a promising quantitative approach, which is to determine whether a research program has generated direct economic value (such as agency cost savings) that exceeds the cost of conducting the research. Also mentioned is the practice of evaluating research nuggets, which are high-payback projects that produce direct economic benefits far exceeding the cost of the research program.

The 2002 review and NCHRP Synthesis 300 illustrate similarities and differences in the needs and techniques within and outside transportation research. Many reviews of evaluation techniques have been published since the late 1990s. Techniques in selected reviews are summarized in Table 2, which includes publications from the United States and Europe for research within and outside transportation. The European publications are both by RAND Europe, a not-for-profit research institute that is part of the RAND Corporation. Approaches outlined in Table 2 under the heading “Europe 2009” consist largely of those described in the COSEPUP report. Both European studies include health and medical research assessment methods, which can be viewed as more advanced than most other fields (including transportation research).

Techniques in Tables 1 and 2 suggest that complementing qualitative with quantitative information may produce more complete assessments. Some analysts have observed that relying on one indicator could mislead analysts and decision makers (*10*). In addition to use of more than one technique and measure, some investigators have recommended using many sources of information and several separate investigators in a technique referred to as triangulation (*11*).

The summary in Table 2 leads to several observations, including the following:

- Qualitative and quantitative measures are well represented.
- Many techniques are cited in at least two publications.
- The most common methods are cost–benefit or savings analysis, peer review, and surveys.
- These common methods are used in transportation as well as nontransportation research.

Transportation Research

Federal Research In assessing federal investments in infrastructure research from 2006 through 2009, TRB Special Report 295 observed that evaluations of FHWA research found substantial savings and

TABLE 2 Evaluation Techniques

	Transportation		Nontransportation	
Method	United States, 2003 (*16*)	United States, 2008 (*9*)	Europe, 2009 (*11*)	Europe, 2006 (*12*)
Qualitative				
Peer and expert review	✔		✔	✔
Survey	✔	✔		✔
Case study—descriptive			✔	
Training and education		✔		
Tracing and logic modeling			✔	✔
Benchmarking				✔
Sociometric analysis			✔	
Quantitative				
Cost–benefit, savings analysis	✔	✔	✔	✔
Bibliometrics	✔			✔
Safety (fewer crashes and fatalities)		✔		
Econometrics			✔	
Outputs (products and reports)		✔		
Performance	✔	✔		

extension of service life far higher than the research cost (*17*). This observation is based largely on a 2003 FHWA report (summarized in Table 2) that presented retrospective evaluations of benefits from FHWA-sponsored research (*16*). Contractor analysts conducted independent evaluations. The report presents results and describes various techniques used in evaluations of projects in three research areas:

- Highway safety information system: bibliometrics, survey, and expert peer review;
- QuickZone software: survey; and
- Infrastructure (pavements and structures): quantitative and qualitative assessment.

The report observed that estimating cost savings was "the most demanding part of the assessment," but projects for which data were obtained showed very high agency, road user, and safety cost savings. These reports estimated that costs savings at a national level were worth more than 10 times the annual research funding (*16, 17*).

NCHRP Project 20-63 Recent developments have introduced frameworks with many performance measures and techniques. Frameworks have been developed that are referred to as a "toolkit" or a "toolbox." Toolkits have been developed in the United States and are in different stages of implementation for transportation research and nontransportation federally funded research (*18, 19*). A recent addition to this approach is the NCHRP Project 20-63 toolbox (*9*), which is outlined in Table 2. The project's main objectives were to define performance measures for transportation research and to assemble a practical toolbox of techniques (with examples) for use by DOTs. Following a literature review, surveys were conducted of DOT, federal, and private-sector managers and researchers. Survey respondents rated their organizations' experience with each measure and perceived value of each measure in their organization. The study identified 30 performance measures. Return on investment [or benefit–cost ratio (BCR)] tied with agency cost savings for third, just below lives saved and reduction in crashes.

The toolbox contains performance measures programmed in software for DOTs, which can import other measures to customize the toolbox for their specific needs. Software automatically calculates the present value of cost savings based on user inputs. The measures are mostly quantitative and are categorized under five headings:

- Outcomes: agency cost savings, lives saved, fewer crashes;
- Outputs: products, research reports published, graduate students;
- Resource allocation: funding and contractors issues, quality of life, safety projects;
- Efficiency: BCR, percentages of projects on time, within budget, implemented; and
- Stakeholders: customer satisfaction and input.

The NCHRP Project 20-63 report does not analyze or provide guidance about cost–benefit analysis but provides a catalogue of measures. Several DOTs are evaluating the toolbox, which also has attracted international interest.

Scanning Tour of Europe and Asia

Research administrators in the United States conducted a scanning tour of Europe and Asia in 2008 to review transportation research programs. Sponsored by FHWA, NCHRP, and AASHTO, the scan team looked for policy and process improvements. They met with senior research program administrators in France, the Netherlands, Sweden, Japan, and South Korea and at the European Commission. Key findings include the following (*20*):

- Unlike in the United States, research programs in many other countries do not have to continually justify expenditures and foster acceptance that the value of research promotes strong programs.
- Although research programs in all countries have a process for evaluating results, the techniques vary in complexity, effectiveness, and success.

- Research programs face continuing challenges in quantifying benefits, but no country has a technique deemed satisfactory.

Several countries considered the United States a leader in quantifying research benefits. Many countries expressed interest in the United States' sharing measurement tools, including the NCHRP Project 20-63 toolbox.

Direct Economic Benefits

There are many publications on quantifying the benefits of transportation improvement projects (capital and maintenance or rehabilitation). However, echoing the findings from a study in the late 1980s on methods to evaluate the benefits of research, information on quantifying benefits (especially economic benefits) of transportation research projects is much rarer (*21*).

Techniques proposed for measuring economic returns from research investments have been categorized into three groups: macroeconomic, microeconomic, and direct outputs. Direct economic benefits, on which this paper focuses, are the immediate, first-order impacts typically expressed in agency and user cost savings. A synthesis by the Florida DOT and an evaluation by SHRP illustrate various approaches.

Florida DOT Synthesis

A 2002 study sponsored by the Florida DOT examined techniques to assess direct economic benefits of transportation research (*22*). The overall goal was to recommend a method for retrospective and prospective evaluation of the value of research including economic return. Investigators reviewed past projects sponsored by the Florida DOT, searched the literature (including nontransportation sources) for previous efforts to quantify research benefits, and evaluated which tools appear best suited to transportation research. Their literature review identified techniques from studies within transportation (DOTs and private sector), as well as outside transportation, including medical, chemical, agricultural, and telecommunications. In transportation research, dominant approaches were cost–benefit analysis, net present value, and return on investment. Techniques and measures used outside of transportation varied widely and included utility analysis and financial indicators such as return on investment and payback period. The Florida DOT study examined an alternative financial approach, called Real Option, which views research investment opportunities as financial options and applies investment theory to evaluate potential returns. The Florida DOT synthesis concluded that none of the (then) available methods were suitable for all categories of research but recommended a matrix of techniques for calculating benefits. The matrix recommends cost–benefit analysis that uses BCR, net present value, return on investment, and Real Option.

SHRP Evaluation

In the late 1990s direct economic impacts (in agency and user cost savings) were assessed for SHRP (*23, 24*). The evaluation was a prospective assessment that used case studies to evaluate future benefits, which were calculated as an assumed percentage of expected costs projected over a long period. The assessment was completed by 1997 as SHRP results were being communicated and product implementation was getting under way. The timing of the assessment required relying on available information plus many assumptions on which to base projected benefits. The SHRP evaluation used a deterministic approach and projections over a time horizon of up to 20 years. In addition to identification of future qualitative benefits, projected agency and user cost savings on the basis of assumed values were calculated with MicroBENCOST. In contrast to this application, MicroBENCOST is more often used to evaluate various alternatives in the planning phase of transportation improvement projects. This approach of projecting future benefits contrasts with retrospective evaluation, where benefits have accrued long after research products are implemented.

TECHNIQUES AND CASE STUDIES OF APT RESEARCH BENEFITS

NCHRP Syntheses

In 2004, NCHRP Synthesis 325 reported results from a review of APT programs worldwide. Included in the report were direct economic benefits in net savings and BCR (*25*). Responses from APT program operators to a survey questionnaire indicated that cost savings exceeded US$2 million for six of the seven agencies that responded (no upper limit was defined in the questionnaire). BCRs given by respondents varied from 1 to higher than 20 (no upper limit). Savings and BCRs were reported as provided by respondents and compared without additional analysis. Few details of techniques and assumptions were given. New Zealand's CAPTIF program was outlined as predicting various outcomes, assigning probabilities and savings for each outcome to calculate an overall expected value, and then dividing by the APT project cost to derive a BCR. Australia's APT program included cycle cost analysis, client discussions about implementation of APT outcomes, and estimation of savings from specific projects. The discounting of costs and benefits is not discussed in the report.

The Synthesis 325 report does not give details, guidance, or recommendations about techniques and inputs to calculate benefits but instead provides anecdotal examples of economic assessments from various APT programs in Europe, South Africa, and the United States. In accord with the project's goal, the report presents overviews of results from assessments but not detailed discussions of techniques. The anecdotal highlights were meant to supplement the limited assessments found in 1996 in NCHRP Synthesis 235, which reviewed APT state of the practice and described diverse technologies in use at more than 40 APT programs worldwide (*25*).

APT International Conference

The growing global interest in, and awareness of, efforts to quantify the economic benefits of APT research was a major topic at the 2008 international APT conference in Madrid, Spain. An introductory workshop described the value of pavement testing and analysis methods in benefits versus costs (*26*). Previous characterizations emphasized the quantity of data and its reliability (instead of benefits) versus the amount of time used to produce results (instead of cost). Conference discussions explicitly associated technical activities with their relative costs and benefits, which are suitable for cost–benefit analysis. Emphasis on assessing the economic value of APT research extended to technical sessions. To better inform participants, foster interest, and encourage dialog, one workshop was dedicated solely to discussing the basics of cost–benefit analysis and its use in case studies (*27*). The continuing need for high BCRs of APT research in Europe was emphasized in a keynote paper (*28*). A technical session was devoted to “Benefits and Economic Evaluation of APT Programs,” where papers were presented on cost–benefit assessments done in recent years in South Africa and the United States that have built on previous work in Australia.

Case Studies Evaluating Economic Benefits of APT

Australia

A cost–benefit analysis technique was developed by Australia’s ARRB Group in the early 1990s and applied to retrospective evaluation of research results from its Accelerated Load Facility (ALF) program (*2*). Their goal was to provide a credible evaluation of dollar-value benefits and costs of the first seven ALF trials. This required comparison of road agency costs in two scenarios: agency costs that occurred as a result of outputs from ALF trials and agency costs that would have been expected in the absence of ALF trials.

Comparison of costs would be straightforward except for uncertainty about the likelihood of events (e.g., selecting alternative designs and materials) in the ALF trial versus no-ALF-trial scenarios. To address this, the ARRB technique used the concept of expected value, which is a tool for decision making under uncertainty. Uncertainties were partially accounted for by setting probabilities for each alternative under consideration. These subjectively assigned probabilities were then multiplied by the cost of each alternative to yield an expected cost. The ARRB case studies focused on agency costs for specific outcomes of each ALF trial.

The decision-making process was represented by decision tree diagrams. The decision tree for the Benalla ALF trial (shown in Figure 2) illustrates the technique. Positive results from the ALF trial led to the construction of a flexible granular pavement with double seal, indicated in the bottom branch. In the absence of the ALF trial there were four design alternatives (including flexible granular and double seal), as shown in the top branch in Figure 2. Probability values for alternatives were derived from discussions with individuals who worked at the time in the pavements area of the Victoria state road authority. For each design alternative the individuals estimated the probability that the agency would have chosen to construct that alternative. The probabilities sum to 1.00 in each of the two separate branches. Individuals assigned probabilities that were collectively consistent for each alternative. A sensitivity analysis examined effects from various probabilities and discount rates in the analysis. Life-cycle agency costs for each alternative reflected those at the time of the ALF trial. The expected cost of each alternative was calculated as shown on the far right in Figure 2.

The total expected cost of the no-ALF-trial scenario is the sum of the expected costs of the four alternatives. The total expected cost of the ALF trial scenario equals the cost of the tested and constructed design (C). Benefits in agency cost savings from the Benalla trial were calculated by subtracting these two total expected cost values. The resulting savings were economic benefits attributed to the ALF trial. Dividing benefits by costs of the ALF trial produced a range of BCR values, which provided evidence of a healthy return on investments in the ALF program (*2*).

South Africa

The Australian case studies contributed significantly to the body of knowledge about benefits assessment of APT. The ARRB technique was later applied in South Africa to assess direct economic benefits from the heavy vehicle simulator (HVS) APT program (*3, 4*). In 2003, the South African province of Gauteng faced increasing pressures on their road budget and sought a way to assess the benefits from its HVS tests. Gauteng commissioned an evaluation of their HVS research program. In searching for techniques, investigators reviewed the ARRB’s ALF program evaluation and concluded that it provided a well-documented record, incorporated best practices for assessing research benefits, and could be used to establish a framework for evaluating future HVS tests. Despite differences between ALF and HVS technology and approaches, South African investigators expected that the ARRB’s technique might help meet their short- and long-term needs for evaluating benefits of the HVS research program.

Similar to the ARRB’s retrospective analysis, case studies were performed to assess benefits for Gauteng’s agency costs. One of the studies evaluated benefits from the use of a high-quality crushed stone base (called G1) that was implemented and in use for many years after research that included HVS testing (*4*). Like the ARRB’s work, the G1 case study relied on input from pavement practitioners to provide probabilities. Probabilities recommended for each

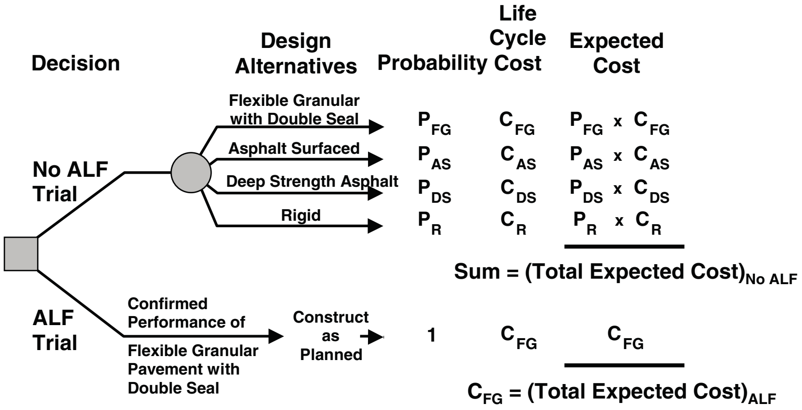

FIGURE 2 Decision tree for Benalla ALF trial [adapted from Rose and Bennett (*2*)].

alternative were collectively consistent. Benefits in agency cost savings were calculated in this case by subtracting the total expected cost of the HVS test scenario from the no-HVS-test total expected cost. Sensitivity analyses were performed to examine the influence of a discount rate on the benefits.

An enhancement that builds on the ARRB approach stemmed from questions in South Africa about the amount of benefits actually attributable to the HVS tests. Gauteng's study acknowledged that any advancement has several contributing sources and concluded that benefits from the use of G1 bases should be attributed proportionately to those sources. To enable this attribution, the ARRB technique was augmented by adding the use of a contribution ratio (*3, 4*). The contribution ratio, like the probabilities for alternatives, ranges from 0% to 100% and is derived from pavement practitioner responses in survey interviews. The Gauteng study recommended and included sensitivity analysis to examine how a range of contribution ratio values affects benefits. The range of resulting BCR values was similar to the range reported for the overall ALF program evaluation (*2*). The results showed substantial economic returns from HVS testing and presented another successful case study in the use of this cost–benefit analysis technique.

California

HVS testing in California since 1994 resulted in technical advances and an interest in evaluating the direct economic benefits from the research. Some of the same driving forces, such as budgetary pressures, that led to the Australian and Gauteng studies also existed in California. Successful outcomes in those earlier studies provided a promising approach for use in California. A previous study had estimated larger-scale benefits than might be expected from early HVS tests (*29*), but interest then shifted to a more narrowly focused and retrospective assessment that would examine impact long after implementation of research results.

The California Department of Transportation (Caltrans) initiated a pilot project that is in progress. Part of the pilot project identified and reviewed the various techniques described earlier in this paper. The Australian and South African studies presented an opportunity to apply the same method as in California but adapted for local conditions, where road user delay is an important economic factor. Whereas the Gauteng study added the contribution ratio, the Caltrans study adds the calculation of user costs in addition to agency costs. User costs were not part of either the ARRB or the Gauteng study, but benefits to users from pavement innovations is a focus of the Caltrans study. Savings in user costs that can be attributed to HVS testing may be very high but must await final results from the ongoing pilot project.

Final results from the California study are expected to be published in 2011. Preliminary results (for a discount rate of 4%) show BCRs ranging from 5.3 to 7.1 for low contribution ratio and 22.4 to 30 for high contribution ratio (*1*). These values are somewhat higher than the range of 1.4 to 11.6 for individual ALF trials (*2*) and the range of 2.2 to 10.2 from the HVS G1 case study (*4*). These results underscore the need for sensitivity analysis in cost–benefit assessments.

Application of this technique presents challenges that include sensitivity to assumptions, subjective input, and substantial cost, time, and labor commitments. Some of these may become less significant through improved procedures and controls. In comparison with other methods described in this paper, this technique provides some advantages, including quantitative benefits in terms of monetary cost savings. The technique enables analysis of multiple alternatives and explicitly incorporates uncertainty of outcomes. Surveying the implementers of research findings provides essential input for analysis and validation of assumptions. As used in the ongoing Caltrans pilot project, the technique addresses many of the traditional challenges to evaluating benefits of research.

CONCLUSIONS

The synthesis of techniques presented in this paper shows variability in approaches taken worldwide to assess research benefits. The most prominent qualitative measures are peer review and surveys. For quantitative assessment, cost–benefit analysis continues to lead and bibliometrics are popular. An Australian cost–benefit analysis technique was enhanced in South Africa, with successful case studies reported in both countries. Further developments of this technique are continuing through an ongoing pilot project in California.

Future directions and next steps toward improving and using methods for evaluating benefits from APT research are suggested here from the studies and recurring themes discussed in this paper. APT researchers and operators might consider the following needs and potential ways to resolve them, whether as an individual APT program, in coordination with others at various levels (i.e., state, regional, national, and international), or through consortia, professional societies, or research organizations such as TRB:

- Recognize the need for more frequent, formal, and quantitative assessments of APT research.
- Organize and perform coordinated studies of evaluation techniques (perhaps beginning with cost–benefit analysis) for APT research.
- Investigate techniques that may be suitable for both retrospective and prospective assessments.
- Evaluate previous and existing efforts at establishing frameworks to assess research benefits.
- Pursue and promote systematic and consistent practices for evaluating APT research results, which could start with developing guidance on the use of cost–benefit analysis of APT.
- Identify conditions and criteria for assessing APT at various levels of evaluation (test, project, and program).
- Scan fields of study outside of APT, pavement, and transportation research for advances in ways to evaluate benefits of research.
- Evaluate new approaches, such as the NCHRP Project 20-63 toolbox, to determine suitability for assessing benefits of APT.
- Investigate potential development of a multifaceted approach that combines complementary techniques and measures and that may be suitable for APT research, as well as other pavement or transportation research.
- Develop standardized and commonly accepted (between APT programs) techniques and measures for evaluating costs and benefits of APT research.
- Identify credible evaluation techniques that potentially are acceptable to international agencies.

ACKNOWLEDGMENTS

The authors thank pavement practitioners for their input; the ARRB Group, Broadway, New South Wales, Australia, for foundational work developing their method; and enhancements sponsored by the

South African Gauteng Provincial Government and developed by South African engineers. HVS testing and research were performed by Caltrans' partners at the University of California Pavement Research Center University of California, Berkeley; Dynatest Consulting; and Council for Scientific and Industrial Research. Caltrans and FHWA funded testing and research in California. The authors thank the Caltrans Library for assistance in conducting the literature search and acquiring references.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data. The contents do not necessarily reflect the official views or policies of the State of California or South Africa's Council for Scientific and Industrial Research. This paper does not constitute a standard, specification, or regulation.

The Full-Scale Accelerated Pavement Testing Committee peer-reviewed this paper.

11. APPENDIX B: Published Journal Article 2

“Economic Benefits Assessment of Accelerated Pavement Testing Research in California: Case Study”

For simplicity and clarity, this article is referred to as “*The initial case study*” throughout the body of the thesis.

Economic Benefits Assessment of Accelerated Pavement Testing Research in California

Case Study

L. du Plessis, W. A. Nokes, M. Mahdavi, N. Burmas, T. J. Holland, and E.-B. Lee

A cost–benefit analysis method for determining the economic benefits of heavy vehicle simulator testing was evaluated. The University of California and its research partners began conducting accelerated pavement testing in 1994 on behalf of the California Department of Transportation. The authors present the findings of a pilot project intended to define a method suitable for measuring the direct economic benefits of heavy vehicle simulator testing in California. The chosen method was based on a cost–benefit analysis initially developed in Australia and later enhanced and applied in South Africa to determine economic benefits of their respective accelerated pavement testing programs. Results of a case study applying the Australian–South African method to heavy vehicle simulator tests conducted in California are presented. The case study evaluated benefits (in cost savings) from heavy vehicle simulator tests performed to validate innovative pavement mixes and designs proposed for the rehabilitation of a high-traffic urban Interstate route in the Los Angeles, California, area. Although local conditions in these countries differed significantly, the method was successfully applied and consistently showed positive results, presented as discounted net present value and benefit–cost ratio. Sensitivity analysis is recommended to determine a range of savings instead of a single benefit–cost ratio.

The California Department of Transportation (Caltrans) established an accelerated pavement testing (APT) program and began testing in 1994 with the purchase of two heavy vehicle simulator (HVS) machines. The original program evolved into the University of California Pavement Research Center (UCPRC), a partnership between University of California, Davis; University of California, Berkeley; South Africa's Council for Scientific and Industrial Research; Dynatest Consulting; and Caltrans. The APT program has been highly productive for nearly 17 years and has helped pavement technologies advance in California.

The need to assess benefits from APT in California comes from many sources, including Caltrans' commitment to its strategic goal of effective stewardship of California's resources and assets. In managing HVS tests and pavement research overall, the Caltrans Division of Research and Innovation supports the department's vision, mission, and strategic goals through processes that include the following:

- Feedback, to ensure that sound investments are made in the pavement research program;
- Continuous improvement, to identify and overcome barriers in the research process; and
- Accountability and performance measurement, to identify and communicate benefits of research.

The first step in assessing benefits from APT in California was to conduct a pilot project that included a case study, which is described in this paper. The primary goal of this case study is to assess a cost–benefit analysis (CBA) method developed in Australia to assess its APT program and later enhanced in South Africa for evaluating the economic benefits of its HVS testing. The ultimate purpose of the pilot project is to determine the potential for adapting the method to California conditions.

BACKGROUND

Use of economic analysis such as CBA provides many benefits. In addition to showing research managers and decision makers the return on investment and cost-effectiveness, CBA can help inform stakeholders and the public. The process of quantifying and assigning value to benefits and costs also provides documentation about the decision-making process. When applied retrospectively, CBA can clarify the forces and barriers that led to a project decision, reveal opportunities and lessons learned, and possibly lead to process improvements for future projects.

In 1992, Horak et al. presented an investigation of the benefits from HVS testing in South Africa (*1*). They detailed a comprehensive list of specific technical effects of the HVS program at the time. These included the improved use of new and innovative construction materials and methods, improved design and analysis procedures, and specific rehabilitation investigations. The analysis found an overall benefit–cost ratio (BCR) of 12.8 and reported that

> it should be appreciated that such economic quantification, in this instance attempting realistically to compare the "with HVS" and "without HVS" scenarios, is invariably both imprecise and conservative (the latter to minimize potential contention). (*1*)

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Transportation Research Record: Journal of the Transportation Research Board, No. 2225, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 137–146.
DOI: 10.3141/2225-15

The subjectivity in determining benefits (though conservative) and the lack of benchmarking with other expert opinions make the 1992 study difficult to update. Building on the work of Horak et al. (*1*), Jooste and Sampson presented a methodology in 2004 in which the direct economic benefits of HVS work done in South Africa to develop a high-quality crushed aggregate base pavement design (called the G1 base) were evaluated (*2, 3*). Their methodology was largely based on initial development work done by Rose and Bennett (*4, 5*), who calculated BCR values for the evaluation of the Australian APT program. Enhancements to the methodology were described by Jooste and Sampson (*2, 3*).

This pilot project investigates the BCR as one of the many ways to evaluate the economic efficiency of a project. FHWA also recommends BCR (or net present value) for most economic evaluations of projects. The method used in this pilot project is consistent with Caltrans practices in evaluating economic benefits and life-cycle analysis of transportation projects and procedures presented in the FHWA economic analysis primer (*6, 7*).

DEFINITION OF BCR

The BCR is the quotient of total discounted benefits divided by total discounted costs. Projects with a BCR higher than 1 have greater benefits than costs, that is, positive net benefits. The higher the ratio, the greater the benefits relative to the costs. BCR is insensitive to the magnitude of net benefits and therefore may favor projects with small costs and benefits over those with higher net benefits. This can be overcome by also presenting the net present value (NPV), which results when the total discounted costs are subtracted from the total discounted benefits. Both measures are used in this case study.

Because of time-related separation between a project's development, completion, and its ultimate effects and benefits realization, it is important to account for the time value of money and to compare discounted costs and benefits. Agencies around the world rely on a basic set of key cost–benefit indicators, including the following:

- NPV,
- Present value of benefits (PVB),
- Present value of costs (PVC),
- BCR = PVB/PVC, and
- Net benefit = PVB − PVC.

BENEFIT ASSESSMENT OF UCPRC PROJECTS

Evaluation of the economic returns of research and development is difficult. An economic benefit can be calculated only if the outcome of a technology development effort can be compared with a scenario that would have existed had the development not been undertaken. Such an assessment includes a significant amount of uncertainty and subjective judgment. The methodology adopted for this study takes this uncertainty into account, as suggested by the framework in the Australian and South African studies with some modifications.

It was decided that the case study in California would use the approach that Jooste and Sampson applied in their HVS benefit evaluation for Gautrans, the road authority in the South African province of Gauteng (*2, 3*).

Like the pilot project in California, the South African HVS evaluation needed a suitable method for determining benefits from HVS testing. In an initial effort to meet Gautrans' needs, South African investigators developed a best-practice approach. Elements of best practice include the following (*2, 3*):

- Pick the best performing project to quantify benefits.
- Collect information and validate estimates of benefits from road authorities and practitioners who will implement the research results (not from the researchers).
- Explicitly address uncertainty through methods such as calculating a range of values and using probability measures.
- Acknowledge other sources that contribute to technology advances, and ask practitioners how much they believe the research results (e.g., from HVS tests) contributed to the advances.

The adopted method is based on decision analysis, value of information concepts, and use of expected values, which are the product of probabilities of outcomes multiplied by the cost of each outcome. A payoff table or decision tree (as used in this case study) is a framework for calculating expected costs for a decision. Each decision, such as not conducting a test, results in its associated expected cost. Conducting a test may provide more information that might reduce the expected cost. Depending on the cost of conducting a test, the difference in expected costs may show a cost savings (i.e., benefit). If savings exceed the cost of testing, then the benefits are worth the cost of the test. The BCR of conducting a test can then be calculated (*8, 9*).

KEY ELEMENTS OF METHODOLOGY

The steps in applying the adapted methodology are as follows:

1. Situations with and without the benefit of HVS testing are identified.
2. Uncertainty in assumptions and outcomes is accommodated by assigning a probability (on the basis of input from interviews) to each alternative outcome.
3. Cost (life cycle) of each alternative outcome is calculated.
4. Expected value (cost) of each alternative outcome is calculated by multiplying its probability by its cost.
5. Total expected for value for each decision (with HVS test and without HVS test) is calculated as the sum of expected costs of alternatives.
6. Benefit (expressed as NPV of cost savings) of the information from the HVS test is determined by subtracting the total expected cost without the HVS test from the total expected cost with the HVS test.
7. BCR is derived by dividing the benefit by the total costs of the HVS test.

A key part of the assessment and validation effort is estimating the likelihood of technical advances that would have occurred if HVS testing had not been performed. To explicitly address alternative scenarios of technology development, Jooste and Sampson adopted decision tree analysis that takes uncertainty into account and that was successful in previous analyses (*2, 3, 8, 9*). An example of the approach (for HVS tests in South Africa) is shown in Figure 1.

The expected cost of each design alternative is determined by multiplying the life-cycle cost for each alternative by its assigned probability. The sum of all probabilities must equal 1 in each decision branch.

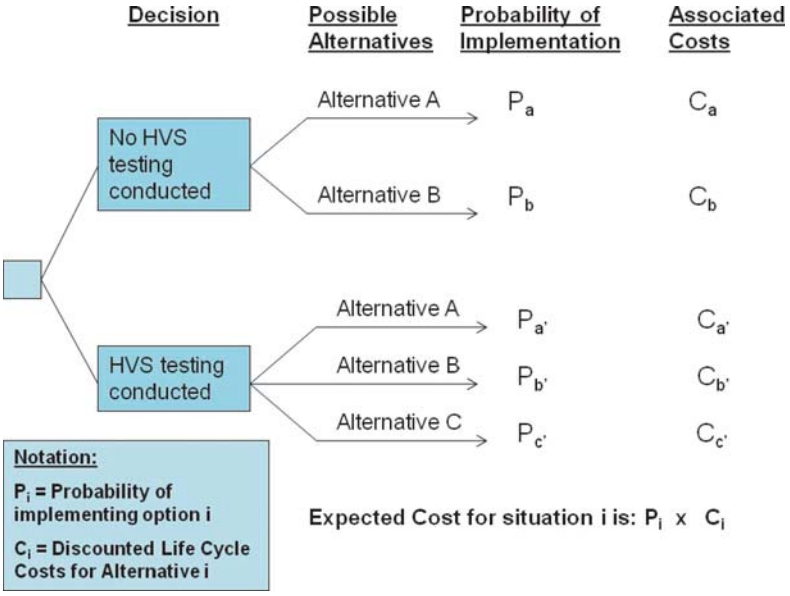

FIGURE 1 Assessing benefits.

The total expected cost for each decision (with and without HVS test) is calculated as the sum of expected cost of the alternatives. The difference of these two total expected costs represents the benefit (cost savings) that results from the HVS investigation. The calculated benefit along with the cost of HVS testing can then be used to determine an economic indicator, such as the BCR.

For benchmark objectivity and credibility, each impact identified was validated through formal interviews with pavement engineers within and outside of Caltrans. These engineers have first-hand knowledge of the HVS test and rehabilitation project that are the subject of this case study. During these interviews, the various rehabilitation alternatives, probabilities for implementation, costs, and perceived effects and benefits were discussed (*10*). Interviews provided a wide range of opinions as well as the inputs needed for analysis, such as the probability for each alternative and the extent to which the HVS test contributed to benefits. To accommodate the variability in the perceptions of the interviewees, sensitivity analysis was conducted to examine how the range of their inputs affects CBA results.

It is important to take into consideration that benefits (e.g., from a less-expensive design) cannot be realized over the whole road network where an innovation is applicable, nor immediately after having been proved. The potential benefit would be phased in depending on needs of the road network, budgets, and other priorities.

Savings in road user cost and other user benefits can make a significant contribution to total economic benefits. The pilot project analyzes user (reduced travel time) and agency costs. These costs are combined in this paper to meet space limitations.

CASE STUDY

To evaluate the CBA methodology, a case study was conducted on an HVS test on hot-mix (asphalt concrete) pavement associated with the Long-Life Pavement Rehabilitation Strategy (LLPRS) program begun by Caltrans in 1998. Criteria for the LLPRS program were fast construction (within a limited number 55-h weekends), at least a 30-year service life, and minimal maintenance. The project selected is a rehabilitated section of I-710 in Long Beach, California (*11–14*).

I-710 Long Beach Rehabilitation Project

In 2003, the LLPRS rehabilitation project was completed on heavily trafficked I-710. The 30-year design loading of the rehabilitated pavement is 200 million equivalent 80-kN standard axle loads. At that time, with average daily traffic of 155,000 on weekdays with 13% trucks, asphalt concrete pavements based on the (then) standard Caltrans design method could not meet the LLPRS criteria. This provided an opportunity for development and implementation of innovations proved through HVS testing.

Innovative mixes and designs were reported by Monismith and Long (*12, 13*). The project consisted of three full-depth asphalt concrete (FDAC) replacement sections (approximately 8.7 lane miles total) under freeway overpasses with vertical clearances lower than required by federal standards. Two sections (approximately 15.8 lane miles) between overpasses were rehabilitated with crack, seat, and asphalt concrete overlay of existing 50-year old portland cement concrete (PCC) slabs.

Rehabilitation Alternatives

Through various interviews, a list of possible rehabilitation strategies for LLPRS projects with climatic and traffic demands similar to those of I-710 were identified. These alternative strategies are as follows:

1. Standard Caltrans crack, seat, and asphalt concrete overlay;
2. Innovative crack, seat, and asphalt concrete overlay;
3. Standard Caltrans FDAC replacement;
4. Innovative FDAC replacement; and
5. Long-life PCC lane and slab replacement.

Development of innovative mixes and designs for crack, seat, and asphalt concrete overlay and FDAC (Alternatives 2 and 4) was based on mechanistic–empirical design, laboratory testing, and professional judgment (*12, 13*). HVS testing was performed subsequently to validate the performance of the mixes and designs.

Two designs were required. Substandard vertical clearances under the overcrossings required lowering the existing grade. Between the overcrossings, where there were no clearance concerns, a different design could be used. Though two pavements structures were developed, both designs used innovative mixes, and both had to meet the LLPRS criteria. The two benefits identified for this case study reflect the two design approaches:

Benefit 1. Innovative mixes enabled the improvement of vertical clearance under overcrossings while meeting LLPRS criteria.

Benefit 2. Innovative mixes enabled meeting the LLPRS criteria where no vertical clearance constraints existed.

Benefit–Cost Analysis

To determine the BCR, a number of analysis steps were followed:

1. Validation interviews were conducted with pavement engineers within and outside of Caltrans who had first-hand knowledge of the HVS test and I-710 rehabilitation project. They identified likely alternative designs (with and without HVS tests), probabilities for each alternative, maintenance and rehabilitation schedules, and contribution of HVS tests to innovative designs.
2. The Caltrans life-cycle cost analysis procedures manual and RealCost 2.2 software were used to calculate the costs (NPV) for each alternative. Along with CA4PRS software, estimates were calculated for construction schedules, work zone user costs, and agency cost for initial and future maintenance and rehabilitation. Costs were discounted to determine the present value of agency and road user costs for each alternative (*11, 15*).
3. The resulting costs and probabilities were applied to determine the total expected cost (discounted NPV) for the two decisions, with and without HVS testing. Sensitivity analysis was conducted to take reconnaissance of the range of probabilities from the interviewees' perceptions. [$\Sigma(p_1, \ldots, p_5) = 1.0$ and similarly for $p_{1'}$ to $p_{5'}$.].
4. The maximum expected payoff (i.e., cost savings in this case) was the greater total expected cost of the two decisions.
5. The benefit (cost saving) was the difference in the total expected cost of the two decisions and was determined by subtracting the total expected costs of the without-HVS decision from the with-HVS decision. A positive value indicated a positive net benefit.
6. Scaling up of the benefit was based on the projected number of lane miles where the innovation may be implemented. Projecting the likely number of lane miles required input from interviews, programmed roadway improvements, and judgment. The total benefit was then calculated by scaling up the benefit to the correct expected lane miles suitable for these rehabilitation strategies.
7. Determining the development costs required identifying historical records along with judgment about the costs of operations, testing, and analysis in developing the I-710 innovative mixes and designs.
8. The BCR was determined by dividing the total scaled-up benefits by total development costs.

The base year for all cost comparisons was 2000, and Caltrans' standard 4% discount rate was used. The decision tree used in the case study is shown in Figure 2.

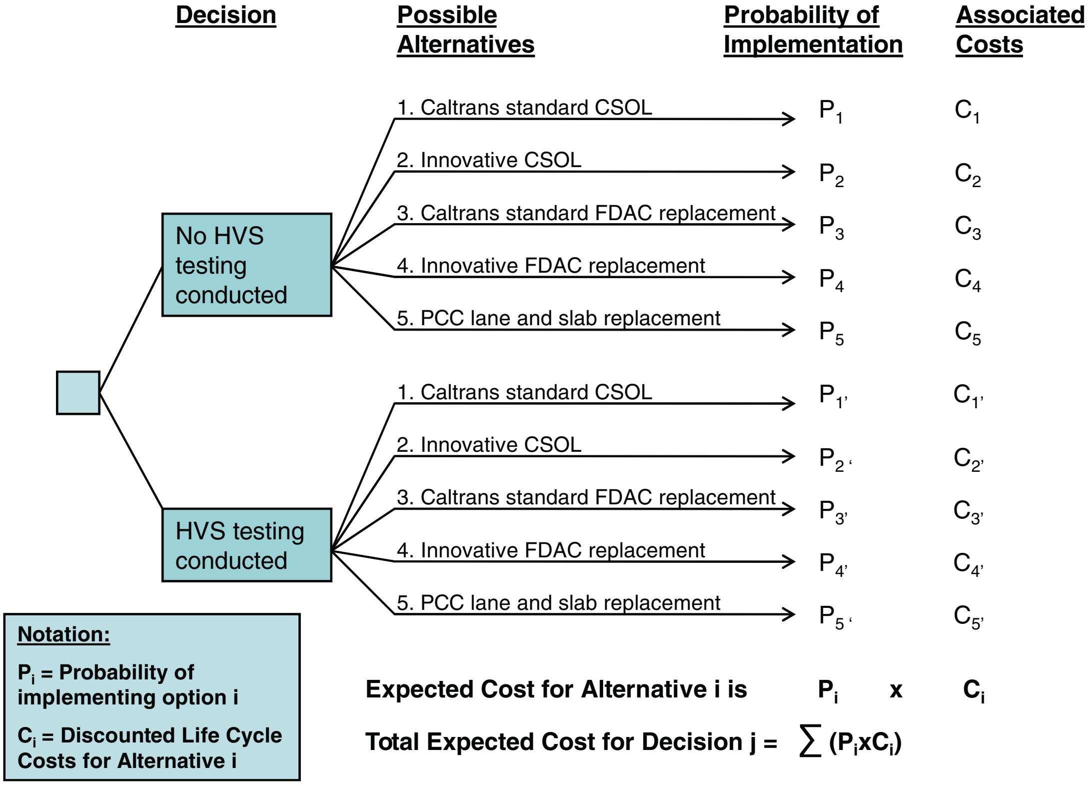

FIGURE 2 Decision tree used in case study (CSOL = crack, seat, and asphalt concrete overlay).

Assumptions

Making a life-cycle cost analysis with RealCost software requires several inputs (*15*). Because the I-710 rehabilitation is an LLPRS option, an analysis period of 60 years was selected in accordance with the guidelines in the Caltrans life-cycle cost analysis procedures manual (*6*). Zero salvage value is assumed at Year 60, and the cost of any maintenance treatments at Year 60 is excluded from the life-cycle cost analysis. The assumptions and inputs including all costs (agency and road user) are detailed elsewhere (*15*).

Traffic Data

Annual average daily traffic is used from September 2001 to March 2002:

- Annual average daily traffic = 135,113,
- Single-unit trucks: 5% of annual average daily traffic,
- Combination trucks: 10% of annual average daily traffic,
- Annual growth rate of traffic: 2.5%,
- Capacity of free flow: 2,000 vehicles per hour per lane, and
- Capacity of queue dissipation: 1,800 vehicles per hour per lane.

Road User Cost Calculations

The value of time for user costs is as follows:

- Value of time for passenger cars: $13.50/h,
- Value of time for single unit trucks: $18.50/h, and
- Value of time for combination trucks: $21.50/h.

Construction Costs

The initial construction costs are shown in Table 1 (at Year 0), as are the costs of the various interventions during the 60-year period. The long-life PCC alternative consists of two subalternatives: under the overcrossings, where PCC lane replacement with dig-outs is required because of substandard clearance, and between overcrossings

TABLE 1 Maintenance and Rehabilitation Costs per Lane Mile for Standard Alternatives

	Alternative 1 CSOL		Alternative 3 FDAC	
Year	Description	Cost ($) (NPV)	Description	Cost ($) (NPV)
0	Rehabilitation construction 30-mm OGFC 75-mm DGAC 30-mm DGAC	510,379.75	Rehabilitation construction 30-mm OGFC 550-mm DGAC AR-4000	2,166,437
10	CAPM (a) 30-mm mill and rep OGFC 60-mm mill DGAC 90-mm rep DGAC	405,316.46	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	302,069
15	CAPM(b) 30-mm mill OGFC 30-mm mill and rep DGAC 30-mm rep OGFC	191,202.53	na	
20	Rehabilitation 30-mm mill and rep OGFC 90-mm mill DGAC 120-mm rep DGAC	359,936.71	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	209,310
30	CAPM (a) 30-mm mill and rep OGFC 60-mm mill DGAC 90-mm rep DGAC	220,126.58	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	148,506
35	CAPM (b) 30-mm mill OGFC 30-mm mill and rep DGAC 30-mm rep OGFC	96,898.73	na	
40	Rehabilitation 30-mm mill and rep OGFC 90-mm mill DGAC 120-mm rep DGAC	178,734.18	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	107,471
45	na		na	
50	CAPM (a) 30-mm mill and rep OGFC 60-mm mill DGAC 90-mm rep DGAC	101,392.41	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	79,080
55	CAPM (b) 30-mm mill OGFC 30-mm mill and rep DGAC 30-mm rep OGFC	50,063.29	na	
Total		2,114,051		3,012,874

NOTE: Discount rate 4%, 2000 base year. OGFC = open-graded friction course; DGAC = dense-graded asphalt concrete; AR-4000 = asphalt cement grade with viscosity of 4000 at 140°F; CAPM = capital maintenance; rep = replace; na = not applicable.

(no vertical clearance concerns), where only PCC lane replacement is required. The costs for the various designs are based on the project scope of the I-710 (24.5 lane miles) and 2000 base year (*14, 15*).

The LCCA results presented in this paper (that are specific to the initial phase of the I-710 project) are based on costs for various pavement rehabilitation types as of 1999 to 2003 and a discount rate of 4% as used by Caltrans for LCCA cost-benefit analysis. The results could change with different material cost changes (such as differences in inflation rate between asphalt and concrete costs), changes in project configuration (such as the ratio of truck lanes needing replacement relative to passenger car lanes not needing rehabilitation), different discount rates, and other project-specific factors.

Maintenance, Preservation, and Rehabilitation Costs

Time lines of the various alternative rehabilitation strategies are shown in Figure 3. These were derived from the suggested maintenance and rehabilitation strategies in the life-cycle cost analysis procedures manual (*6*), input from interviewees, and judgment. Recurring maintenance costs per annum are shown in the figure. Agency and road user costs for maintenance and rehabilitation are given in Tables 1 and 2 for the five alternative strategies.

Tables 1 and 2 show milling and replacing the open-graded friction course as well as the dense-graded asphalt concrete for the standard and innovative asphalt concrete alternatives. These are part of the various capital maintenance, routine maintenance, and preservation activities shown in Figure 3. Also shown in Figure 3 are the levels of concrete pavement rehabilitation, which includes surface grinding, spall and joint seal repair, and slab replacement; this can be minor (indicated as a), moderate (b), or significant (c), depending on extent of slab cracking (*6*).

Analysis of Benefits

Table 3 compares the final costs of the five alternatives. The table shows the NPV of all alternatives, including the total of all rehabilitation interventions, annual maintenance costs, and user costs per lane mile.

For both Benefits 1 and 2, the NPV of the innovative I-710 rehabilitation strategies was lower than current standard Caltrans rehabilitation alternatives for LLPRS.

The steps described earlier can be used to determine the net benefit of implementing the HVS-validated innovative mixes and designs. These are shown for both benefits in Table 4. Values in the table include agency and road user costs, as well as the range of probabilities recorded from the interviews.

As expected, the probabilities of implementing an untested pavement design are low, as reflected by the low probabilities assigned to the innovative crack, seat, and asphalt concrete overlay and FDAC designs without HVS testing. For example, for Benefit 1, without HVS testing, PCC lane replacement was assigned a high probability (70%) of implementation, and the innovative FDAC was given only a 5% probability. These mean values contrast with those associated with validation through HVS testing: the innovative FDAC was assigned a 70% probability of implementation and PCC lane replacement only 25%. This reversal pattern is consistent for both benefits.

Given the various probabilities of implementation, the value of benefits from HVS testing can be calculated by subtracting the total expected cost of the with-HVS situation from the without-HVS situation. Cost savings for both benefits (agency and road user costs) were realized:

Benefit 1. A cost saving of $733,865 (range $633,968 to $833,761) per lane mile and
Benefit 2. A cost saving of $470,017 (range $398,618 to $541,415) per lane mile.

The preceding calculations were repeated, isolating the agency costs from the road user costs. The cost savings of agency costs alone were as follows:

Benefit 1. An agency cost saving of $688,898 (range $604,266 to $773,530) per lane mile and
Benefit 2. An agency cost saving of $295,220 (range $264,524 to $325,916) per lane mile.

In the context of the various pavement rehabilitation alternatives available for LLPRS strategies, the HVS tests resulted in more cost-effective pavement designs with substantial savings depending on the degree of implementation.

Scaling Up

The determination of the total potential benefit depends on the degree of market penetration. Information available as of early 2011 suggests that a minimum of 115 lane miles will be rehabilitated with the innovative mixes and designs. This includes subsequent rehabilitation phases on the I-710 corridor rehabilitation. Assuming future projects have a proportion of lane miles that require a similar distribution of dig-out sections (36.4% in the I-710 project) with remaining sections (63.6%) not requiring dig-out, then the total mean cost savings presented can be scaled up as follows:

$$\text{total cost savings (mean)} = 115 \text{ lane miles} \times \left[(36.4\% \times \$733{,}865) + (63.6\% \times \$470{,}017)\right]$$

This results in total cost savings (sum for Benefits 1 and 2) of $65,096,588 (mean) with extremes of $55,692,815 and $74,500,361, depending on the range of probabilities, as shown in Table 4.

Analysis of HVS Test Costs

For calculation of BCR, the total costs of HVS testing and related activities must be calculated and compared with the benefits. Separating the innovations developed for the I-710 rehabilitation from the UCPRC's other research is complex. Reasonable assumptions are, therefore, required before an estimate can be made of the total development cost.

The bulk of the implementable research used for the I-710 rehabilitation project took place during the 4 years of 1997 to 2000. The total costs of the HVS tests, associated laboratory, and analysis for the I-710 project are estimated at $2,113,200, which consists of

- $1.011 million for the HVS testing to validate the innovative mixes and designs (this includes operational costs, instrumentation, data collection, analysis, and reporting);
- $250,000 for the mechanistic–empirical design of the two pavement rehabilitation designs;
- $300,000 for development of CA4PRS and subsequent modeling of the I-710 project;
- $250,000 for the laboratory studies, which went toward the characterization of the materials used in the I-710; and

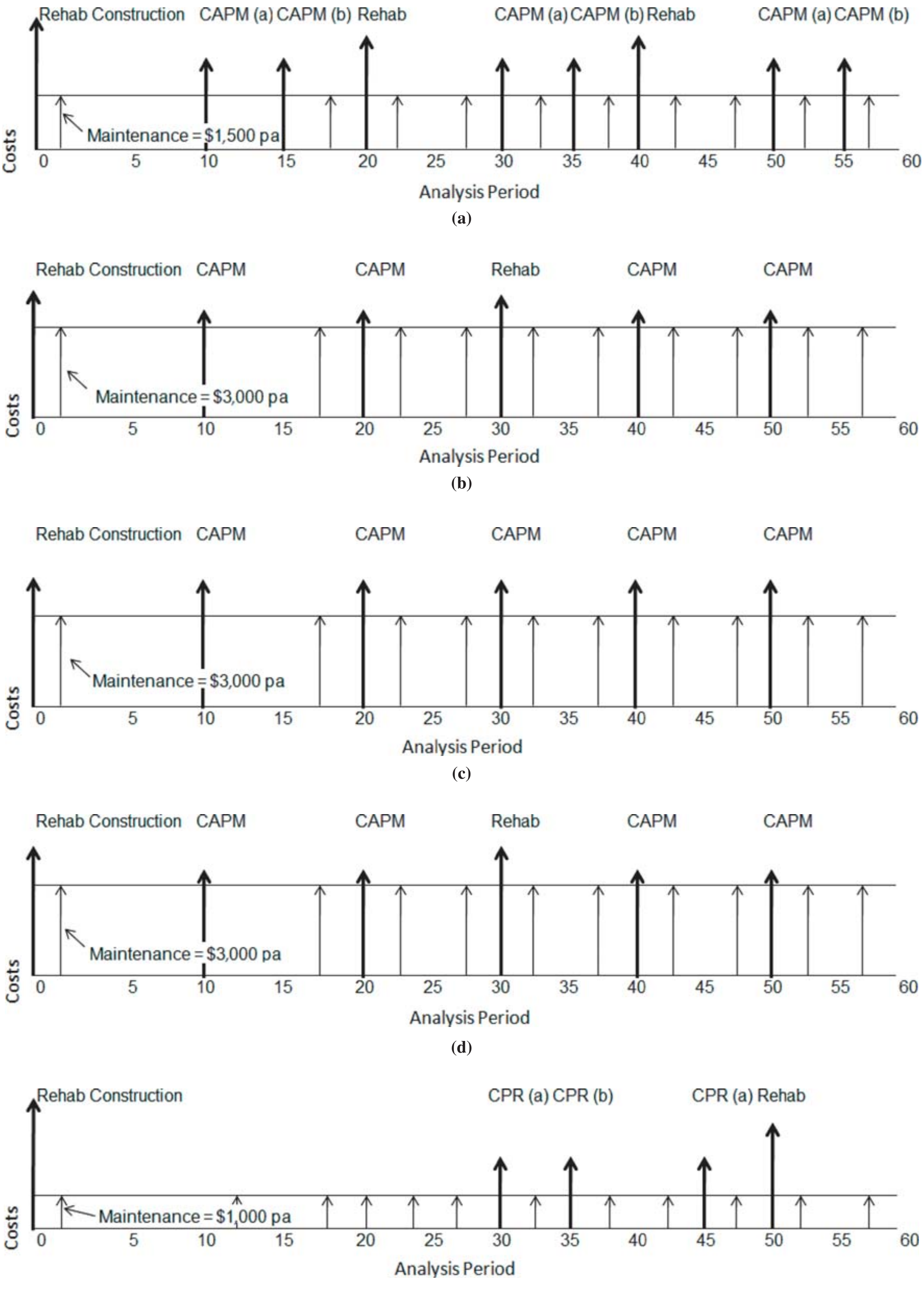

FIGURE 3 Maintenance and rehabilitation strategies over life cycle: (*a*) Alternative 1, standard Caltrans crack and seat overlay (10-year design life); (*b*) Alternative 2, innovative crack and seat overlay (30-year design life); (*c*) Alternative 3, standard Caltrans full-depth rehabilitation (30-year-plus design life); (*d*) Alternative 4, innovative full-depth rehabilitation (30-year-plus design life); and (*e*) Alternative 5, standard Caltrans PCC lane replacement rehabilitation (30-year-plus design life) (rehab = rehabilitation; pa = per annum).

TABLE 2 Maintenance and Rehabilitation Costs per Lane Mile for PCC and Innovative Alternatives

	Alternative 2 CSOL		Alternative 4 FDAC		Alternative 5 PCC	
Year	Description	Cost ($) (NPV)	Description	Cost ($) (NPV)	Description	Cost ($) (NPV)
0	Rehabilitation construction 30-mm OGFC 75-mm PBA-6a 100-mm AR-8000 30-mm DGAC	845,633	Rehabilitation construction 30-mm OGFC 75-mm PBA-6a 150-mm AR-8000 OBC 75-mm AR-8000 +0.5%	1,465,287	Rehabilitation construction 300-mm PCC 150-mm HMA or LCB	2,700,571
10	CAPM 30-mm mill and rep OGFC	133,797	CAPM 30-mm mill and rep OGFC	140,460	na	
15	na		na		na	
20	CAPM 30-mm mill and rep OGFC	96,203	CAPM 30-mm mill and rep OGFC	100,230	na	
30	Rehabilitation 30-mm mill and rep OGFC 75-mm mill and fill PBA6a	206,266	Rehabilitation 30-mm mill and rep OGFC 75-mm mill and fill PBA-6a	220,115	CPR(A)	40,898
35	na		na		CPR(B)	97,102
40	CAPM 30-mm mill and rep OGFC	49,177	CAPM 30-mm mill and rep OGFC	50,460	na	
45	na		na		CPR(A)	106,163
50	CAPM 30-mm mill and rep OGFC	35,000	CAPM 30-mm mill and rep OGFC	37,356	Rehabilitation 300-mm PCC with dowels & tie bars	307,469
55	na		na		na	
60						
Total		1,366,076		2,013,908.05		3,252,204

NOTE: Discount rate = 4%, 2000 base year. PBA-6a = polymer-modified asphalt binder; HMA = hot-mix asphalt; LCB = lean concrete base; OBC = optimum bitumen content; CPR(A) = concrete pavement rehabilitation (minor); CPR(B) = concrete pavement rehabilitation (moderate).

- 20% of all the preceding figures, added for managerial, analysis, reporting, and administrative costs.

Calculation of BCR

The final step in the determination of the quantifiable benefits from HVS testing is comparison of the total costs of the research to benefits derived after implementation. Table 5 shows results of the final calculations for both benefits.

The HVS was not solely responsible for the development of the cost-saving innovative mixes and designs in the I-710 project. However, the interviews revealed that full-scale validation provided by HVS tests was a key contributor to the decision to use the innovative mixes and designs in the I-710 rehabilitation. The extent of cost savings that may be attributed to the HVS tests is accounted for by assigning a contribution ratio, which is multiplied by the presented total cost savings. The contribution ratio is an indicator of how much of the savings from implementing the innovative mixes and designs are the result of the HVS tests. The contribution is estimated to be between 20% and 85%, as determined in accordance with inputs from the interviews. Interviewees who assigned low contribution ratios acknowledged that the innovative mixes and designs would not have been implemented without HVS tests.

Table 5 shows that the NPV of the final potential cost saving realized is between $11.139 million and $63.325 million, depending on

TABLE 3 Final Cost Comparison, NPV, per Lane Mile, 4% Discount Rate

	Standard AC			Innovative AC			Long-life PCC		
Item Cost	Alternative 1 CSOL	Alternative 3 FDAC	1 + 3	Alternative 2 CSOL	Alternative 4 FDAC	2 + 4	Alternative 5a PCC (overlay)	Alternative 5b PCC (dig-out)	5a + 5b
Agency cost ($)	1,414,747	2,481,379		1,073,797	1,635,057		2,843,448	2,835,117	
Annual cost ($)	33,924	67,931		67,911	67,931		22,636	22,569	
User cost ($)	699,304	531,494		292,278	378,851		412,143	410,936	
Total cost ($)	2,147,975	3,080,805		1,433,987	2,081,839		3,278,203	3,268,665	
Final cost ($)			5,228,780			3,515,826			6,546,868

NOTE: AC = asphalt concrete.

TABLE 4 Expected Costs for Benefits 1 and 2

	Probability of Implementation			Total LCC ($) From RealCost	Expected Cost ($)		
Decision or Rehabilitation Alternative	Mean	Low	High		Mean	Low	High
Benefit 1. Innovative Mixes Enabled the Improvement of Vertical Clearance Under Overcrossings While Meeting LLPRS-AC Criteria							
Without HVS test					3,162,359	3,181,145	3,143,573
Alt 1. Caltrans standard CSOL	0	0	0	2,147,975			
Alt 2. Innovative CSOL	0	0	0	1,433,987			
Alt 3. Caltrans standard FDAC	0.25	0.15	0.35	3,080,805			
Alt 4. Innovative FDAC	0.05	0.05	0.05	2,081,839			
Alt 5. PCC lane replacement	0.7	0.8	0.6	3,268,665			
With HVS test					2,428,494	2,547,176	2,309,811
Alt 1. Caltrans standard CSOL	0	0	0	2,147,975			
Alt 2. Innovative CSOL	0	0	0	1,433,987			
Alt 3. Caltrans standard FDAC	0.05	0.05	0.05	3,080,805			
Alt 4. Innovative FDAC	0.7	0.6	0.8	2,081,839			
Alt 5. PCC lane replacement	0.25	0.35	0.15	3,268,665			
Unit costs savings (saving per lane mile)					733,865	633,968	833,761
Benefit 2. Innovative Mixes Enabled Meeting the LLPRS-AC Criteria Where No Vertical Limits Existed							
Without HVS test					2,607,702	2,720,724	2,494,679
Alt 1. Caltrans standard CSOL	0.45	0.35	0.55	2,147,975			
Alt 2. Innovative CSOL	0.05	0.05	0.05	1,433,987			
Alt 3. Caltrans standard FDAC	0.05	0.05	0.05	3,080,805			
Alt 4. Innovative FDAC	0.05	0.05	0.05	2,081,839			
Alt 5. PCC lane replacement	0.4	0.5	0.3	3,278,203			
With HVS test					2,137,685	2,322,107	1,953,263
Alt 1. Caltrans standard CSOL	0.05	0.05	0.05	2,147,975			
Alt 2. Innovative CSOL	0.55	0.45	0.65	1,433,987			
Alt 3. Caltrans standard FDAC	0.05	0.05	0.05	3,080,805			
Alt 4. Innovative FDAC	0.05	0.05	0.05	2,081,839			
Alt 5. PCC lane replacement	0.3	0.4	0.2	3,278,203			
Unit cost savings (saving per lane mile)					470,017	398,618	541,415

NOTE: Based on discount rate of 4%. LCC = life-cycle cost; alt = alternative.

the range of probabilities and the contribution ratios. The BCR calculation varied between 5.3 and 30.0, depending on the same probability ranges and contribution ratios.

Discussion of Results

Comparing BCR values for a discount rate of 4% reported in the Australian, the South African, and the Californian CBA studies in their respective APT programs reveals the following:

- The Australian ALF program reported a BCR of 4.9 for the overall APT program and BCRs of between 1.4 and 11.6 for individual accelerated loading facility tests (*4, 5*).
- The South African HVS study on the G1 base course technology reported BCR values from 2.2 to 5.6 (low contribution ratio) and 3.6 to 10.2 (high contribution ratio) (*3*).
- The California I-710 HVS tests calculated BCR values from 5.3 to 7.1 (low contribution ratio) and 22.4 to 30.0 (high contribution ratio).

Although the California study has a higher variability of BCR values, these results are similar to the other two APT programs. The benchmark credibility of this type of analysis lies in the acceptance of the results by road authorities and practitioners. Their input and the variability of their responses are the main reasons behind the range of BCR values calculated in this paper. One of the criticisms of BCR (and CBA itself) is the effect of inputs, assumptions, and subjectivity (e.g., probabilities) on results, as shown in the sensitivity analysis reported here. However, sensitivity analysis is recommended because it allows examination of these effects for interpretation and use of CBA results.

Another possible reason for the wider range and higher values in the Californian study is the inclusion of road user costs. Neither the Australian nor the South African study evaluated user costs and instead included only agency costs in their investigations.

CONCLUSIONS

This paper summarized a study done to determine the direct economic benefits of validation tests of innovative materials and pavement designs with the HVS in California. Developed and tested in Australia, applied and enhanced in South Africa, and adapted to California conditions for evaluating benefits from APT, the method shows promising results.

The NPV of cost savings is between $11.139 million and $63.325 million with associated BCRs of between 5.3 and 30.0, depending on the range of probabilities and contribution ratios as determined through an extensive interview process. The study highlights the importance of sensitivity analysis to determine ranges of savings instead of a single BCR value.

TABLE 5 NPVs and BCRs of Investment in HVS Development and Implementation

	Range of Probabilities		
Benefit	Mean	Low	High
Contribution Ratio 20% (Low)			
Benefit 1. Innovative mixes enabled the improvement of vertical clearance under overcrossings while meeting the LLPRS-AC criteria ($)	6,143,916	5,307,582	6,980,249
Benefit 2. Innovative mixes enabled meeting the LLPRS-AC criteria where no vertical constraints existed ($)	6,875,402	5,830,981	7,919,823
Total benefit (2000 base year): agency & road user costs ($)	13,019,318	11,138,563	14,900,072
Total HVS testing cost (2000 base year) ($)	2,113,200	2,113,200	2,113,200
Benefit–cost ratio	6.2	5.3	7.1
Contribution Ratio 85% (High)			
Benefit 1. Innovative mixes enabled the improvement of vertical clearance under overcrossings while meeting the LLPRS-AC criteria ($)	26,111,641	22,557,222	29,666,060
Benefit 2. Innovative mixes enabled meeting the LLPRS-AC criteria where no vertical constraints existed ($)	29,220,459	24,781,671	33,659,247
Total benefit (2000 base year): agency & road user costs ($)	55,332,100	47,338,893	63,325,307
Total HVS testing cost (2000 base year) ($)	2,113,200	2,113,200	2,113,200
Benefit–cost ratio	26.2	22.4	30.0

NOTE: Based on 4% discount rate.

ACKNOWLEDGMENTS

The authors thank the pavement practitioners who provided crucial input for this pilot study, the foundational work done by the ARRB Group, and subsequent work by South African engineers. Caltrans' research partners at UCPRC; Dynatest Consulting, Inc.; and the Council for Scientific and Industrial Research performed HVS testing and research, which was funded by Caltrans and FHWA. The authors thank the Caltrans library for assistance in acquiring references.

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The Full-Scale Accelerated Pavement Testing Committee peer-reviewed this paper.

12. APPENDIX C: Published Journal Article 3

“Case Study for Evaluating Benefits of Pavement Research Final Results”

For simplicity and clarity, this article is referred to as “*The final case study*” throughout the body of the thesis.

Case Study for Evaluating Benefits of Pavement Research

Final Results

L. du Plessis, W. A. Nokes, M. Mahdavi, N. Burmas, T. J. Holland,
J. Harvey, and L. Liebenberg

Heavy-duty pavement innovations developed through research for a major rehabilitation project in California were evaluated. The performance benefits of the innovations were examined, and the economic benefits from implementation of the pavement designs were analyzed. Benefits are presented through descriptions of the rehabilitation project, background on the development of long-life pavement rehabilitation innovations, and design requirements that limit permanent deformation (rutting) within the first 5 years of service. Results from field measurements confirmed that the innovative pavements met the performance criterion. The final results of a pilot study to quantify direct benefits stemming from accelerated pavement testing are presented. Cost–benefit analysis that included agency costs with and without road user costs was used, and the influence of the discount rate in net present value calculations is given. Road user costs had a significant influence on cost–benefit calculations, especially in the case of a heavily congested freeway. This influence led to cost savings ranging from $1.128 million to $121.570 million, which emphasized the importance of performing a sensitivity analysis instead of reporting a single estimate of savings and benefit–cost ratio. The final results showed clear field performance benefits of the pavement innovations and indicated positive economic benefits from the research that led to innovations.

The California Department of Transportation (Caltrans) established an accelerated pavement testing (APT) program and began testing in 1994 with the purchase of two heavy vehicle simulator (HVS) machines. The original program evolved into the University of California Pavement Research Center, a partnership of UC Davis, UC Berkeley, South Africa's Council for Scientific and Industrial Research, Dynatest Consulting, and Caltrans. The APT program has been productive for 18 years and has helped pavement technologies advance in California.

To provide long-lasting, heavy-duty asphaltic pavements in urban areas, Caltrans established the long-life pavement rehabilitation strategy (LLPRS) program in 1998. Criteria for implementing the LLPRS program were fast construction (within a certain number of 55-h weekend construction windows), at least a 30-year service life, and minimal maintenance. The first major project on which LLPRS was implemented on asphaltic pavement was the first phase of rehabilitation on I-710 near Los Angeles, California (*1, 2*). Accelerated pavement testing with an HVS provided quick results, which validated the proposed innovative asphalt mixes and pavement designs.

The case study presented here addresses a cost–benefit analysis method developed in Australia (*3, 4*) for assessing that country's APT program and was later enhanced in South Africa (*5, 6*) for evaluating the economic benefits of HVS testing. The purpose of the pilot project is to determine the potential for adaption of the method to California conditions. The original and interim work has been published elsewhere (*7–9*). This paper presents the final results from June 2012.

DEVELOPMENT OF MIXES AND DESIGNS FOR THE I-710 REHABILITATION PROJECT

The first asphalt pavement project selected for LLPRS rehabilitation was on the heavily trafficked I-710 freeway in Long Beach, California (*1, 2*). After the initial development of heavy-duty asphalt mixes and pavement designs from 1998 to 2000, in 2003 the first segment of the I-710 LLPRS rehabilitation project was completed. The 30-year design loading of the rehabilitated pavement is 200 million equivalent 80-kN single axle loads. With average daily traffic of approximately 155,000 on weekdays and 13% trucks, asphalt concrete pavements designed with the (1998) standard Caltrans method could not meet the LLPRS criteria. This created an opportunity for development of heavy-duty pavement innovations.

The project consisted of full-depth asphalt concrete (FDAC) replacement sections (approximately 13.92 lane kilometers in total) under three freeway overpasses with vertical clearances below federal standards. Two sections (approximately 25.28 lane kilometers) between overpasses (no vertical clearance limitations) were rehabilitated through cracking and seating of the existing 50-year-old portland cement concrete (PCC) slabs and then placement of an asphalt concrete overlay.

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Transportation Research Record: Journal of the Transportation Research Board, No. 2367, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 63–75.
DOI: 10.3141/2367-07

Use of HVS Testing to Validate Expected Performance

HVS testing was conducted to validate the proposed innovative mix designs for permanent deformation (rutting) as well as fatigue cracking (*10*). HVS testing of potential rutting of the mixes is highlighted here. Details are provided in project reports (*1, 2, 11*). Although fatigue cracking was evaluated through computer modeling and HVS testing, this study concentrates on evaluation of the rutting performance of the I-710 designs.

The innovative designs satisfying the LLPRS criteria are shown in Figure 1, which also shows the old (before rehabilitation) pavement structures. The details of these mixes can be found elsewhere and are not discussed here (*1, 2*).

By June 2000 test plans were ready for validation testing of the proposed long-life mixes, test sections were built, and HVS testing started. A key purpose of the HVS tests was validation of the heavy-duty pavement's asphalt concrete mix overlay design and its expected rutting performance. Longer-term use of the HVS test data included development and validation of refinements in mechanistic–empirical procedures for predicting rutting of mixes.

HVS tests were performed for Caltrans by the University of California Pavement Research Center. Results provided validation performance data that Caltrans used in its decision to implement the innovative mixes and pavement designs on I-710.

Figure 2 is an example of rutting performance results under HVS loading. The rut depths and trends represent the innovative polymer modified asphalt type 6A (PBA-6A) used for rehabilitation as well as the asphalt rubber gap-graded hot mix and conventional dense-graded asphalt concrete mixes. Tests were done at an elevated temperature of 50_C (80-kN axle load, tire pressure of 690 kPa). The PBA-6A mix performed significantly better for rutting than the other mixes. The study concluded that the HVS tests suggest that "the PBA-6A mix should satisfactorily carry the anticipated traffic on the I-710 without excessive deformations" (*10*).

The HVS testing validated both the long- and short-term performance expected from laboratory materials tests and extensive analysis of the pavement structure. Laboratory test results were studied in conjunction with computer modeling techniques (finite element and linear layer elastic). Long-term results from this analysis showed that the pavement structure should withstand between 22.7 and 155.5 million 80-kN standard axle loads depending on the conditions and strengths of the layers (*11*). This meets the LLPRS requirement of 200 million equivalent 80-kN standard axle load design with a 50:50 directional split and a lane distribution factor of 0.67 (in the slow lane).

Short-term performance was evaluated to determine rutting potential under expected construction traffic (during construction) and during the first 5 years under in-service traffic. With a limiting criterion of 12.5-mm rut depth, HVS testing showed the innovative mixes would not exceed this maximum value within the first 5 years of service. If permanent deformation did not occur within this period, then later development of substantial rutting was deemed unlikely. The validation results from HVS testing were a crucial part of the Caltrans decision to construct the innovative heavy-duty asphalt pavements on I-710.

Measured Performance Under In-Service Traffic

During the first 5 years of service, from 2003 to 2008, the innovative heavy-duty pavements performed better than expected. No exceptional maintenance was required, and surface ruts were not evident.

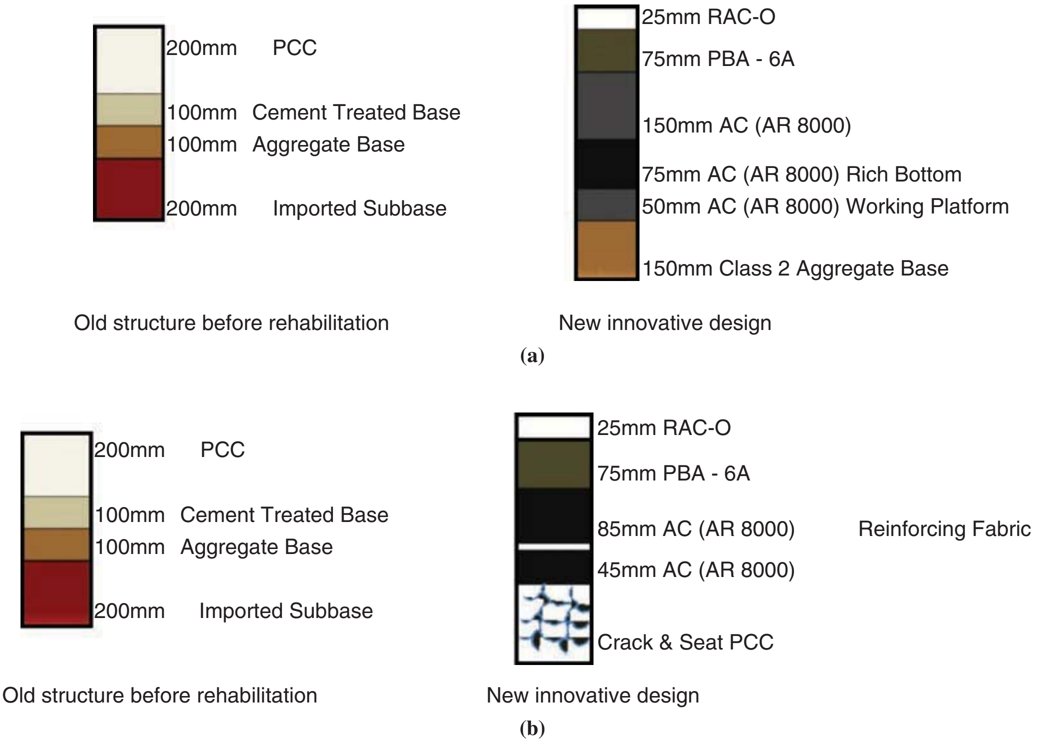

FIGURE 1 Existing structure and innovative designs: (*a*) full-depth asphalt concrete (AC) sections and (*b*) crack and seat sections (RAC-O = recycled asphalt concrete, open-graded mix).

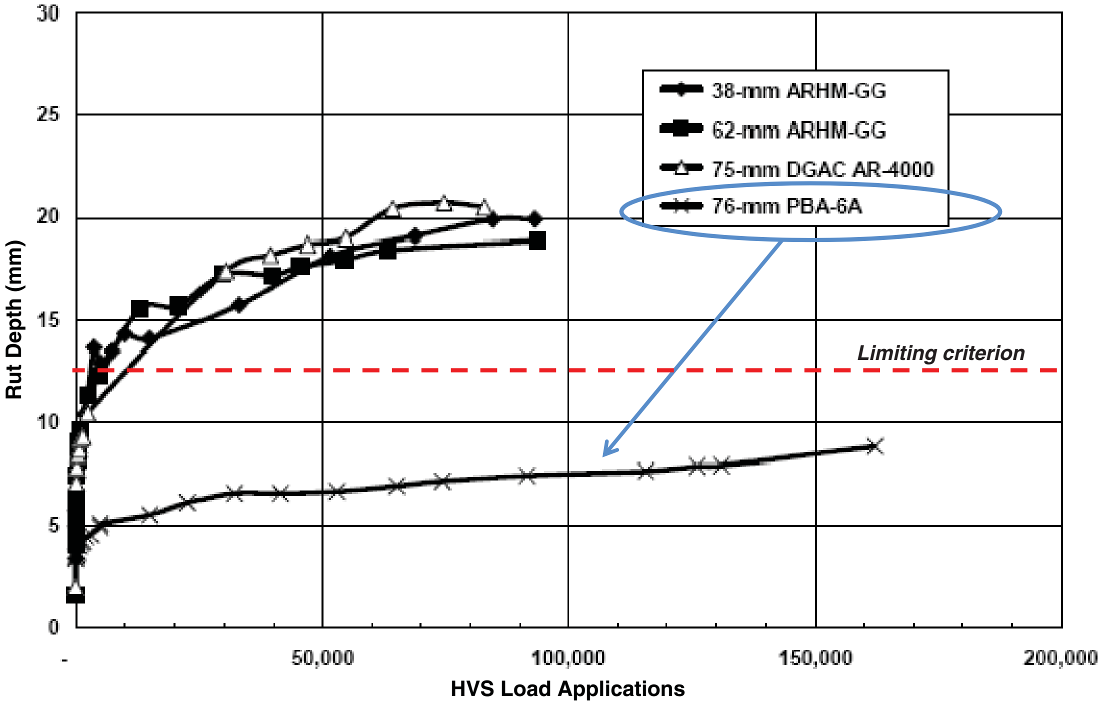

FIGURE 2 Rut depth versus HVS load applications on innovative PBA-6A mix (*3*).

Rutting performance was determined and compared with predictions through measurement of surface rutting across the project (*10*). Rut depth measurements from the middle lane (Lane 2) and the slow lane (Lane 3) for both northbound and southbound traffic are shown in Figures 3 and 4, respectively.

Rut depth averages of less than 5 mm developed during the first 5 years of service despite heavy traffic conditions (155,000 average daily traffic). Measurements showed rutting was well below the 12.5-mm maximum.

Field performance provides the ultimate validation of the innovative heavy-duty pavement mixes and designs. Results from these field measurements suggest these pavements on I-710 will perform satisfactorily throughout the design life (*1, 2, 10*). The success of these innovative pavements stimulated interest in determining the cost-effectiveness of the research that led to the innovations, which is discussed in the next section.

ECONOMIC BENEFIT ASSESSMENT

Background of Cost–Benefit Analysis Method

A cost–benefit analysis was applied for evaluation of the direct economic benefits of research on the I-710 innovative pavements. [More information and background details are available elsewhere (*7–9*).] The cost–benefit method used in this study is consistent with Caltrans practices for evaluating economic benefits and life-cycle analysis (*12*) of transportation projects and procedures in the FHWA economic analysis primer (*13*). Costs and benefits are discounted in a cash flow analysis to reflect the time value of money. Standard economic parameters used in this method are net present value (NPV) and benefit–cost ratio (BCR).

In 1992 Horak et al. presented an investigation of the benefits of HVS testing in South Africa (*14*). Horak et al. provided a comprehensive list of specific technical impacts from the HVS program and reported economic benefits with an overall BCR of 12.8. Building on the work of Horak in 2004, Jooste and Sampson used a methodology to calculate the direct economic benefits of HVS work in South Africa (*5, 6*). Their method was based on enhancements to initial developments by Rose and Bennett, who calculated economic benefits of the Australian APT program (*3, 4*).

An enhancement introduced in the South African studies resulted from questions about how much of the benefit was directly attributable to research. Most pavement advancements have more than one contributing source, so benefits should be attributed proportionately to their sources. The South African studies added a contribution ratio to proportion economic benefits attributed to research versus to other sources. The contribution ratio ranges from 0% to 100% and was derived cost–benefit analysis method is based on decision analysis, value of information concepts, and expected values, which are the product of probabilities of outcomes multiplied by each outcome's cost (*15, 16*). The method is based on Bayesian statistics and is suitable for events in nonrepeatable random experiments or when the process of sampling is mooted by circumstance. The Bayesian approach relies on states of knowledge and beliefs (including probabilities) of knowledgeable individuals. This paper follows Bayesian analysis as described in the literature and as applied in the South African and Australian studies.

Alternative Rehabilitation Strategies and Benefits

In a retrospective analysis the decision that was reached and implemented is already known. There were alternatives to the innovative pavement mixes and designs. Doing nothing was not an alternative because of the importance of the I-710 segment, its poor pavement condition, and its urgent need for rehabilitation. The alternatives that

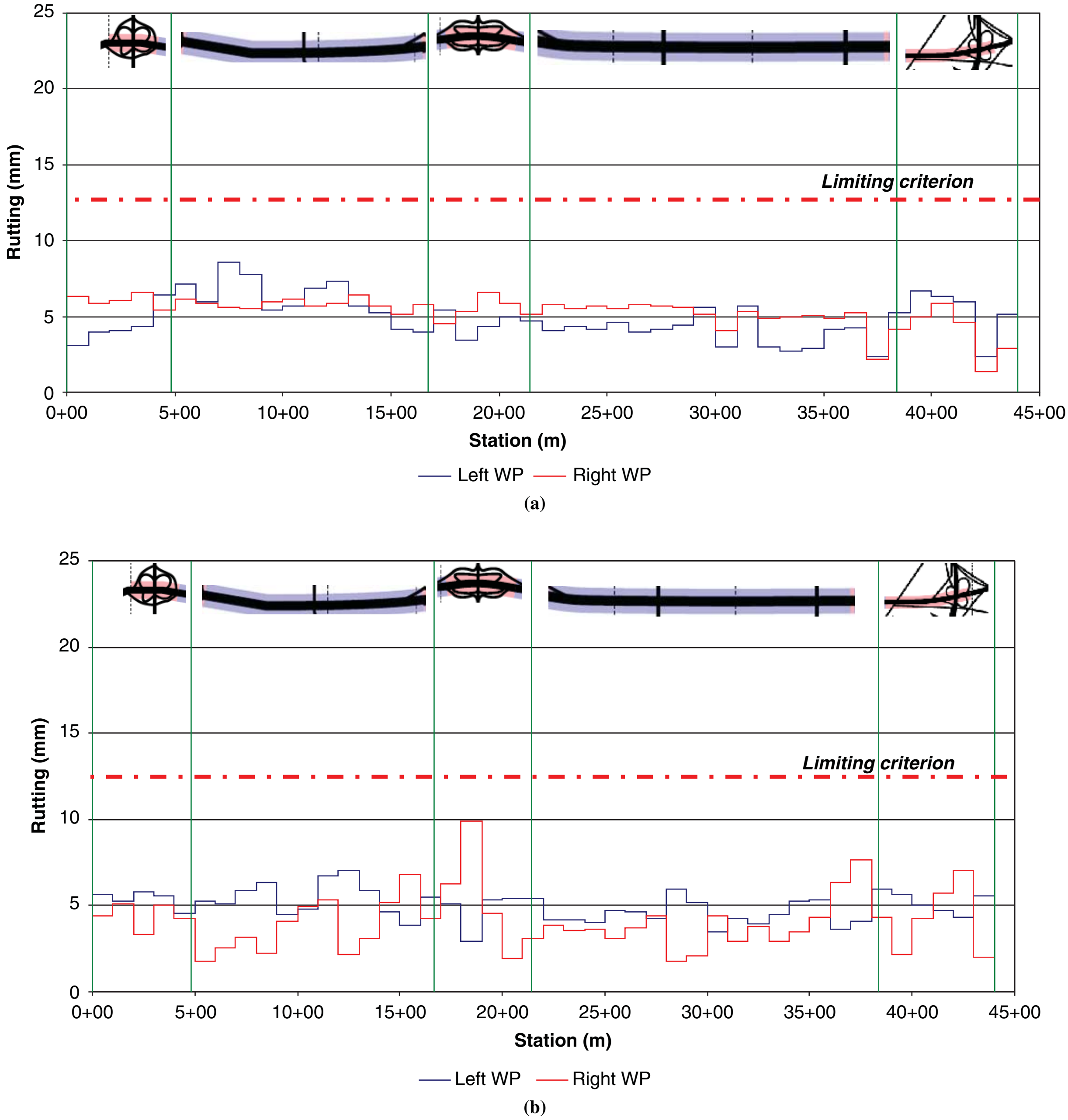

FIGURE 3 Rut of northbound section after 5 years of traffic: (*a*) middle lane and (*b*) slow lane.

may have been selected were identified through interviews with pavement experts familiar with the climate, traffic, and other attributes of the I-710 rehabilitation project. The alternatives included the following:

1. Standard Caltrans crack and seat overlay (CSOL),
2. Innovative CSOL,
3. Standard Caltrans FDAC replacement,
4. Innovative FDAC replacement, and
5. Long-life PCC lane and slab replacement.

Development of innovative mixes and designs for CSOL and FDAC was based on mechanistic–empirical design, laboratory testing, and professional judgment, as shown in Figure 1 (*1, 2*). HVS testing was performed to validate the performance of the mixes in these two innovative design alternatives (*11*). Caltrans considered the other three alternatives for the I-710 project.

Two designs were needed to meet the I-710 project constraints. First, substandard vertical clearances under the overcrossings required lowering of the existing grade. The FDAC and PCC designs were alternatives for meeting this constraint. Second, between the overcrossings where clearance was not constrained, a different design could be used and so the CSOL and PCC designs were alternatives. Although two pavements structures were developed, both designs considered innovative mixes and both had to meet the LLPRS criteria. The following two benefits were used in the cost–benefit analysis

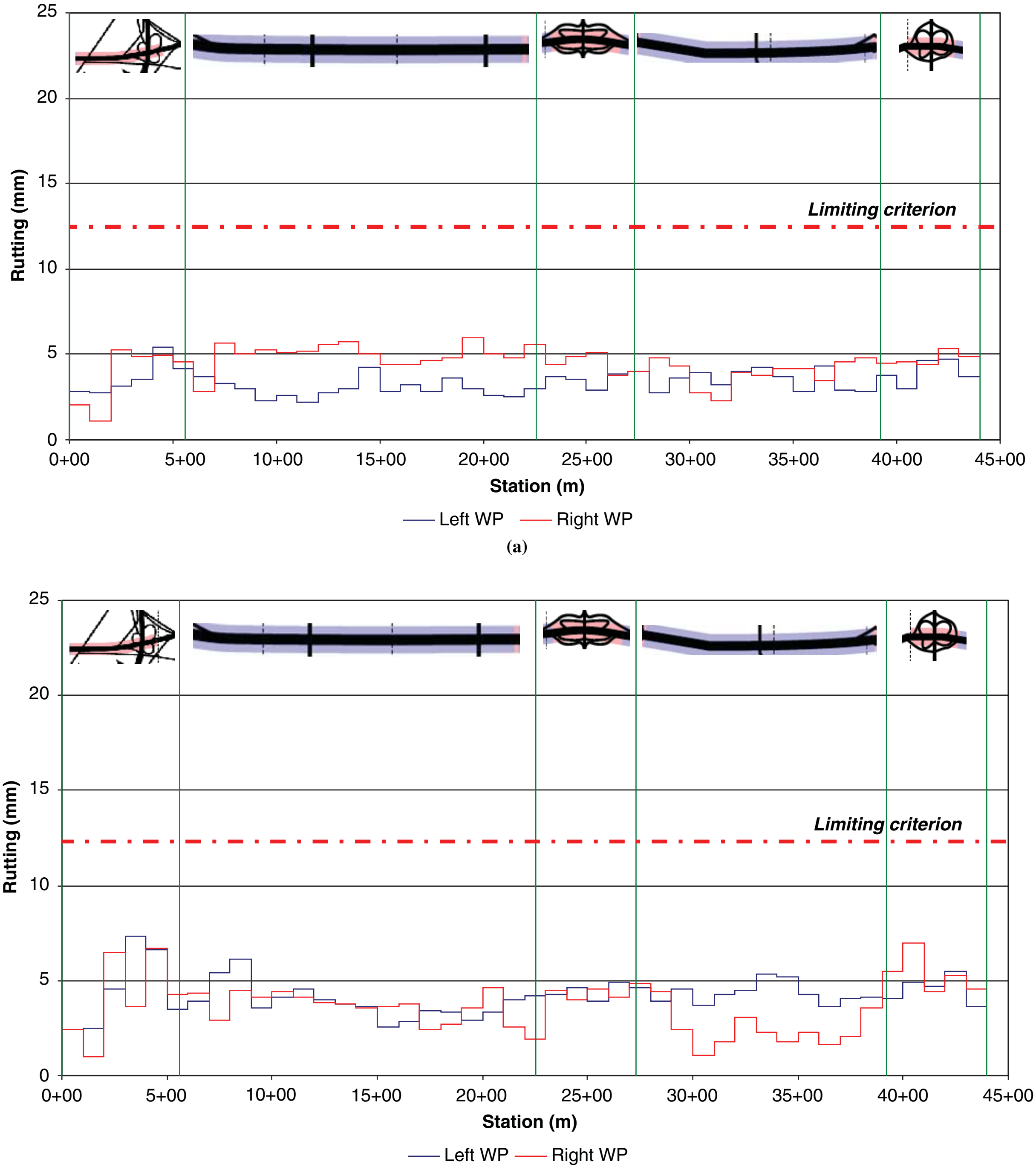

FIGURE 4 Rut of southbound section after 5 years of traffic: (*a*) middle lane and (*b*) slow lane.

because each was the intended purpose of HVS testing and therefore was directly attributable to HVS testing; identifying benefits and attributing them to specific research is a key starting point in benefits assessment:

Benefit 1. Innovative mixes allowed improvement of vertical clearance under- and overcrossings while LLPRS criteria were met.

Benefit 2. Innovative mixes allowed the LLPRS criteria to be met where no vertical clearance constraints existed.

Analysis of Economic Benefits

Detailed descriptions of the methodology for calculating the benefits of HVS research have been published elsewhere (*6–8*). This paper presents the latest results from use of the method (June 2012). The life-cycle cost (LCC) analysis results presented in this paper (specific to the initial phase of the I-710 project) are based on costs for various pavement rehabilitation types as of 1999 to 2003. The results would be expected to change depending on factors including materials cost changes (such as differences in inflation rate for asphalt and concrete costs), changes in project configuration (such as the ratio of truck lanes that need replacement relative to passenger car lanes that do not need rehabilitation), discount rates, and other project-specific factors.

Assumptions

LCC analysis requires several inputs (*12*). Because the I-710 rehabilitation is an LLPRS project, an analysis period of 60 years was selected in accordance with Caltrans guidelines. Zero salvage value was assumed at Year 60, and any maintenance treatment costs at Year 60 were excluded from the life-cycle cost analysis. The assumptions and inputs including agency and road user costs are detailed elsewhere (*8, 9, 17*). The base year for all cost comparisons is 2000, and the standard Caltrans 4% discount rate is used. For comparison, the undiscounted case (0% discount rate) is included in the study. RealCost software was used for the calculation of NPV (*12*), and road user delay was calculated with CA4PRS software (*18*).

Calculated Cost Savings from Research

Various maintenance and rehabilitation strategies are planned to follow the initial construction on I-710 to keep the facility in a serviceable condition for the 60-year design life. The costs of all maintenance and rehabilitation interventions including road user costs as reported by Lee et al. (*17*) are shown in Table 1. The maintenance and rehabilitation interventions developed for the innovative designs are based on input from pavement engineers who had experience with the I-710 project (*9*).

A summary of the total NPV of all the costs is given in Tables 2 and 3. The tables show total LCC for each alternative, including agency and road user costs for initial rehabilitation construction and subsequent maintenance and rehabilitation costs for the 60-year analysis period, along with the pertinent extent of the project and unit cost. Unit costs allow calculation and comparison of the expected economic benefits of alternatives.

Ranking the cost of the five alternatives reveals that for the case of a 4% discount rate (including road user costs), the most cost-effective rehabilitation option is innovative FDAC, with a total life cycle cost of $17.288 million, followed by innovative CSOL, with a total life-cycle cost of $21.746 million. The most expensive rehabilitation option is the PCC alternative, with a total life-cycle cost of $59.795 million. Innovative FDAC and innovative CSOL are not directly in competition with one another; rather, these alternatives are for different designs: under (FDAC) and between (CSOL) overcrossings. A comparison of FDAC alternatives shows that the innovative design life-cycle cost is lower than for the standard design. This is also true for the two CSOL alternatives.

TABLE 1 Maintenance Costs per Lane Mile for Standard Alternatives (*17*)

	Alternative 1. CSOL		Alternative 3. FDAC	
Year	Description	Cost^a ($)	Description	Cost^a ($)
0	Rehabilitation construction (30-mm OGFC, 75-mm DGAC, 30-mm DGAC)	510,379.75	Rehabilitation construction 30-mm OGFC 550-mm DGAC AR-4000	2,166,437
10	CAPM (a) (30-mm mill and rep OGFC, 60-mm mill DGAC, 90-mm rep DGAC)	405,316.46	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	302,069
15	CAPM (b) (30-mm mill OGFC, 30-mm mill and rep DGAC, 30-mm rep OGFC)	191,202.53	na	
20	Rehabilitation (30-mm mill and rep OGFC, 90-mm mill DGAC, 120-mm rep DGAC)	359,936.71	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	209,310
30	CAPM (a) (30-mm mill and rep OGFC, 60-mm mill DGAC, 90-mm rep DGAC)	220,126.58	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	148,506
35	CAPM (b) (30-mm mill OGFC, 30-mm mill and rep DGAC, 30-mm rep OGFC)	96,898.73	na	
40	Rehabilitation (30-mm mill and rep OGFC, 90-mm mill DGAC, 120-mm rep DGAC)	178,734.18	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	107,471
45	na		na	
50	CAPM (a) (30-mm mill and rep OGFC, 60-mm mill DGAC, 90-mm rep DGAC)	101,392.41	CAPM 30-mm mill and rep OGFC 60-mm mill and fill DGAC	79,080
55	CAPM (b) (30-mm mill OGFC, 30-mm mill and rep DGAC, 30-mm rep OGFC)	50,063.29	na	
Total	na	2,114,051	na	3,012,874

NOTE: CAPM = capital maintenance; OGFC = open-graded friction course; DGAC = dense-graded asphalt concrete; rep = replace; na = not applicable.

^{a}Net present value.

TABLE 2 Total and Unit Costs for All Alternatives at Discounted Rate (*17*)

	Standard		Innovative		Long Life
Item	Alternative 1, CSOL	Alternative 3, FDAC	Alternative 2, CSOL	Alternative 4, FDAC	Alternative 5, PCC (Overlay)
Discounted Cost					
Agency cost ($)	20,102,179	18,878,389	16,701,994	13,429,931	48,872,528
Annual cost ($)	984,342	1,124,993	1,968,684	1,124,993	1,289,285
User cost ($)	7,850,605	4,276,867	3,074,899	2,733,027	9,633,265
Total cost ($)	28,937,126	24,280,250	21,745,577	17,287,951	59,795,079
Total unit cost ($/lane km)	1,112,966	1,618,683	836,368	1,152,530	1,469,167
Total unit cost ($/lane mile)	1,780,746	2,589,893	1,338,189	1,844,048	2,350,666
Agency and Annual but Excluding Road User Costs					
Total unit cost ($/lane km)	811,020	1,333,559	718,103	970,328	1,232,477
Total unit cost ($/lane mile)	1,297,632	2,133,694	1,148,965	1,552,525	1,971,963

NOTE: Alternatives 1 and 2 = 26 lane km; Alternatives 3 and 4 = 15 lane km; Alternative 5 = 40.7 lane km.

The total expected costs were calculated for all alternatives, as shown in Tables 4 through 7, for both the discounted (at 4% discount) and undiscounted cases, respectively. The expected cost presented in the tables is the sum of the product of the probability of implementation of each alternative multiplied by each alternative's total LCC (which is the NPV of each alternative as shown in Tables 2 and 3). The tables show the range and mean values of probabilities assigned to each alternative and their life-cycle costs (including and excluding road user costs). The probabilities of implementing the various alternatives were determined through interviews with eight pavement engineers who had experience on the I-710 project.

The probability of implementing untested designs is low, as affirmed by the low probabilities assigned to the innovative CSOL and FDAC designs without HVS testing. For example, for Benefit 1, without HVS tests PCC lane replacement was assigned a high probability (70%), while the probability of using the innovative FDAC was only 5%.

These mean values contrast with those associated with HVS tests: the innovative FDAC probability increased from 5% to 70% probability, while PCC lane replacement dropped from 70% to 25%. This reversal pattern is consistent for both benefits.

The direct economic benefits from HVS testing are calculated by subtracting the total expected cost of the with-HVS case from the without-HVS case. For instance, for the 4% discount case (including road user costs) the savings are as follows:

Benefit 1. Mean cost saving of $377,147 (range $302,563 to $451,732) per lane mile.

Benefit 2. Mean cost saving of $278,270 (range $234,015 to $322,526) per lane mile.

Calculations were repeated for agency costs only (excluding road user costs) and showed the following:

Benefit 1. Mean cost saving of $304,981 (range $246,864 to $363,098) per lane mile.

Benefit 2. Mean cost saving of $141,767 (range $126,900 to $156,633) per lane mile.

TABLE 3 Total and Unit Costs for All Alternatives at Undiscounted Rate (*17*)

	Standard		Innovative		Long Life
Item	Alternative 1, CSOL	Alternative 3, FDAC	Alternative 2, CSOL	Alternative 4, FDAC	Alternative 5, PCC (Overlay)
Undiscounted Cost					
Agency cost ($)	48,220,000	27,740,000	26,000,000	18,690,000	79,000,000
Annual cost ($)	2,610,584	2,983,606	5,221,168	2,983,606	4,561,876
User cost ($)	24,280,000	9,770,000	8,470,000	5,810,000	32,430,000
Total cost ($)	75,110,584	40,493,606	39,691,168	27,483,606	115,991,876
Total unit cost ($/lane km)	2,900,023	2,736,054	1,532,478	1,857,000	2,849,923
Total unit cost ($/lane mile)	4,640,036	4,377,687	2,451,964	2,971,201	4,559,877
Agency and Annual but Excluding Road User Costs					
Total unit cost ($/lane km)	1,962,571	2,075,919	1,205,450	1,464,433	2,053,117
Total unit cost ($/lane mile)	3,140,113	3,321,471	1,928,721	2,343,093	3,284,988

NOTE: Alternatives 1 and 2 = 25.9 lane km; Alternatives 3 and 4 = 14.8 lane km; Alternative 5 = 40.7 lane km.

TABLE 4 Total Expected Costs Including Road User Costs at Discounted Rate

Decision	Rehabilitation Alternative	Probability of Implementation			Total LCC from Real Cost ($/lane km)	Expected Cost ($/lane km)		
		Mean	Low	High		Mean	Low	High
Benefit 1								
Without HVS test	1. CA std CSOL	0.00	0.00	0.00	1,112,966	1,490,714	1,475,762	1,505,666
	2. Innovative CSOL	0.00	0.00	0.00	836,368			
	3. CA std full-depth AC	.25	.15	.35	1,618,683			
	4. Innovative full-depth AC	.05	.05	.05	1,152,530			
	5. PCC lane replacement	.7	.8	.6	1,469,167			
With HVS test	1. CA std CSOL	0.00	0.00	0.00	1,112,966	1,254,997	1,286,661	1,223,333
	2. Innovative CSOL	0.00	0.00	0.00	836,368			
	3. CA std full-depth AC	.05	.05	.05	1,618,683			
	4. Innovative full-depth AC	.7	.6	.8	1,152,530			
	5. PCC lane replacement	.25	.35	.15	1,469,167			
Unit cost saving ($/lane km)		na	na	na	na	235,717	189,102	282,332
Unit cost saving ($/lane mile)		na	na	na	na	377,147	302,563	451,732
Benefit 2								
Without HVS test	1. CA std CSOL	.45	.35	.55	1,112,966	1,268,881	1,304,501	1,233,261
	2. Innovative CSOL	.05	.05	.05	836,368			
	3. CA std full-depth AC	.05	.05	.05	1,618,683			
	4. Innovative full-depth AC	.05	.05	.05	1,152,530			
	5. PCC lane replacement	.4	.5	.3	1,469,167			
With HVS test	1. CA std CSOL	.05	.05	.05	1,112,966	1,094,962	1,158,241	1,031,682
	2. Innovative CSOL	.55	.45	.65	836,368			
	3. CA std full-depth AC	.05	.05	.05	1,618,683			
	4. Innovative full-depth AC	.05	.05	.05	1,152,530			
	5. PCC lane replacement	.3	.4	.2	1,469,167			
Unit cost saving ($/lane km)		na	na	na	na	173,919	146,259	201,579
Unit cost saving ($/lane mile)		na	na	na	na	278,270	234,015	322,526

NOTE: CA = California; std = standard.

TABLE 5 Total Expected Costs Excluding Road User Costs at Discounted Rate

Decision	Rehabilitation Alternative	Probability of Implementation			Total LCC from Real Cost ($/lane km)	Expected Cost ($/lane km)		
		Mean	Low	High		Mean	Low	High
Benefit 1								
Without HVS test	1. CA std CSOL	0.00	0.00	0.00	811,020	1,244,640	1,234,532	1,254,748
	2. Innovative CSOL	0.00	0.00	0.00	718,103			
	3. CA std full-depth AC	.25	.15	.35	1,333,559			
	4. Innovative full-depth AC	.05	.05	.05	970,328			
	5. PCC lane replacement	.7	.8	.6	1,232,477			
With HVS test	1. CA std CSOL	0.00	0.00	0.00	811,020	1,054,027	1,080,242	1,027,812
	2. Innovative CSOL	0.00	0.00	0.00	718,103			
	3. CA std full-depth AC	.05	.05	.05	1,333,559			
	4. Innovative full-depth AC	.7	.6	.8	970,328			
	5. PCC lane replacement	.25	.35	.15	1,232,477			
Unit cost saving ($/lane km)		na	na	na	na	190,613	154,290	226,936
Unit cost saving ($/lane mile)		na	na	na	na	304,981	246,864	363,098
Benefit 2								
Without HVS test	1. CA std CSOL	.45	.35	.55	811,020	1,009,049	1,051,195	966,904
	2. Innovative CSOL	.05	.05	.05	718,103			
	3. CA std full-depth AC	.05	.05	.05	1,333,559			
	4. Innovative full-depth AC	.05	.05	.05	970,328			
	5. PCC lane replacement	.4	.5	.3	1,232,477			
With HVS test	1. CA std CSOL	.05	.05	.05	811,020	920,445	971,882	869,008
	2. Innovative CSOL	.55	.45	.65	718,103			
	3. CA std full-depth AC	.05	.05	.05	1,333,559			
	4. Innovative full-depth AC	.05	.05	.05	970,328			
	5. PCC lane replacement	.3	.4	.2	1,232,477			
Unit cost saving ($/lane km)		na	na	na	na	88,604	79,313	97,896
Unit cost saving ($/lane mile)		na	na	na	na	141,767	126,900	156,633

TABLE 6 Total Expected Costs Including Road User Costs at Undiscounted Rate

Decision	Rehabilitation Alternative	Probability of Implementation			Total LCC from Real Cost ($/lane km)	Expected Cost ($/lane km)		
		Mean	Low	High		Mean	Low	High
Benefit 1								
Without HVS test	1. CA std CSOL	0.00	0.00	0.00	2,900,023	2,771,810	2,783,197	2,760,423
	2. Innovative CSOL	0.00	0.00	0.00	1,532,478			
	3. CA std full-depth AC	.25	.15	.35	2,736,054			
	4. Innovative full-depth AC	.05	.05	.05	1,857,000			
	5. PCC lane replacement	.7	.8	.6	2,849,923			
With HVS test	1. CA std CSOL	0.00	0.00	0.00	2,900,023	2,149,184	2,248,476	2,049,892
	2. Innovative CSOL	0.00	0.00	0.00	1,532,478			
	3. CA std full-depth AC	.05	.05	.05	2,736,054			
	4. Innovative full-depth AC	.7	.6	.8	1,857,000			
	5. PCC lane replacement	.25	.35	.15	2,849,923			
Unit cost saving ($/lane km)		na	na	na	na	622,626	534,721	710,531
Unit cost saving ($/lane mile)		na	na	na	na	996,202	855,553	1,136,850
Benefit 2								
Without HVS test	1. CA std CSOL	.45	.35	.55	2,900,023	2,751,256.06	2,746,246	2,756,266
	2. Innovative CSOL	.05	.05	.05	1,532,478			
	3. CA std full-depth AC	.05	.05	.05	2,736,054			
	4. Innovative full-depth AC	.05	.05	.05	1,857,000			
	5. PCC lane replacement	.4	.5	.3	2,849,923			
With HVS test	1. CA std CSOL	.05	.05	.05	2,900,023	2,072,493.48	2,204,238	1,940,749
	2. Innovative CSOL	.55	.45	.65	1,532,478			
	3. CA std full-depth AC	.05	.05	.05	2,736,054			
	4. Innovative full-depth AC	.05	.05	.05	1,857,000			
	5. PCC lane replacement	.3	.4	.2	2,849,923			
Unit cost saving ($/lane km)		na	na	na	na	678,763	542,008	815,517
Unit cost saving ($/lane mile)		na	na	na	na	1,086,020	867,213	1,304,827

TABLE 7 Total Expected Costs Excluding Road User Costs at Undiscounted Rate

Decision	Rehabilitation Alternative	Probability of Implementation			Total LCC from Real Cost ($/lane km)	Expected Cost ($/lane km)		
		Mean	Low	High		Mean	Low	High
Benefit 1								
Without HVS test	1. CA std CSOL	0.00	0.00	0.00	1,962,571	1,811,766	1,896,533	1,727,000
	2. Innovative CSOL	0.00	0.00	0.00	2,075,919			
	3. CA std full-depth AC	.25	.15	.35	1,205,450			
	4. Innovative full-depth AC	.05	.05	.05	1,464,433			
	5. PCC lane replacement	.7	.8	.6	2,053,117			
With HVS test	1. CA std CSOL	0.00	0.00	0.00	1,962,571	1,598,655	1,657,523	1,539,786
	2. Innovative CSOL	0.00	0.00	0.00	2,075,919			
	3. CA std full-depth AC	.05	.05	.05	1,205,450			
	4. Innovative full-depth AC	.7	.6	.8	1,464,433			
	5. PCC lane replacement	.25	.35	.15	2,053,117			
Unit cost saving ($/lane km)		na	na	na	na	213,112	239,010	187,213
Unit cost saving ($/lane mile)		na	na	na	na	340,978	382,416	299,541
Benefit 2								
Without HVS test	1. CA std CSOL	.45	.35	.55	1,962,571	1,941,694	1,950,749	1,932,639
	2. Innovative CSOL	.05	.05	.05	2,075,919			
	3. CA std full-depth AC	.05	.05	.05	1,205,450			
	4. Innovative full-depth AC	.05	.05	.05	1,464,433			
	5. PCC lane replacement	.4	.5	.3	2,053,117			
With HVS test	1. CA std CSOL	.05	.05	.05	1,962,571	1,989,314	1,987,033	1,991,594
	2. Innovative CSOL	.55	.45	.65	2,075,919			
	3. CA std full-depth AC	.05	.05	.05	1,205,450			
	4. Innovative full-depth AC	.05	.05	.05	1,464,433			
	5. PCC lane replacement	.3	.4	0.2	2,053,117			
Unit cost saving ($/lane km)		na	na	na	na	–47,620	–36,285	–58,954
Unit cost saving ($/lane mile)		na	na	na	na	–76,191	–58,056	–94,327

The HVS tests resulted in more cost-effective pavement mixes and designs with substantial savings depending on degree of implementation.

To investigate the influence of the discount rate the same calculations were repeated with a 0% discount rate (the undiscounted case). The results are given in Tables 6 and 7. The unit costs savings for Benefit 2 turns out to be a negative number, meaning that for the undiscounted case, the costs for implementing the innovative designs are more than the potential saving. The total of Benefit 1 and 2 nevertheless is a positive value.

The pattern of expected costs and cost savings shown in Tables 6 and 7 suggests that a cost–benefit analysis done to determine benefits from HVS testing (and research in general) is sensitive to project-specific conditions, including pavement type, design or strategy, and traffic (i.e., traffic delays that will change depending on the rehabilitation design or strategy), as well as discount rate, assigned probabilities, and assumed values of contribution ratio.

Scaled-Up Cost Savings

Of the design alternatives for I-710 rehabilitation, HVS tests clearly led to more cost-effective designs. However, total savings that can be expected depend on the extent of implementation beyond the first use on I-710.

Determination of the total potential (scaled-up) benefit depends on market penetration. As of early 2011, a minimum 115 lane miles was slated for rehabilitated with the innovative mixes and designs, including subsequent rehabilitation phases on I-710. If future projects have a proportion of lane miles with a similar distribution of dig-out sections (36.4% on I-710) and remaining sections (63.6%) not requiring dig-out, then the total mean cost savings calculated earlier can be scaled up as follows:

$$\text{total cost savings}\,(\text{mean}) = 115 \text{ lane miles} \times [(36.4\% \times \$377{,}147) + (63.6\% \times \$278{,}270)]$$

This results in total cost savings (the proportional sum for Benefits 1 and 2) of $43,371,939 (mean), ranging from $34,794,720 and $51,949,159, depending on the probabilities shown in Table 2 for the 4% discount case (including road user costs).

For the undiscounted case (Table 3) the total cost savings are $71,602,000 (mean), ranging from $61,492,879 and $81,711,122, depending on the probabilities shown in Tables 6 and 7 for the undiscounted case (including road user costs).

Costs of Research and HVS Tests

Costs of HVS testing and related research activities must be determined before the BCR can be calculated. Attributing research projects to the innovations developed for I-710 is complex. Identifying activities and estimating costs requires judgment.

The bulk of the implementable research for I-710 occurred during 4 years, from 1997 to 2000. Costs of the HVS tests, associated laboratories, and analysis are estimated at $2,113,200, as follows:

- $1.011 million for HVS tests (operations, equipment, measurements, analysis, reports),
- $250,000 for mechanistic–empirical design of two pavement rehabilitation designs,
- $300,000 for development of programs and subsequent modeling,
- $250,000 for the laboratory studies to characterize materials, and
- 20% of all preceding costs for managerial, reporting, and administrative activities.

BCR of Research Conducted with the HVS

The final step in determining the economic benefits of HVS testing is a comparison of the total costs of research and benefits after implementation. Table 8 gives results for Benefits 1 and 2 for the 4% discounted and undiscounted cases (with and without road user costs), presenting total benefit (2000 base year) and BCRs. As suggested by du Plessis et al. (*8*), research (in this case HVS testing and related activities) was not solely responsible for cost-saving innovations, so benefits attributed to research should be adjusted by means such as a "contribution ratio." The amount of cost savings attributed to HVS tests and research is calculated by multiplying the contribution ratio with the total cost savings. Although interviews revealed that validation results from HVS tests were a key contributor to the Caltrans decision to use innovative mixes and designs on I-710, percentage values for the contribution ratio varied, and most were below 100%. The contribution ratio ranged from 20% to 85%, reflecting input from the interviews. Some interviewees who assigned low contribution ratios acknowledged that the innovative mixes and designs would not have been implemented without HVS testing.

Benefits vary widely, from $1.128 million to $121.570 million for the undiscounted case and $3.923 million to $ 36.124 million for the discounted case. Figure 5 shows that all cases produced BCR values of greater than 1, except the undiscounted case (excluding road user costs), in which the mean BCR value is 0.8.

The influence of the 4% discount rate is clear. Because of discounting, the calculated NPV (and BCR values) is generally lower in the 4% discounted case than in the undiscounted case, especially when road user costs are included. BCR values are between 0.5 and 57.5 for the undiscounted case and between 1.9 and 17.1 for the 4% discounted case. BCR values lower than 1 were calculated for only two cases (Table 8). Inclusion of road user costs in the calculations favors low-maintenance roads that have substantial road user benefits over roads that require regular maintenance and closures.

CONCLUSIONS

This paper presented performance benefits through a brief description of the I-710 project, background on development of innovative pavement designs and mixes that would not exceed the permanent deformation (rutting) limiting criterion under traffic within the first 5 years of service, and subsequent field measurements. Field measurements confirm that the innovative pavements met the performance criterion, and rut depths were well below the allowable maximum.

Economic benefits of the HVS testing were presented. A cost–benefit analysis method was used to calculate cost savings realized from the research, which interviewed pavement experts said was pivotal to implementation of the pavement innovations by Caltrans.

Results from the cost–benefit analysis show cost savings of between $1.128 million and $121.570 million, reflecting the effects of road

TABLE 8 Total NPV Benefits from HVS Research and BCRs

Benefit	Contribution Ratio (%)	Range of Probabilities ($)			Contribution Ratio (%)	Range of Probabilities ($)		
		Mean	Low	High		Mean	Low	High
Summary of Benefits for Caltrans Investment in HVS Technology Development and Implementation (at 4% discount rate)								
Benefit 1. Innovative mixes enabled the improvement of vertical clearance under- and overcrossings while meeting the LLPRS criteria	20	3,157,477	2,533,056	3,781,899	85	13,419,278	10,765,486	16,073,070
Benefit 2. Innovative mixes enabled meeting the LLPRS criteria where no vertical constraints existed	20	4,070,540	3,423,168	4,717,912	85	17,299,796	14,548,464	20,051,128
Total benefit (2000 base year)		7,228,017	5,956,224	8,499,811		30,719,074	25,313,950	36,124,197
Total HVS testing cost (2000 base year)		2,113,200	2,113,200	2,113,200		2,113,200	2,113,200	2,113,200
Benefit–cost ratio		3.4	2.8	4.0		14.5	12.0	17.1
Summary of Benefits Excluding RUC for Caltrans Investment in HVS Technology Development and Implementation (at 4% discount rate)								
Benefit 1. Innovative mixes enabled the improvement of vertical clearance under- and overcrossings while meeting the LLPRS criteria	20	2,553,299	2,066,745	3,039,854	85	10,851,523	8,783,666	12,919,379
Benefit 2. Innovative mixes enabled meeting the LLPRS criteria where no vertical constraints existed	20	2,073,764	1,856,294	2,291,235	85	8,813,497	7,889,248	9,737,747
Total benefit (2000 base year)		4,627,063	3,923,038	5,331,088		19,665,020	16,672,913	22,657,126
Total HVS testing cost (2000 base year)		2,113,200	2,113,200	2,113,200		2,113,200	2,113,200	2,113,200
Benefit–cost ratio		2.2	1.9	2.5		9.3	7.9	10.7
Summary of Benefits for Caltrans Investment in HVS Technology Development and Implementation (undiscounted)								
Benefit 1. Innovative mixes enabled the improvement of vertical clearance under- and overcrossings while meeting the LLPRS criteria	20	8,340,201	7,162,691	9,517,711	85	35,445,854	30,441,435	40,450,274
Benefit 2. Innovative mixes enabled meeting the LLPRS criteria where no vertical constraints existed	20	15,886,302	12,685,591	19,087,014	85	67,516,785	53,913,760	81,119,810
Total benefit (2000 base year)		24,226,503	19,848,281	28,604,726		102,962,640	84,355,195	121,570,084
Total HVS testing cost (2000 base year)		2,113,200	2,113,200	2,113,200		2,113,200	2,113,200	2,113,200
Benefit–cost ratio		11.5	9.4	13.5		48.7	39.9	57.5
Summary of Benefits Excluding RUC for Caltrans Investment in HVS Technology Development and Implementation (undiscounted)								
Benefit 1. Innovative mixes enabled the improvement of vertical clearance under- and overcrossings while meeting the LLPRS criteria	20	2,854,672	3,201,584	2,507,760	85	12,132,356	13,606,732	10,657,980
Benefit 2. Innovative mixes enabled meeting the LLPRS criteria where no vertical constraints existed	20	–1,114,527	–849,237	–1,379,817	85	–4,736,741	–3,609,259	–5,864,223
Total benefit (2000 base year)		1,740,145	2,352,347	1,127,943		7,395,615	9,997,473	4,793,757
Total HVS testing cost (2000 base year)		2,113,200	2,113,200	2,113,200		2,113,200	2,113,200	2,113,200
Benefit–cost ratio		0.8	1.1	0.5		3.5	4.7	2.3

NOTE: RUC = road user costs.

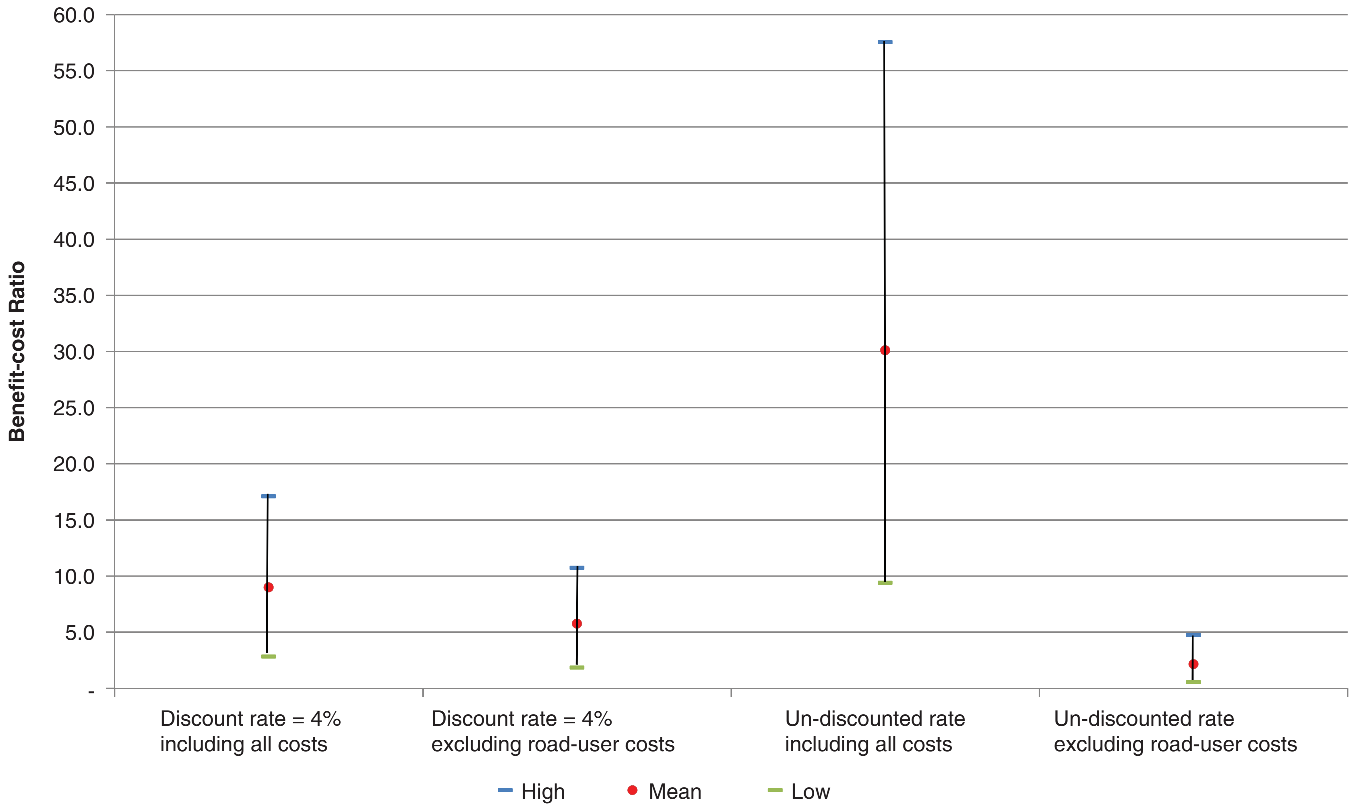

FIGURE 5 Ranges of BCRs.

user costs and varying inputs for probabilities, contribution ratios, and discount rate. This shows that sensitivity analysis is important for determining a range of benefits instead of a reporting a single value for cost savings or BCR.

The results given in this paper show clear performance benefits of the innovative pavements, indicate economic benefits of the research that led to the innovations, and provide guidance to practitioners and researchers for reporting benefits from pavement research.

ACKNOWLEDGMENTS

The authors thank the pavement practitioners who provided input for the pilot study, ARRB for foundational work, and South African engineers for subsequent work. Also thanked are Caltrans' research partners at the University of California Pavement Research Center, Dynatest Consulting, Inc., and the Council for Scientific and Industrial Research, which performed the HVS testing and research funded by Caltrans and FHWA. The authors also thank the Caltrans Library for assistance in acquiring references.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data. The contents do not necessarily reflect the official views or policies of the State of California or of the Council of Scientific and Industrial Research. This paper does not constitute a standard, specification, or regulation.

The Full-Scale Accelerated Pavement Testing Committee peer-reviewed this paper.

13. APPENDIX D: Published Journal Article 4

"Methods, measures and indicators for evaluating benefits of transportation research"

For simplicity and clarity, this article is referred to as "*The final synthesis on the evaluation of benefits*" throughout the body of the thesis.

INTERNATIONAL JOURNAL OF PAVEMENT ENGINEERING, 2016
http://dx.doi.org/10.1080/10298436.2016.1172713

Taylor & Francis
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Methods, measures and indicators for evaluating benefits of transportation research

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ABSTRACT
The purpose of this article is to provide updated information by identifying and discussing methods, measures and indicators for evaluating benefits appropriate for transportation-related research facilities/programmes. The information has been drawn from within and outside transportation research. The article discusses the sources driving the need for evaluating benefits and describes the challenges confronting the evaluation process. It reviews and compares qualitative and quantitative techniques and highlights previous published work, investigations and case studies. Many traditional challenges of determining benefits persist, contributing to the gap between the ability to identify non-technical benefits of research and the growing need to demonstrate such benefits. This article aims to stimulate dialogue and investigations to advance the development of an appropriate robust method to determine quantitative benefits stemming from specifically accelerated pavement testing (APT) type transportation research. The ultimate goal is to help better understand, demonstrate and communicate the benefits of APT research.

ARTICLE HISTORY
Received 15 March 2016
Accepted 15 March 2016

KEYWORDS
Transportation research benefit determination; benefit–cost analysis; accelerated pavement testing

Introduction

The direct economic benefits of an accelerated pavement testing (APT) research programme for potential use by government and research agencies were identified in an earlier pilot study (Du Plessis *et al.* 2011, Nokes *et al.* 2011). The need to understand techniques for assessing the benefits of such research continues to grow. Clear (non-technical) justifications that emphasise costs and benefits (such as cost–benefit analyses) may increase public confidence in decision-makers (Baron and Gurmankin 2013). In this article, we provide a unique description of contemporary techniques and measures for qualitative and quantitative evaluation of transportation-related research.

Accountability for public expenditure has only grown during the recent global economic downturn, leading to demands for greater transparency, more scrutiny of public agency processes and a greater need for the use of state-of-the-practice methodologies. European Co-operation in the Field of Scientific and Technical Research (COST) study suggested that applying methods to evaluate costs and benefits increase funding because of better marketing of transportation research activities and results (European Co-operation in the Field of Scientific and Technical Research 2005). Substantive and proactive efforts to demonstrate the value added from investing in road research have documented previous studies showing qualitative benefits as well as quantified economic returns on funds spent on research.

The international scope of evaluating non-technical benefits of research is indicated by the 2008 scanning tour conducted by United States (US) research administrators to review transportation research programme administration practices. This included the valuation of research and ways to enhance US transportation research administration (Elston *et al.* 2009). Discussions with senior research programme administrators in national governments, the European Commission, non-governmental research consortia, universities and other research organisations in Europe, Japan and South Korea have led to the following findings:

- Unlike in the US, research programmes in many other countries do not have to continually justify expenditures.
- While research programmes in all countries have a process for evaluating results, the techniques vary in complexity, effectiveness and success.
- As in the US, research programmes in all countries face continuing challenges in quantifying benefits of research. No country has a totally satisfactory method. However, an important difference from the US is that justifying research based on the analysis of benefits is not a critical concern in any of the countries visited.

One of the scan team's six recommendations was to improve research evaluation processes by promoting systematic and consistent practices. Future international collaboration may require compatibility of research evaluation methods.

Ongoing activities at the US Department of Transportation (US DOT) Research and Innovative Technology Administration (RITA), which focus on compiling results from cost–benefit assessments of Intelligent Transportation Systems (ITS) in the US and abroad, provide potentially useful examples for benefits evaluation of APT. RITA hosts a knowledge resource portal to help measure and document the benefits of ITS within certain

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goal areas, such as safety, mobility, productivity, energy and environmental impacts (US DOT 2016).

These activities by the US DOT are linked to the International Benefits, Evaluation and Costs (IBEC) Working Group, which was created to coordinate and expand international evaluation efforts, exchange information and techniques, and evaluate benefits and costs of ITS (IBEC Working Group 2014). IBEC facilitates dialogue about topics of interest to the international community of ITS evaluators and encourages the more effective use of information from evaluations. They aim to bring about better informed decisions about ITS investments.

Because of the intended practical use of these qualitative and quantitative transportation research methods, we focus on practical applications. This article is not intended to focus solely on academic literature in this broad and evolving research field. Also, the approaches and case studies that are described in this article are indicative rather than exhaustive.

Indicators of qualitative benefits are described, whilst quantitative methods and measures are emphasised. This article does not discuss macroeconomic impacts, but focus on direct economic impacts that can be attributed to specific research results instead. Research administration, management and policies are not examined in this article, although they are linked to benefits assessment and should gain from the material herein.

Research objectives

The objective of this article is to provide updated information by identifying and discussing methods, measures and indicators that may be suitable for evaluating benefits from full-scale APT. The author's intent is for the information to aid in translating technical pavement measures well known to APT experts into quantitative measures and qualitative indicators, so that public decision-makers can understand and appreciate various returns on investments in APT. The article discusses the sources driving the need for evaluating benefits, describes the challenges confronting the evaluation process, reviews and compares qualitative and quantitative (including direct economic benefits) techniques. It highlights previous reviews, investigations and case studies. The main research objectives are:

- Identify major areas of benefits, determine common methods, measures and information required to reasonably determine benefits of implementing research results.
- Identify current research evaluation methods and (qualitative/quantitative) benefit metrics used by transportation agencies for determining the value of research results.
- Identify the critical knowledge gaps in the evaluation of research results that require further research.
- Suggest appropriate techniques and methodologies suitable for APT-related research benefit determination.

In a recent study published by the Southeast Transportation Consortium (STC) (2014), three elaborate surveys were conducted to capture state of knowledge and practice in determining the value of research in DOTs and to collect the best examples for determining value of transportation research. The study field covered the STC of the United States and included 12 DOTs of the following States: Florida, Louisiana, Arkansas, Mississippi, Alabama, Georgia, South Carolina, North Carolina, Tennessee, Virginia, Kentucky and West Virginia. One of the findings of the report stated:

> Although several methods are proposed for quantifying the benefits of research projects in the research reports collected in the first survey, there is no formal guideline or formal method to evaluate the quantitative and/or qualitative benefits of research projects in State DOTs.

The above findings point to the same conclusion: although several agencies have different ways and methodologies to measure the effectiveness of their research programmes there is a need to develop or adopt a methodology to quantify the value of transportation-related research. The aim of this article is not to develop a generic acceptable methodology or system to quantify the benefits of research projects. That is dealt by additional publications by Du Plessis *et al.* (2011), Nokes *et al.* (2011) and Du Plessis and Prozzi (2008), but rather to investigate methods, measures and indicators that may be suitable for evaluating benefits as detailed above.

Challenges in evaluating benefits of transportation research

The broadest challenge in evaluating benefits is the broad range of expectations by those who focus only on results analysis (ignoring evaluation processes) for such purposes as budget or programme justification, planning or decision-making. A review of the literature suggests three typical and widespread expectations about the evaluation process:

- The process will lead to the 'right' answer.
- The process will produce an 'objective' analysis.
- The process will remove discomfort in determining benefits.

Cited information discussed in this article reveal that the expectations listed above are not met by contemporary approaches and their applications. However, the same information can aid those who must evaluate and communicate research benefits as well as those, such as decision-makers, programme stakeholders or the public, who wish to understand evaluation results and processes.

A 1986 review of approaches used in US Government and by industry to evaluate outcomes of federally funded research remains a landmark study of the past 30 years. The study was performed by the US Congress, Office of Technology Assessment (OTA) to provide information on the feasibility of quantifying outcomes in terms of return on investment (ROI). OTA performed an extensive literature review, conducted their own analysis of quantitative methods and interviewed economists, public policy analysts and research decision-makers in government and industry (US Congress, OTA 1986).

While the OTA study focused on basic research, questions were also examined about measuring ROI with regard to applied research and technology development. The study determined that two-thirds of federal expenditures on applied research was related to the production of public goods 'whose primary value is not measured in economic terms'. The OTA concluded that viewing research as an investment is conceptually valid but such a view is of limited practical value, because factors affecting evaluation of basic research are too complex. They are subjective, pay-offs are too diverse and institutional barriers prevent allowing quantitative models to replace 'mature, informed judgement'. However, the OTA study also concluded that quantitative economic assessment was potentially useful for evaluating applied research and development and research facilities within a single, focused discipline. The latter conclusion appears to apply to APT.

The OTA study also examined non-economic measures, including bibliometrics (assessing research outputs in terms of publications) and 'indicators' (evaluating research in terms of educational degrees, personnel, awards, etc.) as complementary tools. Despite limitations in bibliometrics, the study acknowledged their utility. The study found the utility and reliability of indicators more problematic and referred to them as 'flawed' because of the narrow and subjective assumptions that must be understood to interpret them. The study found peer review (which dominated industry research at the time of the study) to be a necessary complement to the use of bibliometrics and indicators in order to overcome problems stemming from each method separately (US Congress, OTA 1986).

The use of various techniques to evaluate research outputs and their benefits continues to be controversial in government and industry. The OTA investigators deduced the following about the use of quantitative methods from interviews with industry research managers in 1986:

> In industry, where one might expect quantitative techniques to prevail due to the existence of a well-defined economic objective for the individual firm or business, OTA found great scepticism among research managers about the utility of such techniques. Managers found them to be overly simplistic, inaccurate, misleading and subject to serious misinterpretation. There is little systematic data about the use of quantitative techniques. Most articles describe a process adopted by one firm or another without any indication as to how widespread the practice is in industry as a whole.

One of the basic challenges to evaluate research benefits in terms of ROI is the fact (as noted by the OTA investigators) that economic benefits are not the primary drivers for most government research, which focuses more on wide and non-economic aspects of public interests, such as safety, security, environment, health and generally advancing the body of knowledge. It is noteworthy that difficulties in assessing ROI arise in the private sector despite greater awareness and emphasis on economic aspects of research. Whether focused on economic or non-economic types of benefits, many challenges confront investigators when trying to evaluate benefits of research in any sector.

Reviews of approaches for evaluating benefits of research in a wide variety of fields are reported in the literature. Here, we provide an overview intended to assist potential investigations and use by APT owners/operators and researchers. Readers interested in more information about historical reviews may want to examine some of the documents listed in the References section. Descriptions of evaluation approaches reported in the past decade (some of which refer to older studies) are the focus of this article.

Highlights from previous studies show typical concerns, findings and insights about several challenges, including the following:

- Lack of familiarity with this topic;
- Scale of evaluation (i.e. test specific, project specific or programme wide);
- Complexity and context-sensitivity;
- Time domain and
- Recurring procedural challenges.

The scale of evaluation, i.e. test specific, project specific or programme level, must be decided at the outset. The purpose of the evaluation probably determines its scale. Programme-level assessments of research are reported in the literature in terms of determining whether a research programme has achieved some preset targets or goals. Review of evaluations of research (inside and outside of transportation research) reported in the past decade emphasises programme evaluations on a larger-scale and performance reviews. APT research evaluations described in this article show that assessments have been reported for all three scale levels (test specific, project specific or programme level). Each level presents its own challenges. A unifying approach does not exist. However, developments in recent years provide tools that may be customised for the level of evaluation needed.

Complexity is another challenge. Like the research process itself, evaluation of research benefits is a complex effort with uncertain outputs. Any effort to evaluate benefits from research faces substantial difficulties. The evaluation process can be labour-intensive, takes a long time to complete and requires expertise in the subject, all of which can lead to high costs. Deciding whether to proceed with benefits assessment and the process itself are context-sensitive, reflecting the attributes and constraints of the research products as well as those of the evaluators, the organisation and the users of the results. This partly explains why no universal technique has been found or recommended.

Understanding the challenge of the time domain requires stepping back, taking a long-term view of a research project's life cycle and examining the typical sequence of actions in publicly funded transportation research. This helps to reveal some of the complications in assessing benefits. Figure 1 outlines the activities, their sequence and cash-flow (both costs and benefits) for a typical research project (Krugler *et al.* 2006).

The figure does not show the costs and processes in identifying a problem, defining and scoping a research project, incorporating the project into the organisation's overall research plan and obtaining funding as well as securing in-house or contract resources. Two aspects of this pre-research phase present additional barriers to performing evaluations. Firstly, the time required to initiate a project could add one or more years to the left of the timeline in Figure 1, thus further extending the period for evaluation. Secondly, the responsibility for pre-research activities is typically led by personnel dedicated to managerial activities and who often do not perform research or implement the results. These research management personnel are tasked to process the research programme and its projects and not to evaluate possible benefits emanating from research outputs.

In the Active Research phase, the researchers naturally assume lead responsibility for the work, while research management personnel monitor the work and ensure that reporting requirements are met. After completing the Active Research phase, the implementation phase begins. Researchers and research management personnel may be involved in implementation, but often the implementers (typical in operational functions such as design, maintenance and construction) of research outputs assume the

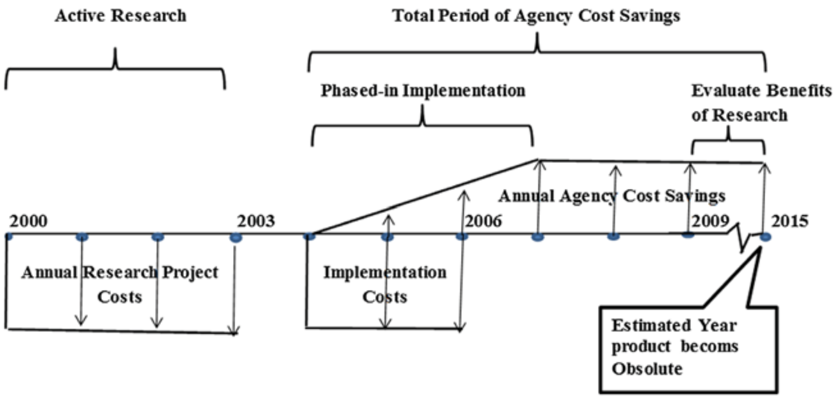

Figure 1. Public-funded project timeline and cash-flow.
Source: Adapted from Krugler.

lead responsibility for moving the research outputs into practice. After paying the costs of research and implementation, the implementation of research outputs should begin to gradually produce benefits. (Only annual agency cost savings are shown in Figure 1, above the timeline). Safety projects are expected to lead to immediate benefits in terms of lives saved and fewer accidents.

This example illustrates the key points: (1) the research project life cycle is long, (2) monetary benefits accumulate long after research is completed and (3) lead responsibilities change with each phase of the project. With successfully completed pre-research, research and implementation, the subsequent accumulation of benefits, which may take longer than any of the preceding phases, most likely requires continuing actions by implementers not associated with the original research project. Not shown in Figure 1 are activities (which would appear to the far right in the diagram) in conducting a retrospective evaluation of benefits. For the most credible results, retrospective assessment of benefits typically must await substantial implementation for most, if not all, benefits to accumulate.

The example in Figure 1 shows fairly constant agency cost savings that would most likely diminish gradually over a time horizon such as 5 to 10 years, or longer. As the research product heads towards obsolescence, new problems will be identified and new projects (possibly stemming from the completed research) will start as the cycle continues.

In a more recent study, STC (2014) reported that a similar research evaluation process will be developed for the Florida Department of Transportation (Figure 2).

Another challenge is estimating the useful service life of a research product before becoming obsolete or being superseded by subsequent research projects or other changes in technology, policies, practices, specifications, etc. Estimating this 'useful life' duration depends on many factors, including the category (e.g. pavement, bridge) and type (e.g. material, construction) of research product, experience and track record of similar innovations, local conditions and institutional aspects. An indication of the variability in estimating the useful life of various categories and types of research products is the range of useful life estimates reported by Krugler *et al.* (2006) and selected categories summarised in Table 1.

The values shown in Table 1 represent the number of responses (in each category) from a survey conducted at the 2004 meeting of the American Association of State Highway & Transportation Officials Research Advisory Committee. The responses were subsequently used to develop recommended useful life values for research product evaluations in a tool developed in a National Cooperative Highway Research Program (NCHRP) project (Krugler *et al.* 2006) described later in this article. The highlighted cells in Table 1 indicate which useful life estimate range (column) contains the median. The entry for Standard Specifications refers to construction and maintenance.

Several recurring procedural challenges in evaluating benefits have been observed. Evaluators of research benefits in any sector must decide which significant aspect should be measured, how and when to measure and how to interpret results. Many benefits are difficult to characterise. Regardless of the approaches used, recurring challenges to the evaluation have been observed (Arjanovic *et al.* 2009), including:

- attributing impacts, which require linking outcomes to a specific research project and discerning previous research that influenced it as well as other projects that were influenced by it;
- setting boundaries, which require identifying the starting point of all contributing research (in retrospective studies) and identifying the time frame and endpoint for analysis (in prospective studies, which are rarer);
- bias in the selection of research projects in case studies, e.g. projects with low payback vs. high payback;
- unclear descriptions of techniques in data collection and analyses, and
- non-uniform definition of terms and concepts, e.g. basic research vs. applied research.

One of the biggest procedural challenges is the attribution of impacts and benefits to a specific research project. A readily apparent linkage between research and identifiable benefits is more the exception than the rule. One review of international practice in assessing research impacts characterised attribution of impacts as a main reason why such evaluations are usually considered 'too hard' (Grant *et al.* 2010). Case studies that evaluate specific research have been successful in mitigating this challenge (Arjanovic *et al.* 2009, Grant *et al.* 2010). This approach focuses on evaluating a low number of benefits by examining a few where the pathway from research outcomes to benefits is evident.

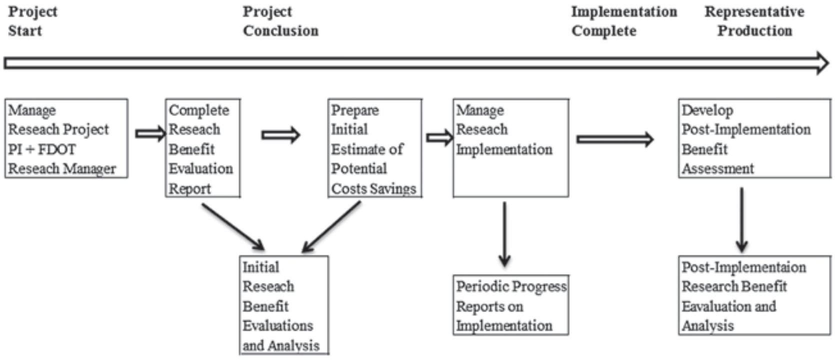

Figure 2. Research evaluation process proposed for the Florida Department of Transportation.
Source: Adapted from Southeast Transportation Consortium, 2014.

Table 1. Useful life estimates of research product categories (Adapted from Krugler).

Categories of research products (may be new approaches or improvements to existing ones)	Useful life estimate (number of responses)					
	<3 Years	3 to 6 Years	7 to 10 Years	11 to 15 Years	16 to 20 Years	>20 Years
Pavement design methods		1	5	3	3	2
Laboratory test methods		1	6	3	3	1
Field test methods for pavements	1	1	7	3	1	1
Standard Specifications		6	5	1	2	
Quality control/assurance methods	1	6	5	1		1
Construction inspection manuals	2	7				

Considering the emphasis of most publicly funded transportation research on solving problems, the practical nature of research products that are implemented and the long timeline needed to produce implementable research outputs that solve problems, it should not be surprising that evaluating benefits from research is a relatively low priority that remains an open field of study across all sectors (government, business and academia) worldwide.

Methods, measures and indicators

The term 'benefits' as used in this article comprises the impacts (both positive and negative) from research outputs. Methods and measures for evaluating benefits generally are categorised as quantitative and qualitative. Quantitative measures have a numerical value, e.g. savings in dollars, travel times or lives, which can be viewed as objective. Qualitative measures are descriptive indicators without implicit numerical value and hierarchy, although numbers are sometimes assigned for analytical purposes. These do, however, reflect more subjective assessment such as satisfaction and quality.

Evaluation approaches offer advantages and disadvantages (depending on project-specific circumstances) that present various trade-offs. For example, a clear correlation of research outputs to benefits can be identified in a case study but may be difficult to determine using econometrics. However, broader assessment by econometric modelling can be difficult to do in a case study (RAND Europe 2007). As mentioned above, selecting an appropriate method is context sensitive, reflecting specific needs such as determining whether a research approach should be terminated, whether results are within accepted quality standards and establishing whether there are direct economic benefits.

Descriptions about techniques to evaluate indirect benefits and larger scale economic impacts of a project on the economy such as job creation, development of knowledge and understanding, are described in the literature and are not repeated here. Rather, this article focuses on direct benefits of APT in terms of qualitative and quantitative techniques.

Qualitative and quantitative techniques

US Congress, OTA (1986)

Findings reported from the 1986 OTA study (US Congress, OTA 1986) identified a variety of approaches used in industry and government at that time, which are still relevant. Qualitative evaluation was dominated by peer review. Quantitative evaluation consisted of a wider set of methods and measures as summarised in Table 2.

National Academy of Science (1999)

Several of the same approaches identified in the OTA study are prominent in a 1999 study by the National Academy of Sciences Committee on Science, Engineering and Public Policy (COSEPUP). COSEPUP conducted studies and workshops with Federal agencies, the research community, industry, states and agencies in other countries (National Academy of Science 1999). The goal of this later effort was to identify and analyse the most effective ways in which to assess research results. The study identified advantages and disadvantages for each method. Like more recent studies, the COSEPUP findings suggest that a multi-faceted approach, which combines measures and indicators in a complementary manner, should enable analysis of outcomes and impacts from many types of research.

Table 2. Quantitative methods and measures to evaluate government and industry research funding (Adapted from OTA).

Category	Methods and measures
Retrospective	
Economic (measures output in terms of productivity or dollars)	• Macroeconomic (production function) • Investment analysis • Return on investment • Cost-benefit analysis • Rate of return • Consumer and producer surplus
Output (measures output in terms of published information)	• Bibliometrics • Publication count • Citations/co-citation analysis • Patent count and analysis • Science indicators (and others)
Prospective	
Project selection	• Economic models • Scoring models • Risk analysis and decision analysis • Portfolio analysis (constrained optimisation)

Transportation research board, NCHRP

Two years after the COSEPUP report, the Transportation Research Board's (TRB) National Cooperative Highway Research Program (NCHRP) Synthesis 300 reported on a review of approaches to measure the performance and effectiveness of transportation research and development (Sabol 2001, TRB Special Report 313 2014). Results were reported from a survey of US state DOTs that found 25 per cent used performance measures for projects after implementation. All measures relied on qualitative information, although respondents described them as quantitative. The report presents a synthesis from the literature and survey responses from state DOTs, private sector research programmes and academia.

Results from this NCHRP study showed substantial differences in the approaches to and concerns about assessing benefits of research in public, private and academic sectors. The study found that most state DOTs were not satisfied with their cost–benefit techniques and that many issues associated with establishing benefits would need to be resolved in order to provide useful and reliable information over a long-term assessment period. Quantifying benefits via cost–benefit analysis in the private sector was also problematic, but aided by higher quality and more extensive cost data as well as a more customer-driven business environment. Less quantification of benefits of research in the academic sector was attributed to greater concern about quality and productivity. The study reported that neither college faculty nor administrators frequently discuss cost–benefits of academic research activities.

NCHRP Synthesis 300 found quantitative assessment to be a much sought after priority but one that faced many challenges, including the need for better quality cost data, more clearly identified benefits and clearer links of research outputs to benefits. The study also found peer review to be the standard for qualitative assessment (Sabol 2001).

The synthesis also reported that state DOTs were not satisfied with their cost–benefit approaches, with the establishment of benefits being a main concern that must be resolved. Another high priority was the need for a measure of pay-off from implementation. The study found that existing measures of pay-off varied substantially and were neither rigorous nor robust. The report found a need for research to provide guidance on the use of cost–benefit analysis, that no existing method was clearly superior and that techniques of estimating benefits compatible with cost–benefit analysis should be emphasised.

Comparisons from published reviews

Several reviews of evaluation techniques have been published in the past two decades. Categories and findings from selected reviews (discussed below) are summarised in Table 3, which shows (with check marks) methods described in publications from Europe and the USA. The European publications, both by RAND Europe (an independent non-profit research institute), come mainly from literature reviews that include earlier US reports (RAND Europe 2007, 2009)

The summary in Table 3 leads to several observations including the following:

- Qualitative and quantitative techniques are both well represented;
- Many techniques are cited in at least two publications;
- The most common methods are cost–benefit/savings analyses, peer reviews and surveys;
- These common methods are used in transportation research as well as non-transportation research.

Evidently, a wide variety of methods are in use. The choice of approach is driven by the purpose and conditions of the study as well as time, resources and other constraints. Each technique offers advantages and disadvantages. It is evident from the different observations and insights provided from various methods why analysts face challenging trade-offs in choosing an approach that is best suited for evaluating benefits in a specific study. Advantages and disadvantages associated with various techniques are outlined in Table 4 (Arjanovic *et al.* 2009).

Tables 3 and 4 suggest that evaluations of research may be more representative if they combine qualitative and quantitative information. Some analysts suggest that relying on one indicator can mislead analysts and decision-makers (Ruegg and Jordan 2007). In addition to using more than one technique, some investigators have recommended using many sources of information as well as several separate investigators to evaluate benefits in a technique referred to as 'triangulation' (Arjanovic *et al.* 2009).

Approaches that enable characterisation of benefits using more than one measure have been evolving in recent years with the development of 'toolbox' or 'toolkit' frameworks, which consist of many measures and methods. Toolkits have been developed in the US and are in different stages of implementation for both transportation research (Krugler *et al.* 2006) and non-transportation federal research in energy at the Department of Energy (Ruegg and Jordan 2007), and technology development at the National Institute of Standards and Technology (NIST) (Powell 2006, Ruegg and Feller 2006). A European review (summarised in Table 3 under 'Europe') highlights the NIST toolkit and refers to it as 'one of the most influential reference works, practical aids and planning guides for practitioners of research evaluation' (Arjanovic *et al.* 2009). The NIST toolkit was developed from extensive evaluations of 45 NIST research projects between 1990 and 2000.

Table 3. Summary of evaluation techniques (References appear in parentheses).

	Transportation		Non-transportation	
	USA (FHWA)	USA (NCHRP)	Europe 2009 (RAND)	Europe 2007 (RAND)
Methods – qualitative:				
Peer and expert review	√		√	√
Survey	√	√		√
Case study – descriptive			√	
Training and education		√		
Tracing and logic modelling			√	√
Benchmarking				√
Sociometric analysis			√	
Methods – quantitative:				
Cost-benefit/savings analysis	√	√	√	√
Bibliometrics	√			√
Safety (less crashes/fatalities)		√		
Econometrics			√	
Outputs (products and reports)		√		
Performance	√	√		

Table 4. Advantages and disadvantages of various techniques (Adapted from Arjanovic).

Method	Brief description	Advantages	Limits
Survey	Asking multiple parties a uniform set of questions about activities, plans, relationships, accomplishments, value or other topics, which can be statistically analysed	• Provides an economical way to gather information about a programme and its participants that is not available through other sources • Accommodates the use of control and comparison groups or the collection of counterfactual information • Usually, diverse audiences can understand the approach and results	• Phone interviews work best when timeliness is important Mailed questionnaires often have low response rates • Does not provide the richness of individual project detail that stakeholders tend to find interesting • Responses are often subjective in nature and respondents may not be truthful
Case study – descriptive	Investigating in-depth a programme or project, technology or a facility, describing and explaining how and why developments of interest have occurred	• Many decision-makers read and process anecdotal cases more easily than quantitative studies • Provides richness of detail • Can be used to identify best practice experience	• The anecdotal evidence provided is generally considered less persuasive than quantitative evidence • The results of one or more individual cases may not apply to other cases • Can be difficult to aggregate findings
Case study – economic estimation	Adding to a descriptive case study quantification of economic effects, such as through cost–benefit analysis	• Focuses on ultimate outcomes and impacts rather than on outputs • Provides quantitative estimates of results • Uses financial methods	• The value of important benefits may not be estimated in monetary terms • Needs to be carried out a long time after the project has finished
Econometric and statistical analysis	Using tools of statistics, mathematical economics and econometrics to analyse functional relationships between economic and social phenomena and to forecast economic effects	• Produces quantitative results with detailed parameters • Demonstrates cause-and-effect relationships	• Difficult for non-specialists to understand, replicate and communicate • Not all the effects can be captured in these highly quantitative methods
Sociometric and social network analysis	Identifying and studying the structure of relationships by direct observation, survey and statistical analysis of secondary databases to increase understanding of social or organisational behaviour and related economic outcomes	• Focuses on the understanding of the process of innovation • Requires relatively modest inputs which can be obtained through survey, interview or existing databases	• Remains largely unfamiliar to most economists and programme stakeholders • Results may not be very informative on a programme's performance
Bibliometric analysis	Use data on numbers and authors of scientific publications and on articles and the citations therein (and in patents) to measure the output of individuals or research teams, institutions and countries, to identify national and international networks and to map the development of new (multidisciplinary) fields of science and technology	• Widely applicable to evaluation of programmes with an emphasis on publishing or patenting • Can address a variety of evaluation topics, including research output, collaborative relationships and patterns and intensity of knowledge dissemination • Diverse audiences can understand the results • Can be applied to a programme with a relatively short time-lag • High degree of credibility	• Treats only publications and patents as programme outputs and ignores other outputs and long-term outcomes • Time must pass before extensive
Historical tracing	Tracing forward from research to a future outcome or backward from an outcome to precursor contributing developments	• Produces interesting and credible studies documenting a chain of interrelated developments • Sheds light on process dynamics	• Chains of events tend to be highly complex with many organisations and researchers involved
Expert judgement	Using informed judgements to make assessments	• Provides a relatively quick, straightforward, feasible and widely-accepted approach to assessment • Offers the opportunity for an exchange of ideas which can lead to new perspectives	• Not much is known to the quality or accuracy of expert judgement as applied to R&D programme impact assessment

Transportation research

Federal research case study

In assessing the federal investment in infrastructure research and development from 2006 to 2009, TRB Special Report 295 (2008) observed that evaluations of past Federal Highway Administration (FHWA) research in materials and structures found substantial savings and extension of service life far in excess of the cost of the research. The observation is based largely on retrospective evaluations of benefits from FHWA-sponsored research.

The FHWA's 2003 report observed that estimating cost savings was '… the most demanding part of the assessment …'. However, those projects for which data were obtained resulted in very high agency, road user and safety cost savings. The report estimated costs savings at a national level that was more than 10 times the annual research funding (Federal Highway Administration [FHWA] 2003).

Under the theme of 'Performance Assessment', the TRB Special Report 313 (2014) it is recognised that in the USA, Europe and Asia-Pacific there is a general trend towards evidence-based decision-making and little evidence is publicly available on the requirements' impacts, whether positive, negative or neutral. Although there are tools used in prioritising research and development activities such as rate of ROI, cost–benefit analysis and bibliometrics (citation analysis, content analysis) it highlights the need for identifying the correct methods and measures used in setting research and development priorities, the time frames involved and to what extent performance assessment of prior investments influences decisions regarding future research investments.

NCHRP project 20-63B toolbox (NCHRP 2016)

A relatively recent addition to the toolkit approach is the NCHRP Project 20-63 toolbox, which is summarised in the column under the heading 'US' in Table 3. The main objectives of the NCHRP project were to define performance measures for transportation research projects and to assemble a useful and practical toolbox of performance measures (with examples) for use by state DOTs. After completing a literature review, surveys were conducted of state DOT staff and managers as well as federal and private sector research managers. Survey respondents rated their organisations' experience with each measure as well as the perceived value of each measure in their organisation. The study identified 30 performance measures to include in the toolbox. ROI or benefit-cost ratio (BCR) tied for third rank (tied with agency cost savings), just following behind lives saved and reduction in crashes.

The toolbox contains 30 performance measures automatically programmed in the Research Performance Measurement (RPM) software available for state DOTs. The RPM software allows users to import other performance measures, enabling customisation of the toolbox to meet a DOT's specific needs. The performance measures, most of which are quantitative, are categorised under five major headings as follows:

- Outputs – products, research reports published and graduate students.
- Outcomes – agency cost savings, lives saved and reduction in crashes.
- Stakeholders – customer satisfaction and input.
- Efficiency – BCR, percentages of projects on time, within budget, implemented, etc.
- Resource allocation – funding and contractor issues, quality of life and safety projects.

NCHRP Project 20-63 was completed in 2010 and was followed by Phase II (designated NCHRP 20-63B), which began in July 2010. Having developed and established electronically formatted tools for evaluating research as described above in the initial project, Phase II focused on enhancements and refinements in functionality of the system as well as ongoing maintenance of a website. The ultimate goal was to expand access to the system for routine use by state DOTs. Phase II is scheduled to be completed in 2016 (NCHRP 2016).

Southeast Transportation Consortium (2014)

A comprehensive literature review regarding the determination of the benefits of transportation research has been done through three fact-finding surveys in which 20 USA states as well as the FHWA and TRB participated (STC 2014). Different methods are used by transportation agencies depending on the transportation focus area such as safety, traffic congestion reduction, engineering design improvement, materials and pavements, increased service life, etc. No single method stands out as the preferred one, but in the case of materials and pavement, the value of research is measured through parameters such as pavement reduced construction, lower operations and maintenance costs. Table 5 summarises these methods along with areas of benefits for which these methods have been utilised to determine the value of research. It can be seen that BCA and benefit (monetary value) analysis are widely used methods to determine the value of research across all focus areas.

The Connecticut Academy of Science and Engineering (2013)

A report released by The Connecticut Academy of Science and Engineering (2013) analysed the economic impacts of transportation projects. Eighteen different analytical tools for analysing economic impacts of transportation investments were reviewed. Although this study is not directly aligned with the topic of measuring the success of transportation-related research, there are significant similarities in the report findings in comparison with the other previous studies investigated. Two types of interrelated analyses are suggested: those for estimating economic impacts (prospective analysis) and those for evaluating economic impacts (retrospective analysis). BCA is suggested for evaluating transportation investments because it captures the costs and most direct benefits of a transportation investment to the society at large. It concludes that typically only direct economic impacts of transportation investments are included in the BCA, while the indirect economic impacts are often ignored due to the difficulty

Table 5. Preferred benefit analysis methods for various focus areas in transportation (STC 2014).

Transportation focus area	Benefit analysis								Benefit ($) analysis	Benefit ($)/cost ($) analysis	Life cycle cost analysis
	Before and after study	Statistical analysis	Simulation analysis	Assumption based estimation	Field exp	Lab exp	Surveys	Benefit in other areas			
Safety	x	x	x	x	x				x	x	
Environment sustainability safety	x		x	x	x	x			x		
Improved productivity and work efficiency				x	x				x	x	
Traffic and congestion reduction	x		x		x				x	x	
Reduced construction operation and maintenance costs									x	x	x
Customer satisfaction					x		x			x	
Engineering design improvements		x	x					x	x		
Increased service life		x			x	x			x		x
Reduced user cost								x			
Reduced administrative cost										x	
Materials and pavements								x			

associated with measuring these and uncertainty associated with realising the impacts.

Conclusions and recommendations

The methods, measures and indicators discussed in this article show substantial variability in approaches used worldwide to evaluate benefits of research in- and outside of transportation research. No universal approach is recommended because there is no 'one size fits all' technique. Despite the recurring observation that no country appears to have a totally satisfactory technique, many approaches have been proposed, applied and reported. Developments during the past decade appear especially promising.

In the case of APT-related research, there are qualitative and quantitative, direct and indirect benefits. The growing global interest and awareness of efforts to quantify the economic benefits of APT research was the main theme at the 2008 International APT Conference in Madrid, Spain (Du Plessis and Prozzi 2008). Conference discussions explicitly associated technical activities with their relative costs and benefits, which are suitable for BCA. In the case of calculating cost savings (better pavement designs, construction processes and materials due to APT results), BCA is the ideal method to measure the impacts and benefits of APT-related research. The key component of this method is obviously market uptake and the acceptance of new technologies. Case studies are suggested to prove a concept and the real benefits can be measured only after implementation on a larger scale.

It is suggested that all measurable parameters mentioned in Table 3 should be captured during APT experiments. Retrospective analysis of both qualitative and quantitative benefits will only be possible if quality information was gathered and kept for each APT experiment including information on implementation projects. BCA and positive BCRs are powerful convincing tools to justify expensive research programmes (such as APT), while bibliometrics, number of PhDs, peer reviewed articles, patents, etc. highlight the importance of APT in academia and political circles.

The authors hope this article encourages further developments in a balanced approach that provides practical improvements, e.g. the use of evaluation methods for retrospective assessment as well as for prospective analysis to aid in research project selection when setting an APT research programme portfolio and in strategic planning for APT. The ultimate goal is to help better understand, demonstrate and communicate the benefits of APT.

Acknowledgements

This work was supported by California Department of Transportation (Caltrans), in particular, the Caltrans Library for assistance in acquiring references and Mr. W.A. Nokes from Caltrans Division of Research, Innovation and Systems for his input, guidance and support

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14. APPENDIX E: Co-authors’ Statements

>>> John Harvey <jtharvey@ucdavis.edu> 20/04/2016 05:29 >>>

I as co-author of the TRR journal article "Case Study for Evaluating Benefits of Pavement Research: Final Results" published in the Journal of the Transportation Research Board in 2014. give permission that Louw du Plessis may use the article to count towards credits for his PhD registered at the the North-West University, South Africa.

I am the Principle Investigator of the Partnered Pavement Research Program (PPRC) at the University of California in Davis and the research done by Louw was under my supervision. My role in the article was purely technical review and I assisted Louw in given direction

since the inception of the study in 2006 until the final completion of the TRB article in 2014.
EB Lee was a co-author of another journal article: "Economic Benefits Assessment of Accelerated Pavement Testing Research in California: Case Study" published in Journal of the Transportation Research Board in 2001. EB Lee was a post doc researcher working for the PPRC under my supervision and left the PPRC two years ago. EB Lee's role in the paper was limited to using the CA4PRS software to determine road-user costs in the rehabilitation of the I-710 as detailed in the Case Study.

Regards,
Professor John Harvey
Principal Investigator of the Partnered Pavement Research Programme
University of California, Davis

>>> "Nokes, Bill A@DOT" <bill.nokes@dot.ca.gov> 20/04/2016 21:25 >>>

TO: North-West University, South Africa
FROM: William Nokes, P.E., ENVI.SP.

SUBJECT: Publications In Support of Registering Ph.D. for Mr. Louw du Plessis

Dear Sir or Madam –

My name is William Nokes. I am employed as a Senior Transportation Engineer in the Division of Research, Innovation and System Information (DRISI) at the California Department of Transportation (Caltrans). This email provides a written statement on behalf of myself and other Caltrans employees who appear as co-authors on selected publications pertaining to pursuit of a Ph.D. by Mr. Louw du Plessis. In addition to myself, the other Caltrans employees who are co-authors are listed below.

- Mr. Nick Burmas, M.S., P.E., Chief, Office of Materials and Infrastructure (OMI), DRISI (Nick.Burmas@dot.ca.gov)

- T. Joseph Holland, Ph.D., P.E., Senior Transportation Engineer, OMI, DRISI, Contract Manager for the Caltrans / Partnered Pavement Research Program (PPRC) Contract (T.Joe.Holland@dot.ca.gov)

- Mahmoud Mahdavi, Ph.D., (Retired) Chief Economist, Caltrans Division of Transportation Planning, Economic Analysis Branch

As Caltrans' Chief Economist, Dr. Mahdavi provided some technical guidance, input, and recommendations on some of the initial work (e.g. regarding calculation of the value of benefits using benefit-cost analysis techniques) before he retired from Caltrans about 2011. Dr. Mahdavi was not involved in writing the pertinence papers, he reviewed and comments on early papers and was consulted on various occasions to ensure that the work was following acceptable methods in benefit-cost analysis and standard practice in life-cycle cost analysis. The work performed by Mr. du Plessis was funded by Caltrans through the PPRC contract, for which Dr. Holland is the Contract Manager. Mr. Burmas is the Office Chief who guides, oversees, and facilitates meeting the requirements of the PPRC as it meets Caltrans' needs and objectives. My role was varied, ranging widely from the inception of the work through publications of results, some of which are listed as pertinent publications below.
The publications pertinent to Mr. du Plessis' Ph.D. are understood to be those listed here.

1) *Evaluating the Benefits of Accelerated Pavement Testing: Techniques and Case Studies*, published in the journal of the Transportation Research Board (Transportation Research Record 2225, 2011)
2) *Economic Benefits Assessment of Accelerated Pavement Testing Research in California: Case Study*, published in the journal of the Transportation Research Board (Transportation Research Record 2225, 2011)
3) *Case Study for Evaluating Benefits of Pavement Research: Final Results*, published in the journal of the Transportation Research Board (Transportation Research Record 2367, 2014)

This email collectively, for the above named Caltrans employees—myself included—(except for Dr. Mahdavi), grants permission for the use of the stated purpose in support of the subject Ph.D. requirements at the North-West University, South Africa, for Mr. Louw du Plessis. The exclusion of speaking on behalf of Dr. Mahdavi is necessitated by the inability to contact him since his retirement from Caltrans nearly five years ago (in late 2011 or early 2012) and his intent to pursue other activities unrelated to and having no interest (as he stated to me before his retirement) in his prior employment at Caltrans.

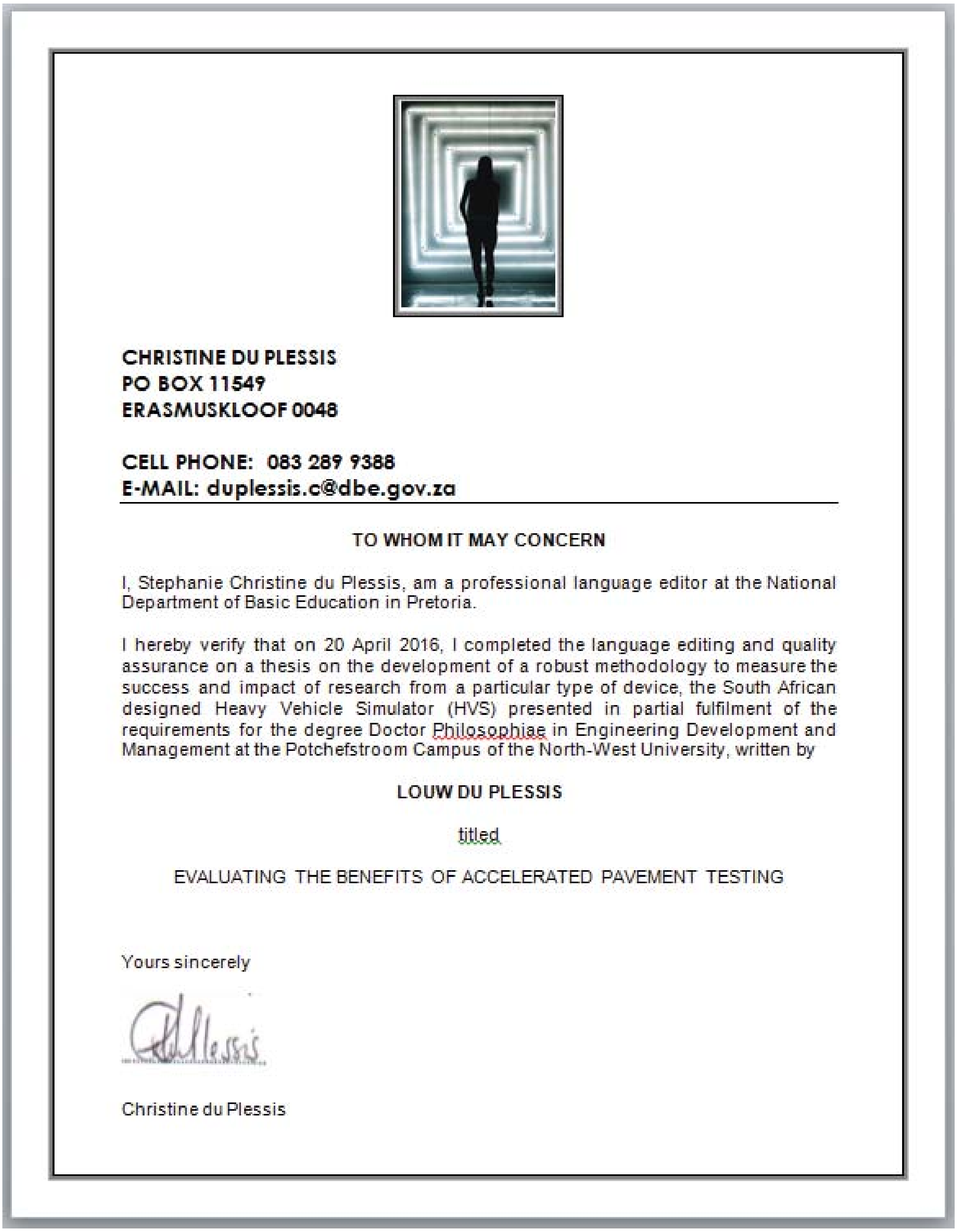
Thank you for considering this attestation and granting of permission on behalf of the Caltrans employees, as listed above in this email, in your determining the registering of the Ph.D. to Mr. du Plessis. Please contact me if you have further inquiries.

Sincerely,

William Nokes, P.E., ENV.SP.
Senior Transportation Engineer

Caltrans - Division of Research, Innovation and System Information
Office of Materials and Infrastructure / www.dot.ca.gov/newtech

15. APPENDIX F: Proof of Language Editing Verification



CHRISTINE DU PLESSIS
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CELL PHONE: 083 289 9388
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TO WHOM IT MAY CONCERN

I, Stephanie Christine du Plessis, am a professional language editor at the National Department of Basic Education in Pretoria.

I hereby verify that on 20 April 2016, I completed the language editing and quality assurance on a thesis on the development of a robust methodology to measure the success and impact of research from a particular type of device, the South African designed Heavy Vehicle Simulator (HVS) presented in partial fulfilment of the requirements for the degree Doctor Philosophiae in Engineering Development and Management at the Potchefstroom Campus of the North-West University, written by

LOUW DU PLESSIS

titled

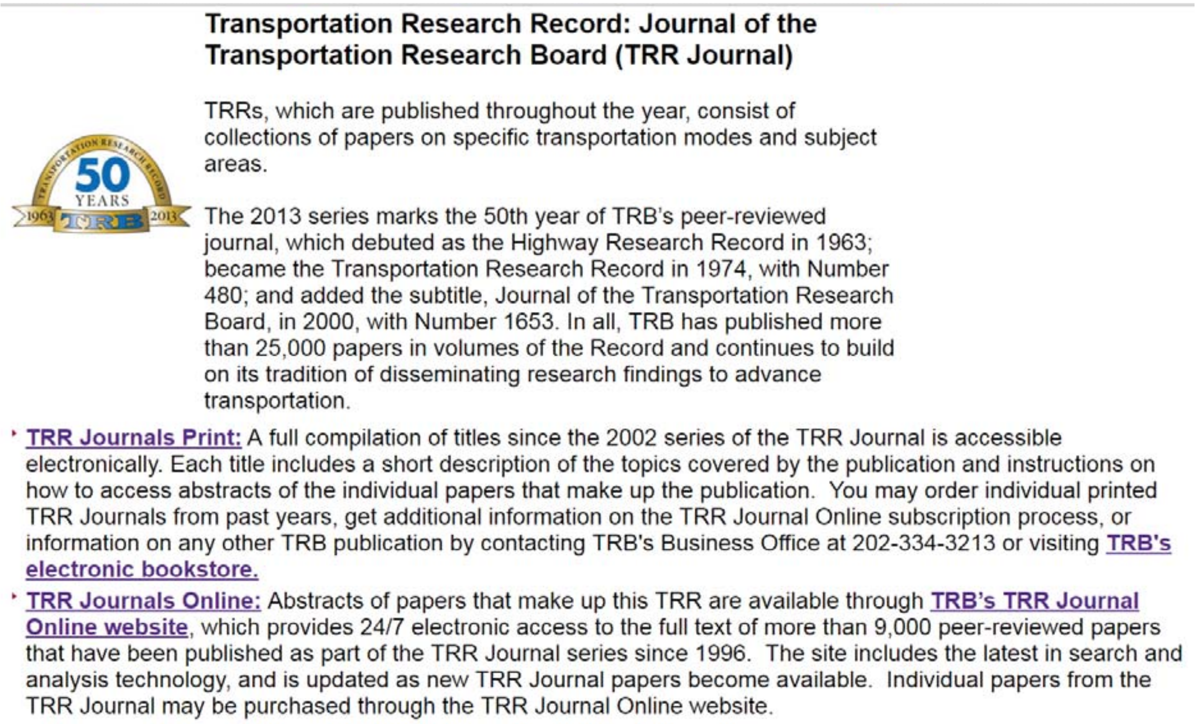
EVALUATING THE BENEFITS OF ACCELERATED PAVEMENT TESTING

Yours sincerely

Christine du Plessis

16. APPENDIX G: Information and Guidelines - Journals Concerned

1) Transportation Research Record Journal



Transportation Research Record: Journal of the Transportation Research Board (TRR Journal)

TRRs, which are published throughout the year, consist of collections of papers on specific transportation modes and subject areas.

The 2013 series marks the 50th year of TRB's peer-reviewed journal, which debuted as the Highway Research Record in 1963; became the Transportation Research Record in 1974, with Number 480; and added the subtitle, Journal of the Transportation Research Board, in 2000, with Number 1653. In all, TRB has published more than 25,000 papers in volumes of the Record and continues to build on its tradition of disseminating research findings to advance transportation.

- **TRR Journals Print:** A full compilation of titles since the 2002 series of the TRR Journal is accessible electronically. Each title includes a short description of the topics covered by the publication and instructions on how to access abstracts of the individual papers that make up the publication. You may order individual printed TRR Journals from past years, get additional information on the TRR Journal Online subscription process, or information on any other TRB publication by contacting TRB's Business Office at 202-334-3213 or visiting **TRB's electronic bookstore.**
- **TRR Journals Online:** Abstracts of papers that make up this TRR are available through **TRB's TRR Journal Online website**, which provides 24/7 electronic access to the full text of more than 9,000 peer-reviewed papers that have been published as part of the TRR Journal series since 1996. The site includes the latest in search and analysis technology, and is updated as new TRR Journal papers become available. Individual papers from the TRR Journal may be purchased through the TRR Journal Online website.

Transportation Research Record: Journal of the Transportation Research Board

Transportation Research Record: Journal of the Transportation Research Board is one of the most cited and prolific transportation journals in the world, offering unparalleled depth and breadth in the coverage of transportation-related topics. TRR Journal publishes approximately 70 issues annually of outstanding, peer-reviewed papers presenting research findings in policy, planning, administration, economics and financing, operations, construction, design, maintenance, safety, and more, for all modes of transportation. This site provides electronic access to a full compilation of papers since the 1996 series.

TRR Journal can be found at:

http://trrjournalonline.trb.org/

Author Guidelines can be found at:

http://onlinepubs.trb.org/onlinepubs/AM/InfoForAuthors.pdf

2) The International Journal of Pavement Engineering

Aims and scope of the International Journal of Pavement Engineering

Pavement Engineering is important for facilitating national and international movement of people, services, and goods. Building and preserving efficient, reliable, and sustainable highway and airport pavement systems is crucial for economic and social development.

The International Journal of Pavement Engineering is dedicated to the publication of cutting edge research and development in such important types of structures and facilities, including advanced analytical and computational techniques and pavement mechanics; material characterization and innovative laboratory testing techniques, non-destructive testing and evaluation; novel design approaches and their implementation; construction techniques and strategies; rehabilitation, preservation, and maintenance strategies and approaches; bound and unbound pavement performance; pavement life cycle assessment and life cycle cost analysis; pavement management systems. The Journal publishes the latest research findings from all over the world as well as case studies. Hence, one of the journal aims is to bring together and disseminate results of advanced research and its implementation across the world. Occasionally, the journal publishes state of the art reviews on pavement engineering aiming to transfer advanced pavement understanding to the international user community as well as special issues focusing on subjects of importance and interest to the pavement community.

All published research articles in this journal have undergone rigorous triple blind peer review, based on initial editor screening and anonymous refereeing by independent expert referees.

International Journal of Pavement Engineering can be found at**:**

http://www.tandfonline.com/toc/gpav20/current

Author Guidelines can be found at:

http://www.tandfonline.com/action/authorSubmission?journalCode=GPAV&page=instructions#.VxkjT_l95ph

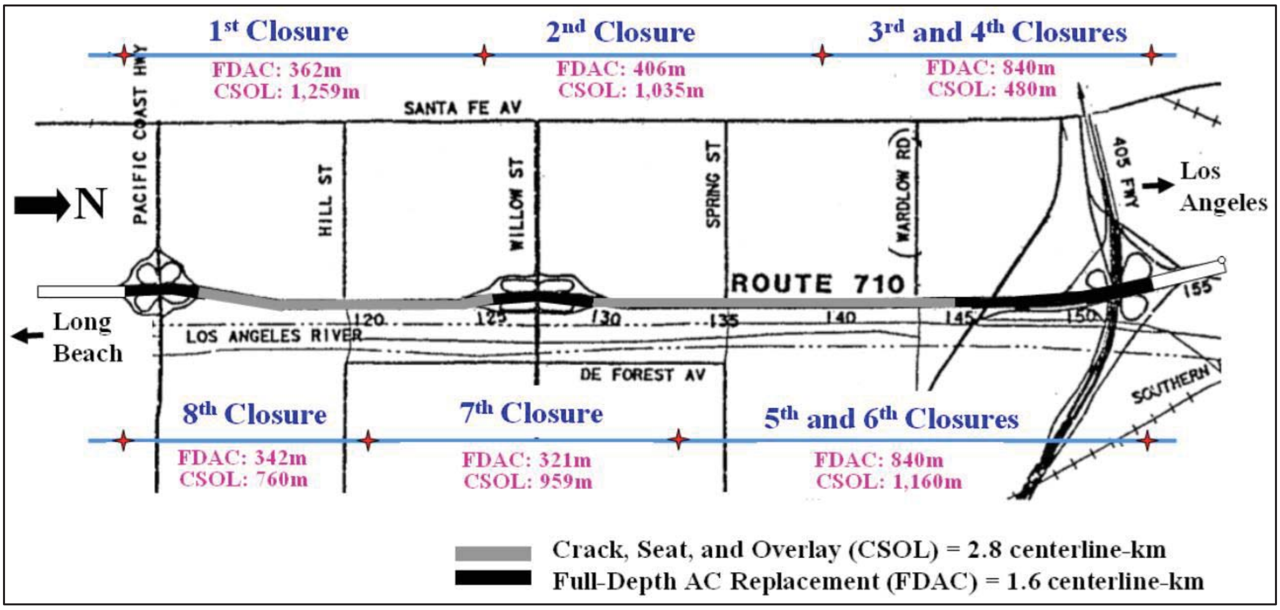
17. APPENDIX H: Supplementary information

The ALF APT device in Australia

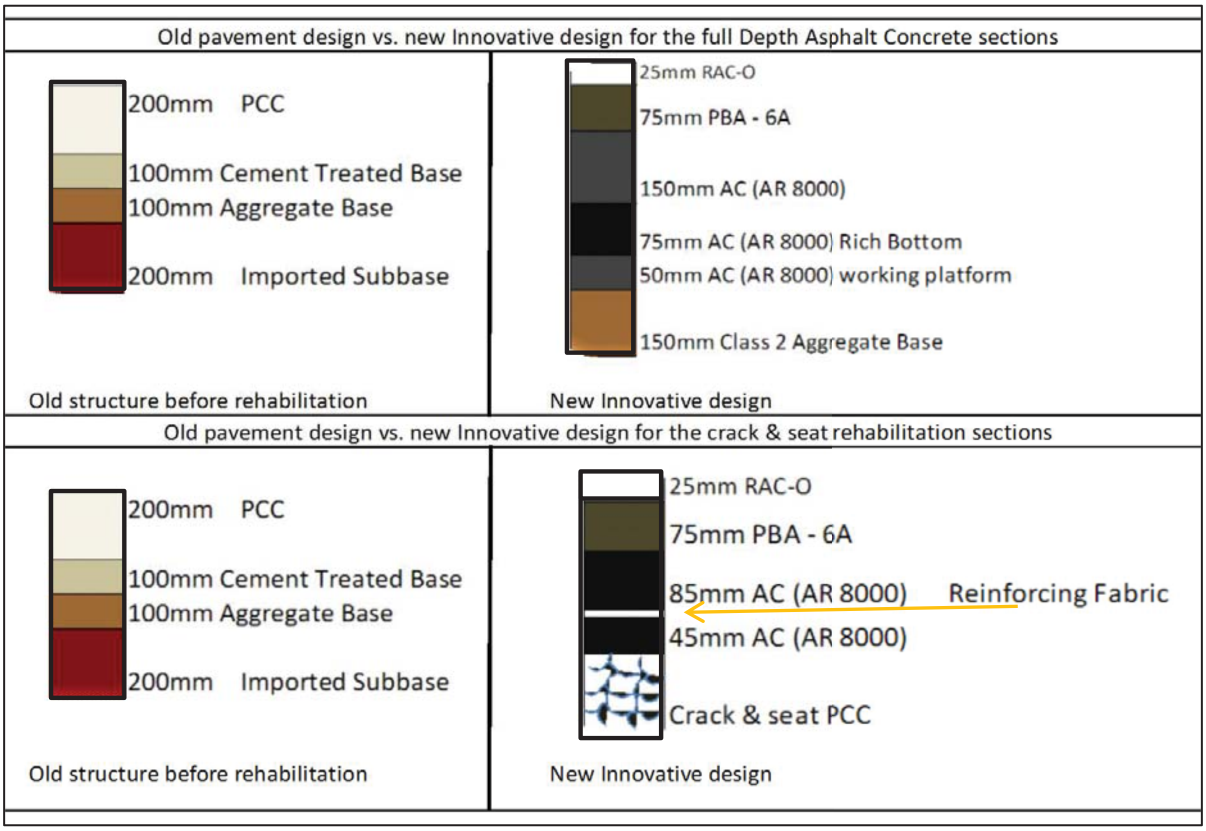
The 2 HVS models in South Africa

The two HVS units used in Berkeley, California for the evaluation of the I-710 innovative pavement designs

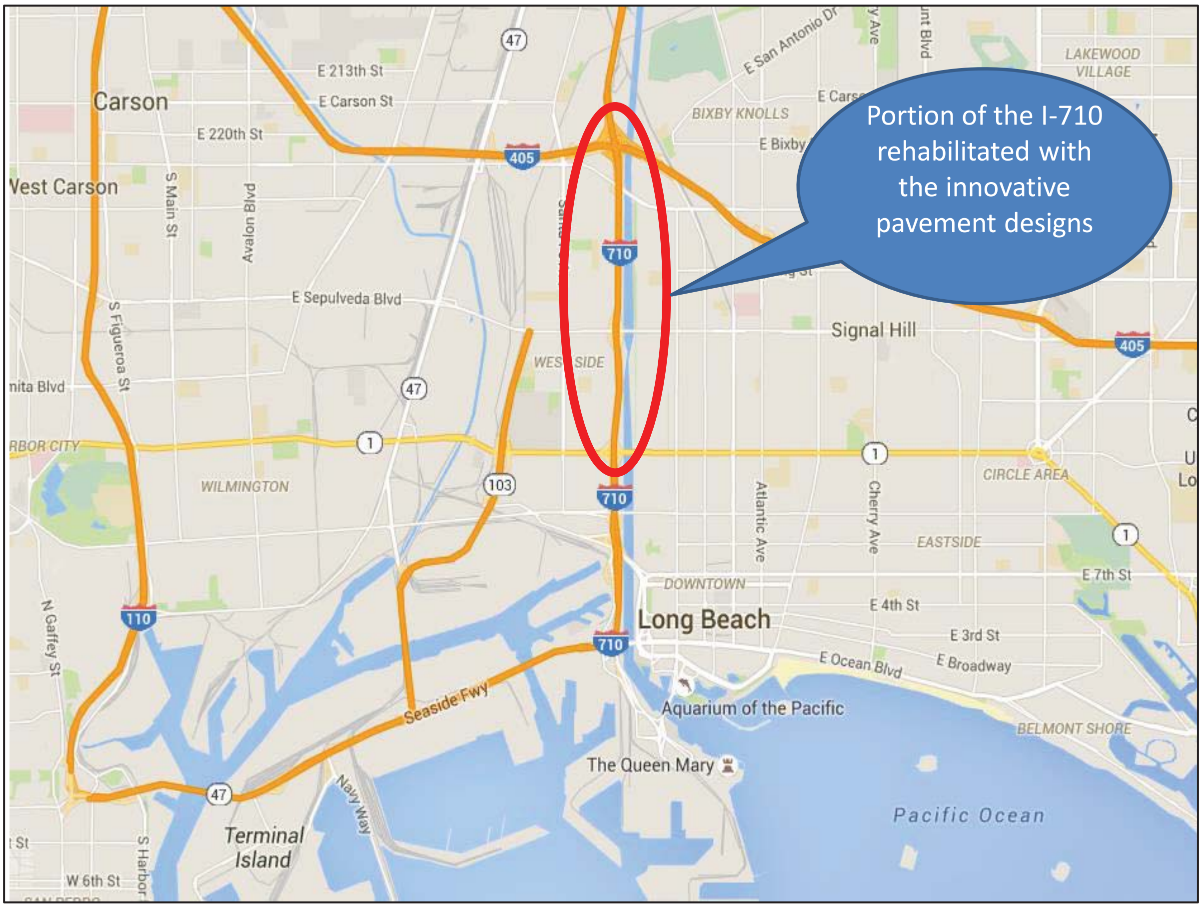
The I-710 rehabilitation construction during a 55-hour weekend closure



The project at the I-710 where two different pavement designs were required in between and under the bridges (overcrossings)



The difference pavement designs used in between and under bridges (overcrossings) during the rehabilitation of the I-710



Portion of the I-710 between Pacific Coast Highway 1 and Interstate 405 which was rehabilitated