

Cost Benefit Analysis of the California HVS Program

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ABSTRACT

The University of California, through the UC Pavement Research Centre (UC-PRC) located at Davis and Berkeley, started conducting Accelerated Pavement Testing (APT) research in 1994. This research is conducted for the California Department of Transportation (Caltrans), which purchased two Heavy Vehicle Simulators (HVS) in 1994. Since then a significant amount of APT-related research has been completed. As part of good business practice, and for continuous improvement of this research program, there is a need to identify, analyze and quantify the direct and indirect benefits obtained from HVS testing. This paper provides an historical overview of previous benefit assessment investigations. Furthermore it highlights the findings of a pilot study aimed at defining an appropriate method of measuring the impact of and the benefits to be gained from HVS testing by the UC-PRC. This approach has also been tested through the evaluation of a recent HVS study in California. The pilot study included qualitative and quantitative analyses of the benefits of HVS testing, together with an evaluation of the calculated benefit/cost ratio.

Keywords: cost benefit analysis, APT benefits, impact measurement, HVS benefits

Conference topic selected: 3.) Implementation of APT findings / 4.) Economic impacts

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INTRODUCTION

The California Department of Transportation (Caltrans) became interested in Accelerated Pavement Testing (APT) in 1989 and, after evaluation of the South African Heavy Vehicle Simulator (HVS), decided in 1993 to purchase two HVSs from the Council for Scientific and Industrial Research (CSIR) in South Africa. At the same time, Caltrans decided to complement its HVS testing program with a laboratory research program using some Strategic Highway Research Program (SHRP) equipment. An extensive laboratory testing program involving the laboratories and other resources of the University of California (UC) at both Davis and Berkeley complemented the full-scale accelerated pavement testing program (1). In 2003 the research program developed into the UC Pavement Research Center (UC-PRC), a partnership between UC Davis, UC Berkeley, Dynatest Inc., and the CSIR.

Over the past 12 years significant technical break-throughs have been made in the PRC program. However, the following questions remain:

- What is the potential impact of the research results?
- How much implementation has taken place?
- What are the practical benefits obtained from the research program?

The aim of this pilot study is to answer some of these questions through the benefit/cost evaluation of HVS studies done in California over the last 12 years.

Previous Assessments of Impacts from HVS Testing

In 1992 Horak *et al.* (2) reported on an investigation of the benefits obtained from HVS testing in South Africa. They gave a comprehensive list of specific technical impacts from the HVS program at the time. These included the improved use of new and innovative construction materials and methods, improved design and analysis procedures, as well as on the results of specific rehabilitation investigations. Their analysis found an overall benefit/cost ratio (BCR) of 12.8. Horak *et al.* (2) state 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 subjectivity in determining benefits (though conservative) and the lack of benchmarking through expert peer review make the 1992 study difficult to update. However, the method used in the current pilot study for Caltrans builds on previous experience and recommendations.

Rust *et al.* (3) reported on the HVS program in South Africa during the period 1978 to 1998. Focusing on work undertaken with the HVS from its commissioning in 1978 to 1998, their report describes the background and purpose of HVS projects, identifies the most significant findings and

highlights the impact of the program both on technological advances in pavement engineering and on perceived cost savings to industry. The purpose of their report was not to measure the impact of the benefits quantitatively, but rather to provide a perspective on the work, as well as a basis on which future HVS work could be assessed.

These approaches, i.e. calculation of direct benefits and identification of indirect impacts, are complementary. For example, Rust *et al.* (3) identified the following as positive, indirect impacts:

- instrumentation developments;
- materials-based developments, such as the development of Large Aggregate Mix Bases (LAMBs), Granular Emulsion Mixes (GEMs) and porous asphalt (open-graded asphalt mixes with 25% voids or more);
- improvements in material testing methods and pavement design specifications, such as the South African pavement structural design method and catalogue;
- enhancement of pavement management systems procedures derived from the HVS program, e.g. the adoption of visual cracking as a trigger for resealing, in contrast with practice elsewhere where changes in deflection are used for triggering such action for the thicker asphalt bases, and
- Characterization of tire/pavement interface stresses and characterization of fundamental road material properties.

The overall benefit of the HVS program in South Africa was assessed by Rust, Mahoney and Sorenson (4). Their paper compares *inter alia* the costs of pavement designs in South Africa with those commonly used in California and Washington State. Their findings are summarized in Figure 1.

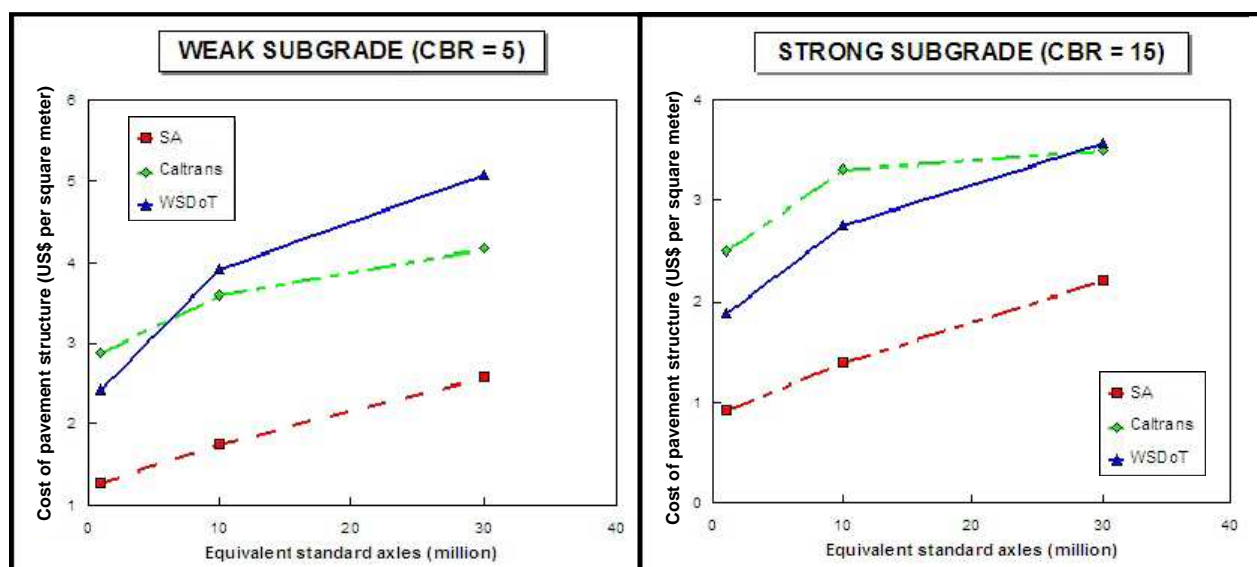


Figure 1: Cost of Comparative designs using a weak and strong subgrade

The pavement structure commonly used in South Africa and validated through many years of HVS testing in this country, consists of high quality granular bases supported by a cemented subbase and covered with a relatively thin asphalt wearing course. As indicated in Figure 1, the South African design philosophy yield more cost-effective designs than those utilizing relatively thick asphalt layers on weaker granular layers. It is evident that, if pavements could be constructed with these materials cost-effectively in the USA, significant initial cost savings could be effected. The saving on initial cost could be somewhere between 30 and 45 percent, depending on the traffic class and the quality of the subgrade support.

Rust, Mahoney and Sorensen (4) conclude that the lower relative cost of pavement structures found in South Africa can mainly be attributed to the results produced by the HVS program in its efforts to determine the most cost-effective design for a particular pavement type and traffic class.

Recent Efforts to assess Benefits from the South African HVS Program

In recent years Jooste and Sampson (5,6) calculated the benefit/cost ratio of the HVS work done in South Africa in order to develop a high-quality crushed aggregate base pavement design (G1 base). They followed a benefit/cost calculation methodology in which an alternative design was compared with the standard design. This methodology was largely based on work done by Rose and Bennet (7), who calculated Benefit/Cost Ratio (BCR) values for the evaluation of the Australian APT program and determined BCR values ranging from 3.8 to 4.9. The following steps show the methodology from Rose and Bennet as adapted and used by Jooste and Sampson:

- Select the standard design used at the time of investigation that would perform similarly to the alternative design (in this case the new G1 base);
- Compile a set of assumptions required for a benefit/cost analysis including analysis period, initial construction costs, routine maintenance costs, rehabilitation timing and costs, discount rate etc.;
- Conduct initial benefit/cost analyses based on these assumptions;
- Test the reasonableness and validity of the assumptions through a questionnaire and series of interviews with practitioners, and
- Rework the benefit/cost analysis if required.

In this study, the key impacts of HVS testing on the G1 base technology were identified as:

- The suitability of pavements with G1 bases for the 12 to 50 million ESALs design class was clearly proved;
- The feasibility of using pavements with G1 bases in wet regions was proved (provided an impervious surfacing could be maintained), and

- It was found that the damage exponent (or n-value) of pavements with a G1 base over a thick cemented subbase was close to 3, and not 4.2, as was commonly assumed.

It was also noted that HVS testing had other impacts, such as those relating to Science and Technology development, but that these could not be readily evaluated in economic terms. The overall benefit/cost ratio of research stemming from HVS testing was calculated as being between 2.4 and 10.2, depending on various factors and assumptions.

Jooste and Sampson conclude that their study does not take into account the additional downstream benefits and the impact of these benefits on the population at large. This means that the benefit assessment probably significantly underestimates the real benefit stemming from HVS testing on pavements with G1 bases. There are several other benefits resulting from this HVS program that could not be converted to economic savings, but which are sure to impact positively on South Africa's road network. These benefits include aspects such as:

- Calibration of the South African mechanistic design method;
- Technology transfer to engineers in practice thus raising their technical competence;
- Improved understanding of the systems behavior of granular base pavements, and particularly of the interaction between the granular base and cemented subbase, and
- Improved understanding of the behavior of cemented subbase layers under loading, which led to further research into the behavior and performance of cementitious pavement layers.

APPROACH FOR BENEFIT ASSESSMENT OF UC-PRC PROJECTS

In view of the above findings, it was decided that the approach Jooste and Sampson followed during the Gautrans HVS benefit/cost evaluation be used to evaluate the benefits of the UC HVS program. The approach and methodology are briefly summarized below.

It is difficult to evaluate the economic returns of R&D work. The economic benefit of a development can only be calculated if the outcome of a technology development effort can be compared with the scenario that would have existed had such development not been undertaken. Such an assessment necessarily includes a significant amount of uncertainty and subjective judgment. The methodology adopted for this study takes this uncertainty into account and is based on the framework established by Jooste and Sampson with some modifications. Key elements of the methodology are:

- The situation *with* and *without* the benefit of HVS testing is assessed;
- The uncertainty in assumptions and outcomes is accommodated by assigning a probability to outcomes;
- The cost of each outcome is calculated and adjusted by application of a probability factor;

- The benefit of the R&D project is determined by subtracting the total effective cost of all options *without* the benefit of HVS testing from the total effective cost of all options *with* the benefit of HVS testing , and
- The calculated benefit divided by the cost is then the benefit/cost ratio.

It is important to take into consideration the fact that benefits (e.g. a less expensive design) cannot be realized over the whole road network where it is applicable in the immediate period after development of the alternative technology. The potential benefit should be based on the required annual use of the road network as determined from annual construction and rehabilitation statistics.

Reductions in road user costs, other user benefits, and cost avoidance (such as the prevention of early failures) could significantly affect the benefit-cost calculation. However these were not included in the benefit calculations in this pilot study.

A key element of the assessment and validation effort is estimation of 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 an approach that took uncertainty into account and which had been successful in previous studies. An example of the approach (for HVS tests in South Africa on the G1 base) is shown in Figure 2 and comprises the following:

- The alternative scenarios (e.g. alternative bases such as concrete, asphalt, and G1 in this example) for situations with and without HVS test findings are identified;
- The uncertainty of each situation and alternative is accounted for by assigning a probability of implementation to each scenario (P_a , P_b , P_c , etc. in Figure 2);
- The life cycle cost of each alternative is calculated, and
- The effective cost of each alternative scenario is determined by multiplying the life cycle cost for each alternative by its assigned probability.

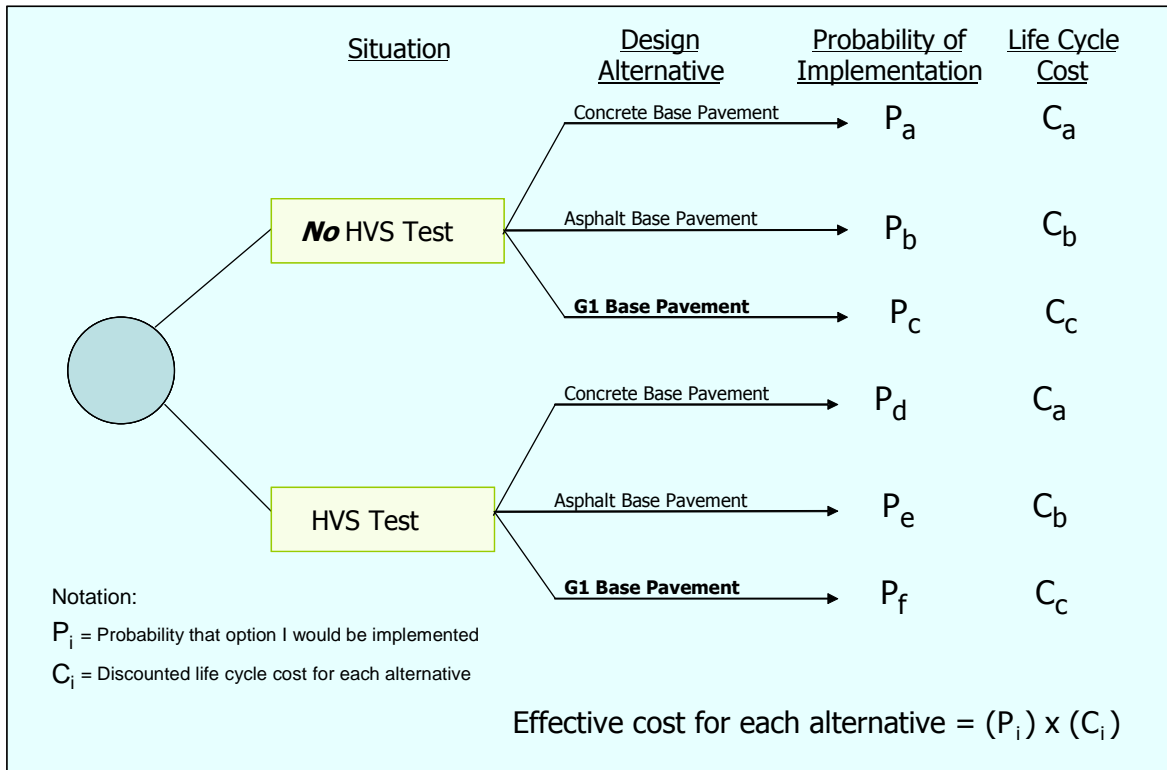


Figure 2: Approach for assessing benefits.

In the UC-PRC study, costs were calculated using the *RealCost* software (8), which is the standard tool used by Caltrans in performing life cycle cost analyses (LCCA) of transportation projects. *RealCost* is a manual and computer software program developed by the Federal Highway Administration (FHWA) in 2004 for the evaluation of the cost-effectiveness of alternative pavement designs (9). It was chosen by Caltrans as the official software for evaluating the cost-effectiveness of alternative pavement designs for new roadways, as well as for existing roadways requiring Capital Preventive Maintenance (CAPM), rehabilitation or reconstruction (8). LCCA is effective when competing project alternatives that produce equally-valued benefits are compared. The *RealCost* software and documentation provide a standardized method for consistent and objective determination of project costs.

In order to ensure accuracy and promote reasonableness and objectivity, the final step is to validate the alternatives, probabilities, costs, benefits and assumptions through formal interviews with technical experts, practitioners and stakeholders.

CASE STUDY

To demonstrate the potential suitability of the above-mentioned methodology for UC-PRC tests in California, a case study was conducted on a project involving an HVS test on flexible pavement as part of the Long-Life Pavement Rehabilitation Strategy (LLPRS) program begun by Caltrans in 1998. The project

selected is a rehabilitated section of Interstate 710 (I-710) in Long Beach close to Los Angeles, California (10,11). The project is briefly described and the potential benefits are presented and evaluated.

I-710 Long Beach Rehabilitation Project in California

In 2001, the LLPRS rehabilitation project started in Long Beach on the heavily-trafficked I-710. The 30-year design loading of the rehabilitated pavement is 200 million equivalent 80 kN standard axle loads (ESALs). At that time concerns were raised about using the Caltrans design methods for asphalt concrete (AC) pavements on a major freight and commuter corridor for such a long design life and heavy traffic level.

These circumstances provided an opportunity to implement findings and technologies proven through HVS testing:

- Crack and seat with asphalt concrete was used on most of the sections. Full-depth replacement sections were used under overpasses and served as a benchmark. Benefits were associated with better utilization and re-use of valuable road building material as well as with the improved pavement structural design.
- Because of heavy traffic (average daily traffic is 155,000 during weekdays, 13 percent of which are trucks), construction was done during a 55-hour weekend period. Benefits were defined in terms of improved constructability (12, 13).
- A “composite pavement” consisting of a rut-resistant, modified binder mix surface layer was built on top of a fatigue-resistant, “rich-bottom”, asphalt concrete layer. Benefits were associated with better quality materials that should extend pavement service life and reduce life cycle costs.

Benefit/cost Analysis

Utilizing the methodology recommended in the Life Cycle Cost Analysis Procedures Manual from Caltrans (April 2007) and the *RealCost* 2.2 (8) software, detailed benefit/cost analyses were conducted on the selected project. The benefit/cost analysis is performed in stages. Firstly the quantifiable benefit resulting from the use of a technology derived from HVS research by comparison with that resulting from standard practice needs to be determined. The second step is determination of the costs of developing the technology. Lastly the benefit/cost ratio is calculated. The steps are:

- Life Cycle Cost Analyses (LCCA) following the procedures in the Life Cycle Cost Analysis Procedures Manual) for the HVS-derived pavement designs developed for the I-710 rehabilitation project;

- Selection of a standard Caltrans pavement rehabilitation strategy (according to the Life Cycle Cost Analysis Procedures Manual) that would have been used instead of the HVS-derived design;
- LCCA of the standard Caltrans designs;
- Compare of the LCCA results from the HVS-derived designs with those of the standard Caltrans designs;
- Determination of the economic benefit of one design over the other;
- Determination of how many lane-miles of the complete network can potentially benefit through use of the more cost-effective design and application of the savings to this length of pavement;
- Comparison of the development cost of the alternative design with the total potential savings should this be implemented on the appropriate portion of the network, and
- Calculation of the benefit/cost ratio based on the total cost of developing the technology (with HVS testing) and the total potential savings.

The base year for all cost comparisons was selected as 2007, the year in which the LCCA manual was launched with the latest construction and rehabilitation costs. Since construction costs of the I-710 project were calculated and reported in May 2005, the Present Values (PVs) of these costs were adjusted to the 2007 base year using a 4 percent discount rate (as suggested in the Caltrans LCCA Procedures Manual).

A 2.73 mile stretch (total of 16.4 lane-miles) of I-710 was rehabilitated over eight 55-hour weekend closures. Construction began in February 2001 and was completed at the end of 2004. The total cost of the rehabilitation project was \$ 21,232,297.00 (14), resulting in a unit cost of \$ 1,400,295.88 per lane mile (2007 base year).

Assumptions

Performance of LCCA using the *RealCost* software requires several inputs. The general input parameters are listed in Table 1. Others are discussed in subsequent sections of this paper. The analysis period and discount rate recommendations in the Caltrans LCCA Procedures Manual were followed. As the I-710 rehabilitation was a long-life rehabilitation (LLPRS) option, an analysis period of 60 years was selected as it has a design life of greater than 25 years. Sensitivity analyses were performed with discount rates of three, four and five per cent.

For traffic data in the analysis, the 2005 vehicle count information was used and a 1.006 percent traffic growth rate was determined by comparing the Caltrans data for annual average daily traffic

(AADT) for 2000 with that for 2005. Other variables conform to suggestions made in the Caltrans LCCA Procedures Manual. All cost calculations are in terms of \$ per lane-mile of roadway.

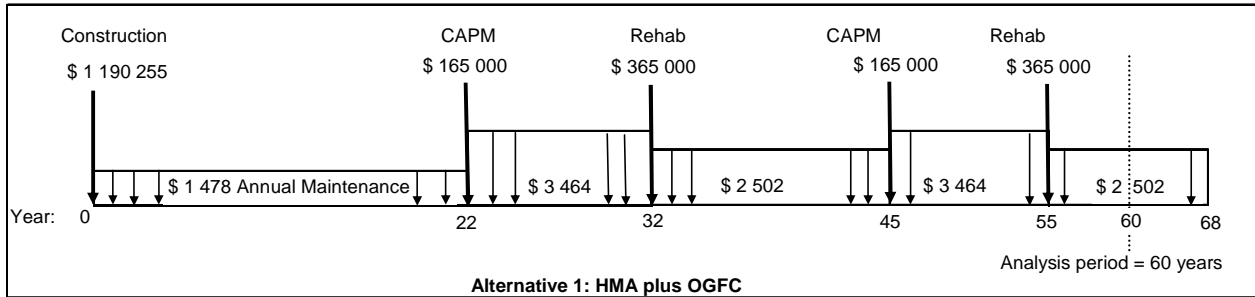
Table 1: Input variables required for LCCA

1. Economic Variables	
Value of Time for Passenger Cars (\$/hour)	\$10.46
Value of Time for Single Unit Trucks (\$/hour)	\$27.83
Value of Time for Combination Trucks (\$/hour)	\$27.83
2. Analysis Options	
Traffic Direction	Both
Analysis Period (Years)	60
Beginning of Analysis Period	2000
Discount Rate (%)	4.0
3. Project Details and Quantity Calculations	
Mileposts	
Begin	10.00
End	12.73
Length of Project (miles)	2.73
4. Traffic Data	
AADT Construction Year (total for both directions)	164 000
Cars as Percentage of AADT (%)	86.3
Single Unit Trucks as Percentage of AADT (%)	1.5
Combination Trucks as Percentage of AADT (%)	12.2
Annual Growth Rate of Traffic (%)	1.0060
Speed Limit Under Normal Operating Conditions (mph)	55
No of Lanes in Each Direction During Normal Conditions	3
Free Flow Capacity (vphpl)	2170
Rural or Urban Hourly Traffic Distribution	Urban
Queue Dissipation Capacity (vphpl)	1700
Maximum AADT (total for both directions)	275 000
Maximum Queue Length (miles)	5.0

Alternative 1: HMA and OGFC

The alternative 1 is a standard Hot Mix Asphalt concrete (HMA) base with an Open Graded Friction Course (OGFC). Using the suggested pavement maintenance and rehabilitation schedules for Caltrans (in the Caltrans LCCA Procedures Manual), a rehabilitation strategy for the Coastal region with a design life of 20 years was selected with a Class 1 Maintenance Service Level. According to Table F1-1 in the Caltrans LCCA Procedures Manual, the selected pavement structure will require maintenance interventions throughout its functional design life as shown in Table 2. All costs are expressed in terms of \$ per lane-mile (2007 base year).

Table 2: Rehabilitation strategy for a standard Caltrans design (Alternative 1)



Capital Maintenance (CAPM) and Roadway Rehabilitation consist of milling out the old Hot Mix Asphalt (HMA) layer and replacing it with a new HMA with an Open Graded Friction Course (OGFC). This scenario details the rehabilitation actions for up to 68 years after reconstruction but the analysis period was limited to 60 years.

The initial construction costs are assumed to be 85% of the construction costs of the I-710 project. All other costs are according to the Caltrans LCCA Procedures Manual.

For comparative purposes the lane closure strategy selected is the same as that used for the I-710 rehabilitation project. Construction work is only done during the 55-hour period from 10 p.m. on Fridays to 5 a.m. on Mondays, at least 2 lanes per direction being left open to traffic during these times. The speed limit in the work zone area is 40 mph and the initial Construction Road User cost was assumed to be \$ 100 000 for both rehabilitation strategies.

Alternative 2: FDAC and CSOL

The complete design of this alternative was reported by Monismith and Long (10, 11) and is summarized here. The project consisted of three full-depth asphalt concrete (FDAC) replacement sections (1.6 km total) under freeway overpasses and two sections (2.8 km total) with crack, seat, and overlay (CSOL) of existing PCC slabs with AC. The designs for the new pavement structure were developed using mechanistic-empirical procedures to accommodate 200 million ESALs over 30 years.

In the FDAC sections, the existing pavement was excavated to a depth of 625 mm and replaced with 150 mm of new aggregate base and 325 mm of asphalt concrete. This FDAC design resulted in the pavement surface being lowered by 150 mm in order to meet current interstate bridge clearance requirements. The FDAC design included a “rich bottom” layer with 0.5 percent additional binder to facilitate compaction to the required air-void content of approximately 3 percent (in comparison to the air-

void content of 6% of the upper AC layer) for increased stiffness and fatigue resistance of the critical bottom AC layer.

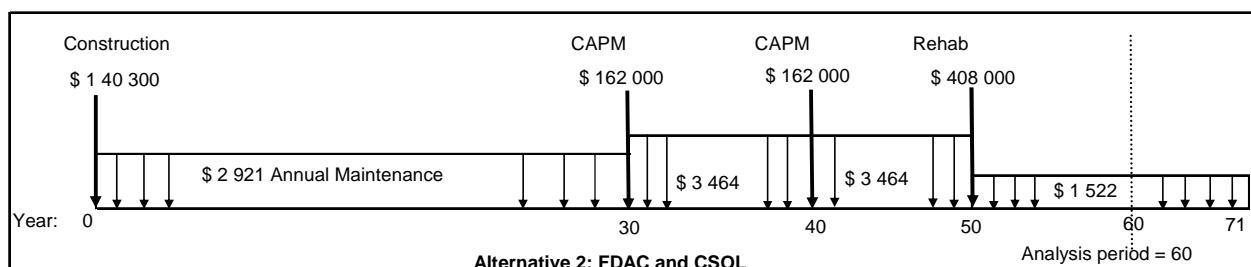
The results of the successful application of a “rich bottom” layer, together with a corresponding 3 percent decrease in air-void content to improve the fatigue resistance of a thick AC mix, are illustrated in this study (10,11). HVS testing was used to validate the use of a rich bottom layer, which increased AC fatigue life without reducing the rutting resistance of the surface mix.

The CSOL sections received a total of 230 mm AC overlay, including mixes with conventional AR-8000 and polymer-modified PBA-6a binders. The CSOL design included a pavement-reinforcing fabric to mitigate reflection cracking. After construction a 25-mm surface layer of open-graded rubberized asphalt concrete (RAC-O) was placed on the complete length of the section to reduce hydroplaning, tire spray and noise. HVS testing was again used to validate the benefits of using the suggested pavement structures.

The results of the I-710 pilot study illustrate the successful use of mechanistic-empirical concepts to develop a cost-effective pavement design. Calibration of the design method was done through extensive HVS testing to determine the fatigue and rutting performance of materials (conventional and modified binders) as well as innovative pavement designs.

The total construction cost for the complete project was \$ 1 400 300 per lane-mile (2007 base year). The following maintenance schedules and costs are detailed in Table 3 (as suggested by the Caltrans LCCA Analysis Procedures Manual) over the service life of the pavement. All costs are expressed in \$ per lane-mile, 2007 base year. As with the first alternative, the analysis period is 60 years although this rehabilitation strategy is programmed to last for 71 years.

Table 3: Rehabilitation strategy for the new alternative (Alternative 2)



Analysis of Benefits

Using the *RealCost* software, the Net Present Value (NPV) and the Equivalent Uniform Annual Cost (EUAC) were calculated for discount rates of 3, 4 and 5 percent for both agency and user costs.

The results for the various discount rates are presented in Tables 4 to 6.

Table 4: Cost calculations for a 3 percent discount rate

Total Cost				
Total Cost	Alternative 1: HMA & OGFC		Alternative 2: I710 Rehab	
	Agency Cost (\$1000)	User Cost (\$1000)	Agency Cost (\$1000)	User Cost (\$1000)
<i>Undiscounted Sum</i>	\$4 120.58	\$1 122.74	\$3 495.82	\$877.69
Present Value	\$2 167.43	\$446.92	\$2 095.12	\$361.02
EUAC	\$78.32	\$16.15	\$75.70	\$13.04
Lowest Present Value Agency Cost		Alternative 2: I710 Rehab		
Lowest Present Value User Cost		Alternative 2: I710 Rehab		

Table 5: Cost calculations for a 4 percent discount rate

Total Cost				
Total Cost	Alternative 1: HMA & OGFC		Alternative 2: I710 Rehab	
	Agency Cost (\$1000)	User Cost (\$1000)	Agency Cost (\$1000)	User Cost (\$1000)
<i>Undiscounted Sum</i>	\$5 518.18	\$1 603.55	\$4 517.07	\$1 242.54
Present Value	\$2 170.43	\$449.17	\$2 100.36	\$364.55
EUAC	\$95.94	\$19.85	\$92.84	\$16.11
Lowest Present Value Agency Cost		Alternative 2: I710 Rehab		
Lowest Present Value User Cost		Alternative 2: I710 Rehab		

Table 6: Cost calculations for a 5 percent discount rate

Total Cost				
Total Cost	Alternative 1: HMA & OGFC		Alternative 2: I710 Rehab	
	Agency Cost (\$1000)	User Cost (\$1000)	Agency Cost (\$1000)	User Cost (\$1000)
<i>Undiscounted Sum</i>	\$7 641.13	\$2 330.43	\$6 064.91	\$1 782.26
Present Value	\$2 173.50	\$451.78	\$2 105.39	\$367.84
EUAC	\$114.82	\$23.87	\$111.22	\$19.43
Lowest Present Value Agency Cost		Alternative 2: I710 Rehab		
Lowest Present Value User Cost		Alternative 2: I710 Rehab		

In all cases the NPVs of the I-710 rehabilitation strategy were lower than those of the traditional rehabilitation strategy. The cost savings are shown in Table 7. Based on the suggested 4% discount rate it

is clear that a total cost saving of \$ 70 070 per lane-mile would be possible if HVS-derived rehabilitation strategies (Alternative 2) are used.

Table 7: Cost savings in using the I-710 rehabilitation design in comparison with standard practice

Discount Rate (%)	Agency Costs (\$ 1000 per lane-mile)			User Costs (\$ 1000 per lane-mile)		
	Standard Rehab	I710 Rehab	Difference	Standard Rehab	I710 Rehab	Difference
3	2 167.430	2 095.120	72.310	446.916	361.024	85.892
4	2 170.430	2 100.360	70.070	449.174	364.552	84.621
5	2 173.500	2 105.390	68.110	451.783	367.843	83.940

The next step is determination of the extent to which this design could be applied over the network level. According to Gillen *et al.* (15), the total road condition in California can be summarized as follows:

Table 8: California road network condition summary

Area	Percent in Poor or Mediocre Condition	Percent in Fair Condition	Total Percent Not in Good Condition	Average Cost per Car Over Life of Car
California	13%	63%	75%	\$857
San Diego	11%	71%	82%	\$1,004
L.A. Area	13%	64%	78%	\$1,325
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 could benefit from the newly developed rehabilitation strategy. This strategy would apply mostly to coastal regions with a Traffic Indices of greater than 16 and where the design traffic is approximately 200 million ESALS. This suggests that approximately 8 330 lane-miles of flexible pavement could potentially be rehabilitated with a design similar to that developed for the I-710 project. The state of the network (in 2000 as reported by Gillen *et al.* and assumed to be representative for this pilot study) is as follows:

- 13% are in poor condition, and
- 63% are in a fair condition.

Another important factor in calculating benefits is the assumption that eventually the improved rehabilitation design strategy (such as that use on the I-710) would have been developed without the aid of the HVS program. However it would have taken considerably longer to evolve and implement. This means that, had the HVS testing not been performed, Caltrans or the road building industry would have

developed a similar, more cost-effective design at some future date. In order to account for this assumption, the period during which benefits will be calculated is limited to 10 years, at which time it is assumed that the technology would have been developed through means other than HVS testing.

If we assume that the portion of the network in a poor condition (13 %) will be rehabilitated at equally spaced intervals over the next 5 years, then the NPV of the benefit of using Alternative 2 can be calculated on the assumption that 13% of 8 330 lane-miles, (1 082.9 lane-miles) will be rehabilitated each year over the next 5 years (year 0 to 5). This implies that 216.6 lane-miles (one-fifth of the total) per annum will be rehabilitated. Based on a discount rate of 4%, the NPV (year 0) of this benefit is calculated as follows according to the following formula (8).

$$\begin{aligned} \text{NPV}(0) &= A \times ((1+i)^n - 1) / (i \times (1+i)^n) \\ &= 216.6 \times \$ 70\,070 \times ((1.04)^5 - 1) / (0.04 \times (1+0.04)^5) \\ &= \$ 67\,566\,028.71 \end{aligned}$$

Where:

A is the length of section to be rehabilitated multiplied by the cost saving;

i is the discount rate, and

n is the number of years.

After 5 years it can reasonably be argued that of the 63% (5 247.90 lane-miles) fraction that was in a fair condition (5 years ago), at least 25% (1 311.98 lane-miles) would need rehabilitation during the following 5 years (years 6 – 10). This means that the Alternative 2 can be used on 1 311.98 lane-miles (or 262 lane-miles per year) between years 6 and 10. Using the same methodology as above, the NPV (year 0) for this period is calculated as follows:

$$\begin{aligned} \text{NPV}(0) &= \text{NPV}(6) / (1+i)^n \\ \text{NPV}(0) &= [A \times ((1+i)^n - 1) / (i \times (1+i)^n)] / (1+i)^n \\ &= [262 \times \$ 70\,070 \times ((1.04)^5 - 1) / (0.04 \times (1+0.04)^5)] / (1.04^5) \\ &= \$ 67\,174\,514.45 \end{aligned}$$

The total potential net present value of the benefit using the HVS-derived technology thus amounts to a saving of \$ 134 740.54 (\$67 566 028.71 + \$ 67 174 514.45). As mentioned previously, it is assumed that the savings would be zero after 10 years, i.e. that the benefits of HVS testing would have been negated by then.

Finally, it should be borne in mind that the development of the cost-saving technology used in the I-710 project cannot be attributed solely to the use of the HVS. The HVS, however, was a key contributor to the refinement and delivery of the I-710 rehabilitation strategy. It would, therefore, be fair to assign a

contribution ratio in calculating the specific dollar saving from the contribution of the HVS tests towards the technology. The contribution attributed by the HVS is estimated as being between 50 % and 75 %, subject to validation through interviews.

The Net Present Value of the final potential cost saving realized over a period of 10 years range is, therefore, between \$ 62.20 and \$ 109.93 million, depending on the discount rate and on the contribution factor used (Table 9).

Analysis of Costs

In order to calculate the Benefit/Cost Ratio (BCR), the total costs of developing the technology have to be calculated and compared with the benefits. This is complex because the UC-PRC has devoted its research efforts to more than just the technologies developed for the I-710 rehabilitation. Certain reasonable assumptions are, therefore, required before an estimate can be made of the total development cost.

The UC-PRC operates two HVS machines and during the last 9 years (1998 – 2007) one of these has been used exclusively for rigid pavement studies and the other for flexible pavement studies for Caltrans, in line with the strategic objectives of the UC-PRC (1,16). As detailed in the strategic document, the main focus areas of the UC-PRC are:

- 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 development of UC-PRC program 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 contents of untreated base and subgrade materials using ground penetrating radar, and
- 7) Economic analysis demonstrating the potential benefits that might accrue with implementation of some of the initial results obtained from the asphalt pavement studies.

Studies for both flexible and rigid pavements include laboratory test programs, HVS tests and pavement analysis and design considerations. It is therefore not a trivial task to isolate the proportion of research that was dedicated to the I-710 rehabilitation study, as the I-710 rehabilitation strategy evolved

through research done across the areas mentioned above. Research done on the composite “rich-bottom” asphalt concrete concept used on the I-710 stems from work done from 1994 to 2000. The development of a California Mechanistic-Empirical (ME) design method, used for rehabilitation of the I-710, started in 1995 and is ongoing.

Because of extreme time, space and resource constraints, during rehabilitation of the I-710, many activities had to be performed concurrently. This required careful scheduling, logistical planning and resource management. A software program called CA4PRS (12, 13) was developed by the UC-PRC and was successfully used to plan the logistics and identify the critical path of the construction. The program helped to identify the maximum amount of work that was logistically feasible during the construction window (55-hour weekend closures). The program aided the contractor and contributed to the overall success of the project.

Utilization of the mix design and analysis systems developed during the Caltrans-sponsored APT program over the past 10 years has reduced the propensity for fatigue cracking and has generally resulted in improved pavement performance. Innovative pavement mix and structural designs used for the I-710 freeway rehabilitation project extend fatigue lives substantially beyond those produced by conventional designs.

In summary, innovations applied to the I-710 rehabilitation project stems mainly from research during a 5 year period from 2000 – 2004. The total research budget of the UC-PRC during that time amounted to \$ 5 million per year. The total amount invested in pavement research was, therefore \$ 25 m (PV = \$ 30.46 m at a 4% discount rate, 2007 base year). Given all the focus areas mentioned above and the fact that approximately half of the research budget went towards rigid pavement studies (utilizing the second HVS), it can conservatively be assumed that, at most, 60% of the research budget went directly and indirectly towards technologies implemented during the I-710 rehabilitation project. Using discount rates of 3, 4 and 5 per cent the total investment applied to the development of the I-710 rehabilitation strategy is shown in Table 9 (below). The contribution ratio of the funds that went into the development of the I-710 pavement technologies will be tested through interviews. It was anticipated that the acceptable range for this investment would be between 40 and 60 percent during the 5 years of UC-PRC pavement research.

Calculation of Benefit/Cost Ratio

The final step in the determination of the quantifiable benefits of the HVS project is the comparison of the total costs of the research with the benefits derived after implementation. Table 9 and Figure 3 show the results of the final calculations.

Table 9: Summary of benefits and costs from HVS research on I-710 project

Benefits				Costs				Benefit / Cost Ratio
	%	Discount rate	PV of benefits (\$)		%	Discount rate	PV of benefits (\$)	
Lower contribution ratio	50%	3%	73,285,984	Higher contribution ratio	60%	3%	17,404,308	4.2
		4%	67,370,272			4%	18,277,879	3.7
		5%	62,202,694			5%	19,189,827	3.2
Higher contribution ratio	75%	3%	109,928,976	Lower contribution ratio	40%	3%	11,602,872	9.5
		4%	101,055,407			4%	12,185,253	8.3
		5%	93,304,041			5%	12,793,218	7.3

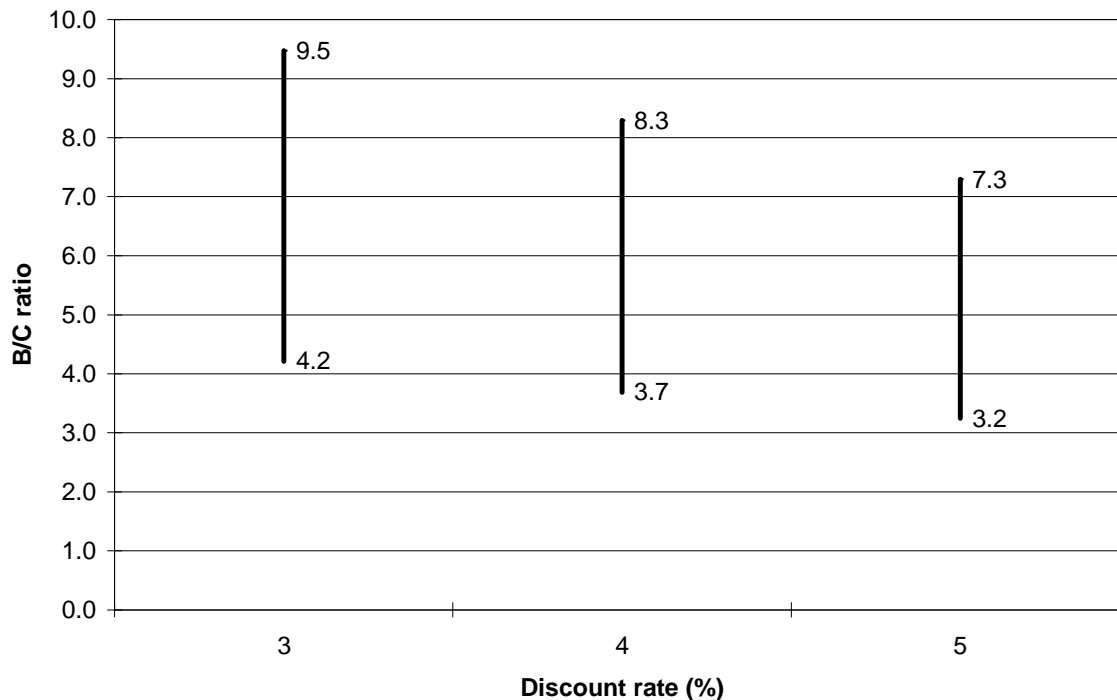


Figure 3: Summary of estimated Benefit/Cost (B/C) Ratio for the I-710 rehabilitation strategy

The data presented in Figure 3 prompt the following observations and conclusions:

- The overall BCR ranges from 3.2 to 9.5 depending on the contribution ratio and discount rate. At a nominal discount rate of 4 percent, the overall benefit/cost ratio ranges from 3.7 to 8.3, depending on the contribution ratio. These estimated BCR ranges are similar to those reported previously for accelerated pavement testing performed in Australia (BCR between 3.8 and 4.9) (7) and in South Africa (BCR between 2.4 and 10.2) (5,6).
- The estimated direct benefit derived from the results from the I-710 rehabilitation project is between \$ 62.20 and \$ 109.93 million (2007 base year), depending on the discount rate and contribution ratio selected.
- It should be noted that the lower bound of the BCR ranges shown in Figure 3 represents a total that consists of the sum of all the lowest estimated contribution ratios. Thus the minimum benefit/cost ratios shown in Figure 3 represent a highly conservative benefit estimate.

It is important to note that the benefits that were evaluated include only those aspects that could be converted to economic savings with reasonable confidence and assumptions. There are several other benefits resulting from the HVS investigations which cannot easily be converted to economic savings, but which are sure to impact positively on California's road network over the long term. These benefits include aspects such as:

1. The UC-PRC developed the CA4PRS software as a planning tool for LLPRS projects (12, 13). CA4PRS calculates the maximum length of highway pavement that can be rehabilitated or reconstructed under a given set of project constraints. CA4PRS was used to optimize construction and traffic management plans for the I-710 rehabilitation project. Optimal scheduling for traffic accommodation, user delay and construction time was calculated and successfully implemented during this project. It has been recommended that construction should not occur for more than three to five weekends in a row.

The traffic monitoring study revealed that no congestion occurred during the 55-hour weekend closures, thus maintaining free flow speed on the whole network during construction. The results clearly showed a significant traffic reduction through the construction work zone, increased traffic on neighboring freeways and detour re-routing to arterials during the weekend closures.

It is important to recall that in this calculation indirect benefits, such as reductions in user delay costs and accident costs (both during construction as well as due to reduction in future maintenance), were not taken into consideration in calculating the BCRs, thus resulting in very conservative estimates of the actual benefits.

2. The project proved that asphalt concrete is viable with respect to construction productivity when designed to meet long-life pavement rehabilitation design criteria, even on routes in the state with the greatest volumes of truck traffic.
3. It is anticipated that the rehabilitation scheme and lane closure tactics adopted for this project, (i.e., repeated 55-hour extended weekend lane closures with counter-flow traffic) will be utilized on future LLPRS projects on urban freeways in California. The results of this study will be useful for transportation agencies and contractors trying to maintain a balance between maximization of construction productivity and minimization of traffic delay in developing construction and traffic management plans for rehabilitation of highways with high traffic volumes.

Since none of the above impacts are included in the assessment of economic benefits, it will be appreciated that the BCR values noted above represent a lower bound estimate of the benefits of HVS research. The simple linear benefit assessment process that was followed in this study did not take into account further downstream benefits or the impact of these benefits on the user community, thus yielding a very conservative estimate of the BCR for the California HVS program.

CONCLUSIONS

The work reported from this pilot study shows conclusively that the method presented can be used successfully to calculate benefit/cost ratios (BCRs) as determined by the direct cost savings during construction and future maintenance, as well as the investment into the research program. The sensitivity analysis conducted yielded BCRs ranging from 3.2 to 9.5. These are however, very conservative because they do not take into account indirect benefits, savings in user delay costs and accident costs, and cost-avoidance. The range of BCRs calculated here corresponds well with those reported for APT research in South Africa and in Australia. In addition, there are a number of other qualitative benefits from HVS testing that are difficult to quantify, such as peripheral software development and the generation of new knowledge that can be applied elsewhere. The method applied in this pilot study is effective in identifying the implementation of results from HVS tests, identifying practical benefits, and quantitatively determining impacts of HVS research. It is therefore clear that Caltrans' investment in APT research with the HVS has been rewarding and well worthwhile.

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