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Assessing the Economic Benefits from the Implementation of New Pavement Construction Methods

Report Prepared for

CALIFORNIA DEPARTMENT OF TRANSPORTATION

by

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1.0 INTRODUCTION

The benefits of highway improvements, or the adverse consequences of neglect, affect not only those who travel the highways, but society in general. Benefits reach the users of the roads primarily through the savings on the operating costs of their vehicles, the reduction in highway accidents, and reduction in travel time, as well as other factors that cannot be quantified as easily, such as better air quality, comfort, and convenience. Non-users can also benefit with a reduction in accidents as well as environmental degradation.

From this point of view, any highway project should be considered an investment, the main objective of which is the highest social return at a given funding level.

While some would debate whether road conditions in general have improved during the past few years, the federal government has distributed more highway money to states to spend on repair and reconstruction. However, the most heavily traveled freeways and principal arterials—those in metropolitan areas—are still not in good shape. According to federal statistics (provided by the states), 57 percent of urban freeways and expressways were found to be in fair to poor condition.(*1*)

The failure to adequately maintain roads is costing drivers. Motorists pay both for road repair and for the damage caused to their cars by bad roads. Dittmar, 1998, estimated the costs of rough roads in terms of increased wear and tear, repair expenses, and decreased fuel economy, and found that poor roads cost American drivers an estimated $5.9 billion a year.(*1*) Rhode Island drivers pay the most, followed by California, Colorado, Maryland, and Illinois. Among metropolitan areas, drivers in the Los Angeles-Anaheim-Riverside area pay $1,325 over the life of their cars because of poor road conditions, second only to Detroit-Ann Arbor residents who pay $1,416. Motorists in the metropolitan areas of Chicago, Denver, and St. Louis follow these cities.

For overall road condition, the San Diego metropolitan area ranked fifth worst in the country with 82 percent of its roads in less than good condition. Other major metropolitan areas in California are not much better, as shown in Table 1:

Table 1 Condition of Roads in Major Metropolitan Areas of California.

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

Each year the California Department of Transportation (Caltrans) and municipal and county agencies in California spend multiple millions of dollars on the rehabilitation, maintenance and construction of roads. The vast majority of this money is spent on rehabilitation and maintenance. Caltrans operates a state highway network of more than 24,000 centerline kilometers, with over 78,000 lane-kilometers of pavements. In 1995, about 22,500 lane-kilometers, nearly 30 percent, required corrective maintenance or rehabilitation. Nearly 7,000 lane-kilometers required immediate attention to avoid rapid deterioration or loss of the facility. Pavement type is split 68 percent flexible and 32 percent rigid in terms of total lane-kilometers in the network, 52 percent flexible and 48 percent rigid in terms of rehabilitation needs, and 49 percent flexible and 51 percent rigid in terms of lane-kilometers requiring immediate attention. In 1998-99, it is estimated that Caltrans will spend approximately $393 million on road and bridge rehabilitation.(*2*) Over the period 1998 through 2004, this figure is expected to be approximately $3 Billion.

When the majority of the roadway system was built in California, the type of construction used was determined by engineering standards based on the expected level of traffic and the resources available for construction. The engineering standards were established in cooperation with the Army Corps of Engineers and the American Association of State Highway Officials (AASHO) through experimentation using equivalent single axle loads (ESALs) and pavement deterioration rates for pavements of different thickness. The concept of life cycle models had not yet been widely adopted, having been introduced in the early 1980s.

1.1 Use of the Life Cycle Model to Evaluate the Benefit of Better Roads

Currently, when Caltrans plans for road maintenance it is based on a life cycle model in which the agency has attempted to minimize the cost of the section of roadway being considered over the life of the roadway. In making this calculation there is the tradeoff between the level of initial investment or the level of intensity of the maintenance and the rate of deterioration from traffic and weather.[1] A stronger, better-built highway will initially cost more, but will deteriorate at a slower rate and hence require less maintenance for a given level of traffic. Maintenance and rehabilitation costs would be incurred in the future and their cost is discounted, thus the trade-off.

In calculating future maintenance cost, the agency would consider the materials and labor costs either directly to the agency or through contracts. What is not considered is the impact on traffic flows, public safety, and the environment. In other words, the impact on users is not considered as part of the cost equation. Yet, in fact, the optimization problem should be to minimize *the sum* of infrastructure, maintenance, and user costs. The first two components reflect the conventional life cycle cost model, however, consideration of user costs is new. What has been missing is the recognition that once user costs over the lifetime of the facility are taken into account, the standard to which a facility is built and the frequency of required repair and rehabilitation would change from that which it is currently.

The cost to users entails both the higher repair cost to vehicles because the facility is in need of repair and the fact that when a road is in need of repair or rehabilitation the facility or a portion of it must be closed, which can cause delays. These delays may result in more accidents and with the slower traffic the amount of air pollution could well rise.[2] By initially providing a more substantial road, (e.g., thicker pavement, better quality construction, or better quality materials), the life of the road will increase as will its ability to withstand higher numbers of ESALs. As a result, it will deteriorate as quickly and will therefore be less likely to have to be closed down for maintenance and rehabilitation. The savings to users will include lower vehicle repair costs and less cost in terms of lost time while pavement repair work takes place. The savings to the broader community will be potential reductions in environmental costs. There may also be net savings in maintenance and repair expenses. However, realizing these savings does not mean that the optimal thickness of roadway is several times the current standard. The opportunity cost of funds used in construction cannot be ignored, nor can the fact that diminishing returns set in at some point as pavement thickness is increased.[3]

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[1] A roadway that is under repair could be completely reconstructed or partially reconstructed or simply patched. The choice taken will determine the rate of repair needed in the future.

[2] There are two opposing forces here. As traffic slows there may be a greater probability of an accident since the variance in speeds may rise resulting in an increase in accidents however the average speed will fall resulting is less severe accidents. Which dominates is an empirical question.

[3] As pavement becomes thicker it can add considerably to the life of the roadway given the loads it is exposed to. However, at some point adding thickness adds successively less to the roadway life and the effects of the damage to the pavement caused by the environment (rain, temperature changes) that are not mitigated by extra thickness may predominate.

1.2 Use of New Pavement Technologies

Another way that an increase in roadway life can be achieved is through changes in technology of the materials or in the way the paving and preparation process takes place. Both may have a sizable impact on the lifetime costs of a facility or segment of it. The use of ‘new pavement technologies’ may not only reduce user costs, but may also have real resource savings for the transportation agency. New paving techniques primarily represent new ways of paving rather than simply adding thickness to pavement designs. The new pavement technology alternatives evaluated in this report are for asphalt concrete pavements and include increasing asphalt concrete compaction, using tack coats, and introducing a fatigue resistant asphalt concrete layer, known as a “rich bottom layer,” into the construction.

Caltrans has begun a program to reduce the lane-kilometers requiring immediate attention, corrective maintenance, or rehabilitation. This program includes increased spending over the next ten years. Improvements can be made in the pavement technology that Caltrans uses for maintenance, rehabilitation, and reconstruction programs that will increase pavement performance. Better pavement performance should reduce future maintenance, rehabilitation, and reconstruction costs and should result in decreased total life cycle costs.

Since soon after its inception in 1994, the Caltrans Accelerated Pavement Testing Program (CAL/APT) has been producing research results and making recommendations for changes in Caltrans pavement technology that will improve flexible pavement performance. In many cases the ‘new pavement technology’ represents a change in the *process of application* rather than a significant investment in new equipment or new materials.

The objective of this study is to evaluate the economic benefits of implementation by Caltrans of three changes in flexible pavement technology recommended by CAL/APT.
The recommended changes are as follows:

1. Increase compaction requirements for asphalt concrete. As part of this recommendation, this study also recommends that Caltrans change the basis for measurement of compaction from the Laboratory Test Maximum Density (LTMD) to the theoretical maximum specific gravity (G_{max}) as determined by ASTM D 2041 (Rice Method) or the equivalent Superpave test method. Caltrans currently typically requires 95 percent or 96 percent compaction relative to LTMD. It is recommended that Caltrans require 93 percent compaction relative to G_{max} for less critical asphalt concrete projects, and 94 percent compaction relative to G_{max} on more critical projects. The recommended change should result in air-void contents of about five percent.
2. Require the use of tack coats to improve bonding between asphalt concrete lifts on all construction projects. Caltrans currently requires placement of a tack coat on overlay projects between the top of the existing pavement and the first lift of the overlay. Caltrans currently does not require tack coats between multiple lifts being constructed as part of the same project, unless directed by the Engineer. It has been found that even under ideal construction conditions, a bond is not always formed between successive lifts of an asphalt pavement without the use of a tack coat.(*3*)
3. Include a Rich Bottom Layer in thick asphalt concrete structures. In asphalt concrete structures that are 150 mm or thicker, include an asphalt concrete layer with increased fatigue resistance as the first lift. This layer is known as a “Rich Bottom Layer”; its increased fatigue resistance is achieved through compaction to two percent air voids and increase of the asphalt content by 0.5 percent. The Rich Bottom Layer should be 50 to 75 mm thick.

1.3 Organization of this Report

This report is organized in the following way: Section 2 provides a brief overview of the current state of the art in road building technologies and methods. The new methods of road building and maintenance that are being advocated are described in detail in Section 3. In Section 4, the attributes of the sample of roadway sections selected for analysis are identified and the methodology is described. Section 5 compares the differential costs of old and new approaches to pavement technologies as well as discusses calculations of the projected savings to Caltrans if it were to adopt the new approach as standard practice in roadway maintenance and rehabilitation. Section 6 contains estimates of the differential returns from the application of different types of new pavement technology including, increased compaction, use of a tack coat, and use of a rich bottom layer. Section 7 contains the summary and conclusions.

2.0 CURRENT STATE OF THE ART IN PAVING

Current state of the practice and current Caltrans practices are summarized in this chapter for the following activities:

- asphalt concrete compaction;
- use of a tack coat between asphalt concrete layers;
- asphalt concrete mix design and compaction in thick sections; and
- life-cycle cost analysis.

The summary of current Caltrans pavement technology provides insight into the magnitude of the changes being proposed by the CAL/APT program. The current practices for life cycles cost analysis used by other state highway agencies in the United States are also summarized.

2.1 Asphalt Concrete Compaction

2.1.1 Measurement of Asphalt Concrete Compaction

Compaction is the removal of air from, and orientation of aggregate particles in the asphalt concrete mix. Compaction increases the stiffness of asphalt concrete, which improves its resistance to fatigue cracking and rutting. Increased compaction also plays a role in reducing the ability of water and air to enter and pass through the pavement, thereby reducing the potential for water damage and loss of support in the underlying layers.

The degree of compaction achieved can be described in terms of the volumetric percentage of air voids in the mix, or in terms of relative compaction. The following is a brief description of how these measurements are made and how the different methods of describing the degree of compaction are related.

A unit volume of asphalt concrete can be divided into its three components: aggregate, asphalt, and air, as shown in Figure 1. The air-void content is typically expressed as the percentage of the unit volume that is air. Air-void content can be measured using the following equation:

$$Air\ \text{-}\ Void\ Content = 100 * \left(1 - \frac{G_{builk}}{G_{\max}}\right) \tag{1}$$

where G_{bulk} is the bulk specific gravity of the compacted mix, which is the density of the compacted mix divided by the density of water, and G_{max} is the maximum theoretical specific gravity of the mix, (i.e., when compacted to an air-void content of zero percent, which is the density of the mix with zero percent air-void content divided by the density of water).

The bulk specific gravity of the compacted mix (G_{bulk}) can be measured from cores taken in the field from the compacted asphalt concrete, or non-destructively using a nuclear density gauge. Caltrans has standard test methods for both procedures: California Test Method (CTM) 308 for cores, and CTM 375 for the nuclear gauge.(*4*) G_{max} is measured using field mix that has been heated, and separated into smallest possible pieces comprised primarily of single aggregate particles and their binder coating, and has the air removed from it by a vacuum. The test is standardized as ASTM D 2041 and AASHTO T209.

The term “relative compaction” refers to the density or specific gravity of the compacted asphalt concrete relative to a reference density or specific gravity. The following two reference densities are used in practice by different agencies:

- Maximum theoretical density or specific gravity (G_{max}), and

- The bulk density or specific gravity obtained for the particular mix under standard compaction energy or some other standard conditions ($G_{bulk/std}$).

Relative compaction is expressed as a percentage, and is calculated using G_{max} as the reference as follows:

$$Relative\,Compaction = 100 * \left(\frac{Gbulk}{G\max} \right) \quad \textbf{(2)}$$

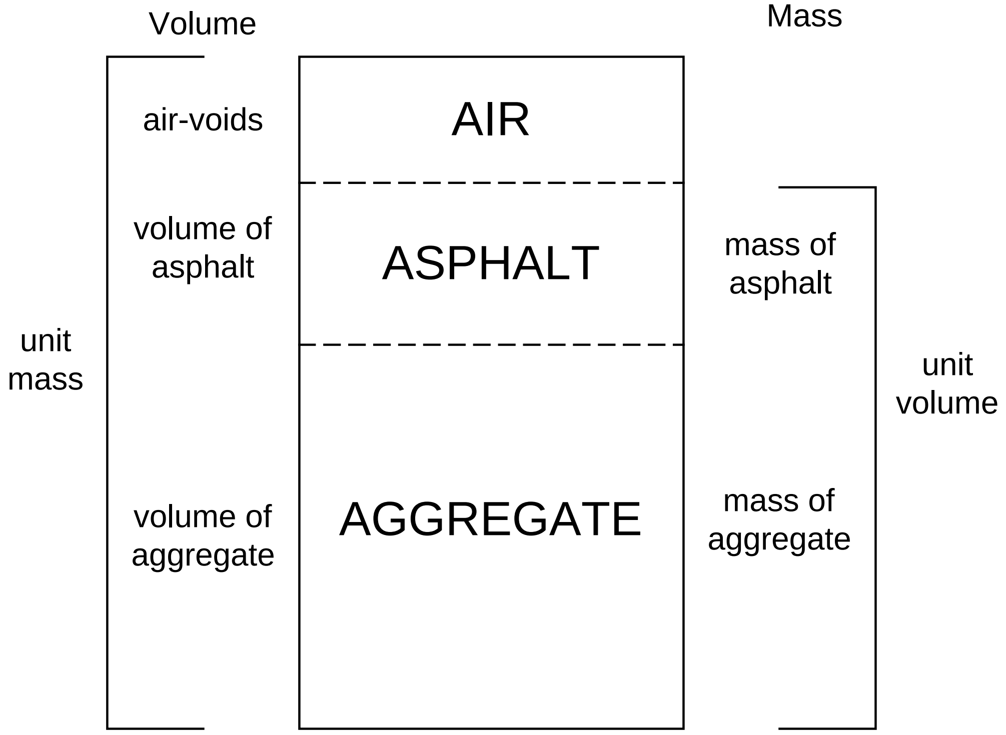
Relative compaction calculated using the bulk specific gravity from standard compaction energy in the laboratory as the reference is calculated as follows:

$$Relative\,Compaction = 100 * \left(\frac{Gbulk}{Gbulk / std} \right) \quad \textbf{(3)}$$

2.1.2 Current Caltrans Practice

Section 39-6.01 of the Caltrans Standard Specifications (*5*) includes requirements for asphalt concrete lift thicknesses, atmospheric temperature limits, and asphalt concrete layer temperature limits. Section 39-6.03 contains a "method" specification for asphalt concrete compaction. Method specifications are requirements for equipment types and their operation, including the number of passes that are placed on the asphalt concrete within layer temperature limits. In the Caltrans method specification, the Contractor is paid the full price of asphalt concrete construction, regardless of the actual compaction achieved, provided that the Caltrans Engineer certifies that the Contractor had performed the prescribed method of compaction.

In the past 10 years, Caltrans has moved to increased use of "end-result" specifications for asphalt concrete compaction. In the end-result specifications, Caltrans uses relative compaction; the compaction is relative to the bulk density obtained from the mix design, referred to as the Laboratory Test Maximum Density (LTMD). Under standard laboratory compaction, both air-void content and stability decrease with increased asphalt content. The interplay of the



Note: boundary between asphalt and aggregate measured at asphalt permeable boundary on surface of aggregate by means of “Rice Method for Maximum Theoretical Specific Gravity” ASTM D 2041.

Figure 1. Volumetric Components of Asphalt Concrete, and Measurement of Degree of Compaction.

stability and air-void content criteria for selecting LTMD is illustrated in Figure 2. The Caltrans mix design procedure (CTM 367) has several criteria for selecting LTMD. The largest value that can be used for LTMD is the density when the mix has four percent air-void content under the standard laboratory compaction effort, the case shown in Figure 2. Under this criterion, LTMD is equal to 0.96 * (G_{max} * density of water).

LTMD may be less than the density corresponding to four percent air-void content if the minimum allowable Hveem stabilometer test value of 37 controls asphalt content selection, if the asphalt content is selected based on “flushing” observed in the compacted laboratory specimen (CTM 367), or if the asphalt content is reduced for other reasons. LTMD then corresponds to the

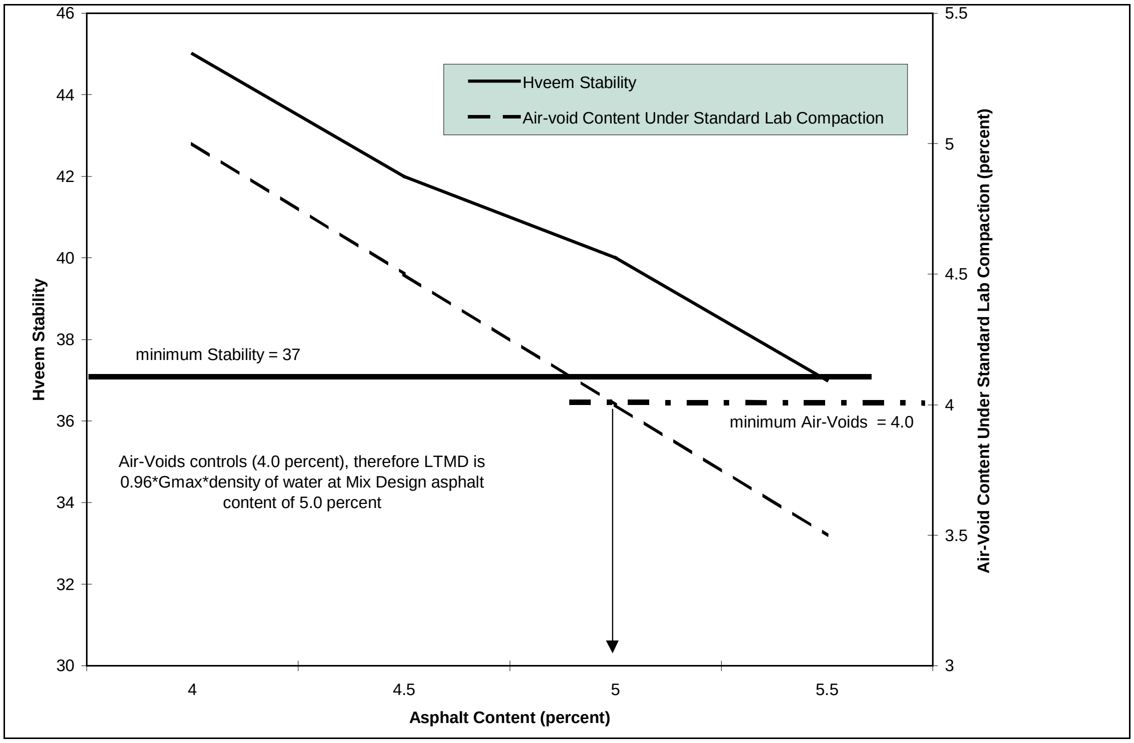


Figure 2. Caltrans Mix Design Criteria for Selecting Asphalt Content, and their Effect on Determination of Laboratory Test Maximum Density (LTMD) – Air-Void Content Controlling Asphalt Content.

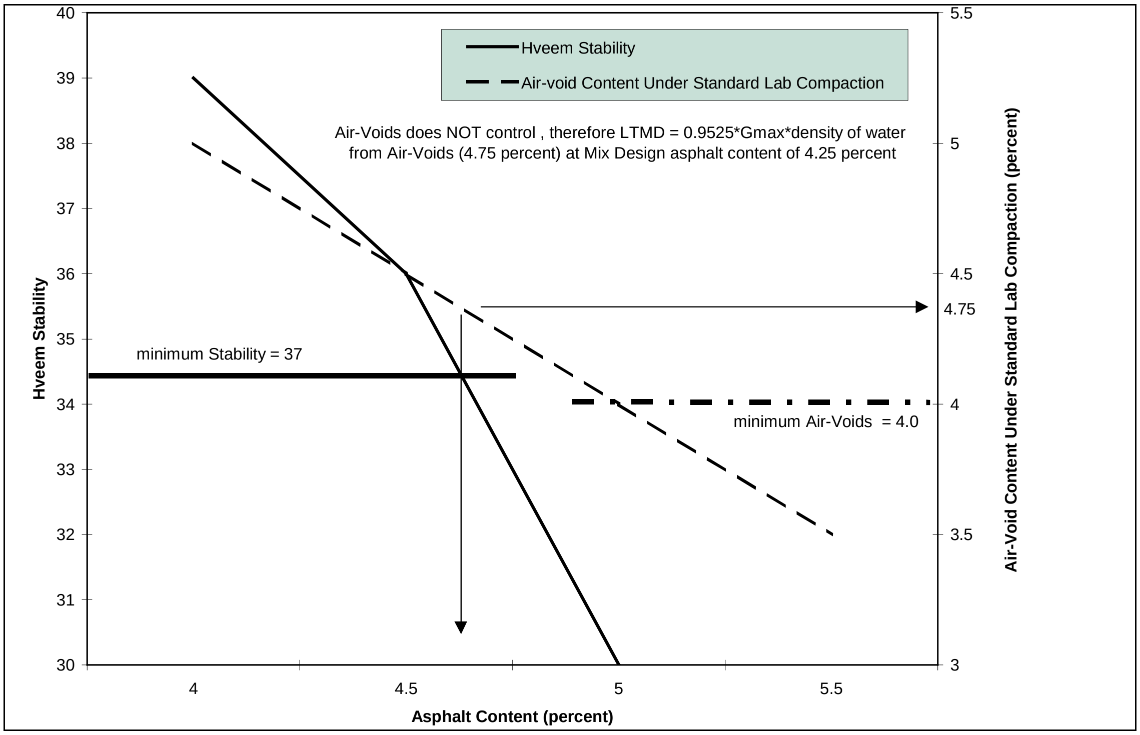


Figure 3. Caltrans Mix Design Criteria for Selecting Asphalt Content, and their Effect on Determination of Laboratory Test Maximum Density (LTMD)—Hveem Stability Controlling Asphalt Content.

density obtained under the standard laboratory compaction effort at the selected asphalt content. This criterion is illustrated in Figure 3. Under this criterion LTMD would be [1-(percent air voids/100)]* Gmax * density of water. The situation described in Figure 3 occurs frequently in practice.

Using the equations for the situation in Figure 3, the maximum permissible air-void contents for several combinations of percent relative compaction and Laboratory Test Maximum Densities corresponding to several mix design air-void contents were calculated (Table 2). It can be seen that the same compaction specification, as a percentage of LTMD, can result in widely different air-void contents.

In practice, air-void contents obtained in field construction have been reduced in recent years as Caltrans has moved from use of the method specification to an end-result specification. Construction end-result specifications have typically required 95 percent compaction relative to LTMD, which permits air-void contents of at least 8.8 percent (see Table 2). Average constructed air-void contents of about 9 percent have been obtained statewide using end-result specifications, and about 12 percent on average using the previous method specification.(*6*)

Table 2 Maximum Allowable Air-Void Contents (Percent) For Different Compaction Levels Relative to LTMD, And Different Mix Design Air-Void Contents.

Percent Compaction Relative to LTMD	**LTMD based on 4 percent air-voids at selected asphalt content**	**LTMD based on 5 percent air-voids at selected asphalt content**	**LTMD based on 6 percent air-voids at selected asphalt content**
95 percent	8.8	9.7	10.7
96 percent	7.8	8.8	9.8
97 percent	6.9	7.8	8.8

Since 1996, responsibility for quality control has been gradually passed from Caltrans to the Contractor for most large projects as Caltrans has implemented a Quality Control/Quality Assurance (QC/QA) system.(*6*) The QC/QA specifications have typically required 96 percent compaction relative to LTMD, which permits air-void contents of at least 7.8 percent (Table 1).(*7*) The recent experience with QC/QA and end-result specifications has demonstrated that better compaction can be obtained through improved control of the construction process. A preliminary estimate of the average air-void content on the QC/QA projects completed between 1996 and 1998 is about 6 to 7 percent.(*7, 8*)

2.1.3 Use of Tack Coat between Asphalt Concrete Lifts

Good bonding between asphalt concrete lifts increases the stiffness of the asphalt concrete as a whole. The increased stiffness achieved through good bonding reduces maximum tensile strains, which are responsible for fatigue cracking, and forces them to occur at the bottom of the asphalt concrete rather than between lifts. The increased stiffness and fatigue life achieved by good bonding is similar in principle to the use of glued laminar beams, where the relatively weak individual wood strips have adequate bending stiffness and strength when glued together. The effects of bonding are illustrated in Figure 4.

A tack coat is a thin layer of asphalt emulsion or hot asphalt cement between an existing pavement surface and a lift of new asphalt concrete, or between successive lifts of new asphalt concrete. Tack coats as well as emulsion and hot asphalt cement tack coats are applied by a spray truck. The tack coat is placed down just before the new asphalt concrete lift, to avoid contamination by dust or traffic. The tack coat is intended to improve bonding between the lifts.

Section 39-6.01 of the Caltrans Standard Specifications (*5*) includes requirements for maximum lift thicknesses when constructing asphalt concrete layers (Table 3). It can be seen that when the total asphalt concrete layer thickness is 75 to 120 mm it will typically be constructed in two lifts; when the total thickness is 135 mm or more, it will be constructed in three or more lifts. Caltrans includes maximum thickness requirements to improve smoothness,

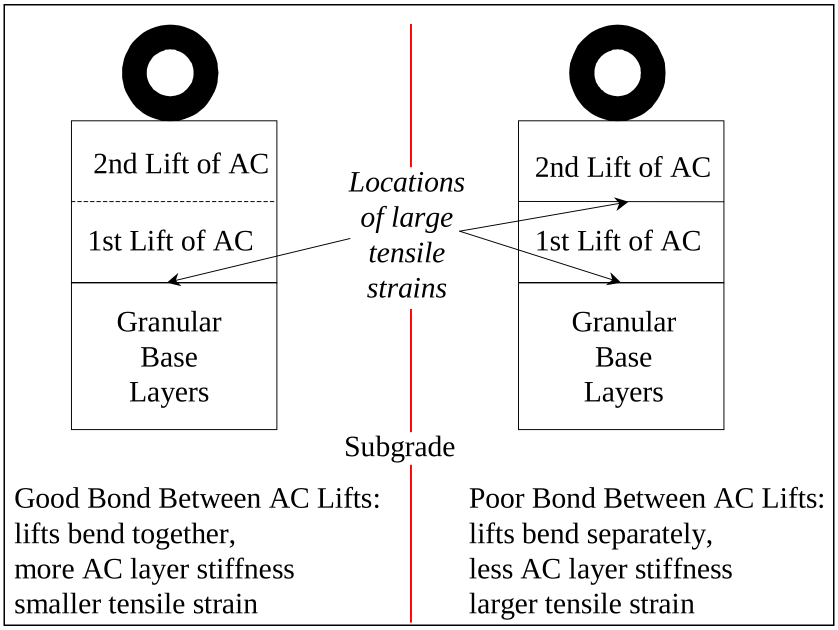


Figure 4. Effect of Bonding on Stiffness, Tensile Strains and Location of Maximum Tensile Strains.

Table 3 Asphalt Concrete Construction Lift Thickness Requirements, from Caltrans 1995 Standard Specifications, Section 39-6.01.

Total Thickness Shown on the Plans*	No. of Layers	Top Layer Thickness (mm)		Next Lower Layer Thickness (mm)		All Other Lower Layers Thickness (mm)	
		Min.	Max.	Min.	Max.	Min.	Max.
60 mm or less	1	-	-	-	-	-	-
75 mm	2**	35	40	35	40	-	-
90 – 120 mm	2	45	60	45	75	-	-
135 mm or more	***	45	60	45	75	45	120

* When pavement reinforcing fabric is shown to be placed between layers of asphalt concrete, the thickness of asphalt concrete above the pavement reinforcing fabric shall be considered to be the "Total Thickness Shown on the Plans" for the purpose of spreading and compacting the asphalt concrete above the pavement reinforcing fabric.

** At the option of the Contractor, may be placed in one layer 75 mm thick.

*** At least 2 layers if total thickness is 135 mm. At least 3 layers if total thickness is more than 135 mm and less than 270 mm. At least 4 layers if total thickness is 270 mm or more.

since it is easier to remove irregularities in the surface of the existing asphalt concrete through placement of successive lifts, as opposed to one thick lift.

Section 39-4.02 of the Caltrans Standard Specifications (*5*) requires that a Paint Binder (tack coat) be applied to existing pavements when they are to be surfaced with new asphalt concrete. Tack coats are also to be placed when the tack coat is a specific item in the contract, or when required by the special provisions of the contract. In current Caltrans practice, tack coats are typically not required between successive asphalt concrete lifts unless one of the following conditions occurs:

- The previous lift has been exposed to general traffic or construction traffic resulting in a dusty or dirty surface that will inhibit bonding,
- Weather that occurs in between paving of successive lifts has resulted in a dusty or dirty surface that will inhibit bonding,
- There is a significant time delay between paving of successive lifts that in the opinion of the Engineer will result in poor bonding, or
- Any other time that the Engineer determines that a tack coat is warranted to promote bonding.

In practice, tack coats are seldom placed between successive asphalt concrete lifts.

2.1.4 Mix Design and Compaction Requirements for Thick Asphalt Concrete Layers

The current Caltrans asphalt concrete mix design method is intended to produce mixes that have a high resistance to rutting. Fatigue cracking resistance is not evaluated in the mix design process. The philosophy is that rutting is of primary importance because rutting failures occur early in the life of the pavement and often require removal and replacement or placement of another overlay to cover the ruts.

More asphalt in the mix will result in greater susceptibility to rutting and less susceptibility to fatigue cracking. In addition, lower asphalt contents make it more difficult to compact a mix. Therefore, Caltrans asphalt contents are typically somewhat lower than those used in other states, and in combination with the compaction specification that uses LTMD as the reference density, Caltrans air-void contents are typically greater than those in other states. Fatigue resistance is typically more dependent on air-void content than asphalt content, with larger air-void contents resulting in less fatigue resistance. The result is that Caltrans mix designs often have relatively low fatigue resistance because they are designed exclusively to prevent rutting.

Rutting has been found to primarily occur within the 100 mm of asphalt concrete at the surface of the pavement. This is because this top 100-mm region is where high temperatures (at least 30 - 40° C or greater), and high shear stresses caused by heavy, high pressure truck wheel loads, are present.

Fatigue cracking is the result of repeated tensile strains caused by truckloads. The maximum tensile strains occur at the bottom of the asphalt concrete layer, assuming that there is good bonding between the asphalt concrete lifts (Figures 4 and 5).

Caltrans currently uses the same rut resistant mix design for all of the asphalt concrete in a new pavement or asphalt concrete overlay, even when the thickness is greater than 100 mm. The result is that a mix design intended to provide rut resistance is used at the bottom of thick asphalt concrete layers, where there is less need for rut resistance and greater need for fatigue resistance.

2.2 Life Cycle Costing

2.2.1 National Practices

Life cycle costing has traditionally been used in pavement engineering to determine the type of new pavement to be built: flexible pavement with an asphalt concrete surface, or rigid

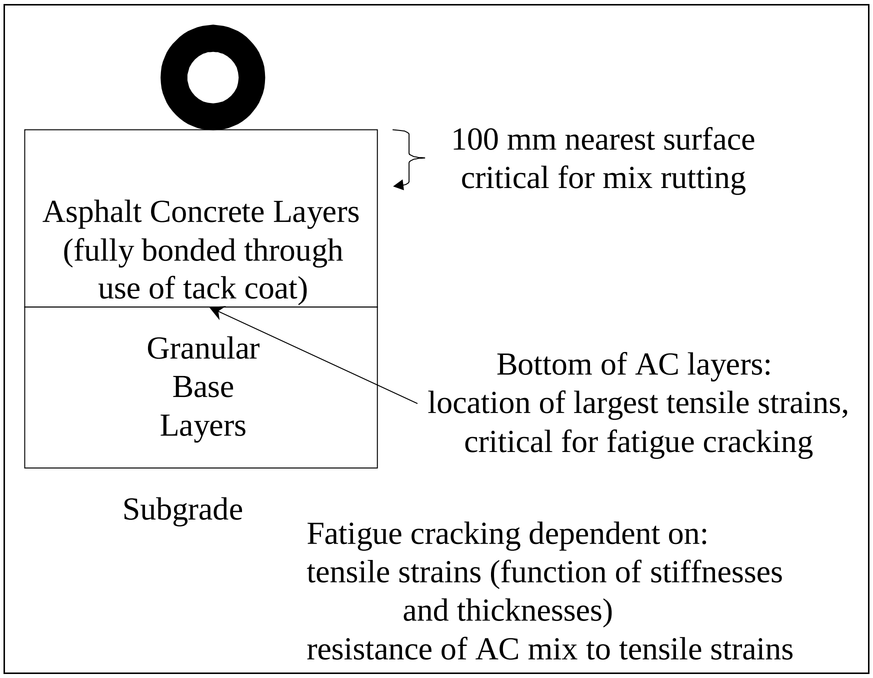


Figure 5. Typical Locations in Thick Asphalt Concrete Layers Critical for Rutting and Fatigue Resistance.

pavement with a portland cement concrete surface. With deployment of the national highway system and increasing attention to preserving and repairing the system, life cycle costing is also used to evaluate and select maintenance, rehabilitation, and reconstruction strategies.

The AASHTO Design Guide for Pavement Structures (*9*) discusses basic principles for economic evaluation of pavement strategy alternatives. The AASHTO Guide lists costs that should be included in life cycle cost analyses (LCCA), typically classified as either agency costs or user costs, as follows:

- Agency costs – initial construction costs, rehabilitation costs, preventative and routine maintenance costs, salvage value, engineering and administration costs, and traffic control costs;
- User costs – travel time, time delay costs during construction and maintenance, vehicle operating costs, accident costs, and discomfort.

The discussion of interest rates, inflation factors, and discount rate in the AASHTO Guide indicates that the discount rate should be based on the opportunity cost of capital. The opportunity cost of capital is defined as the return that would have been earned if the funds had been invested in an alternative public or private project. The discussion in the AASHTO Guide suggests that a market rate of return be used for the discount rate, after adjustment for inflation. It is noted that the final choice of discount rate can have a significant impact on the results of life cycle cost analysis.

In a recent survey by Beg et al. (*10*) of 63 highway agencies with an 86 percent response, it was found that 83 percent of the agencies use an organized procedure for selecting or evaluating alternative strategies. Of those using an economic analysis for decision making, 64 percent use total life cycle cost, 17 percent use only the cost of initial construction paid by the agency, and 17 percent use both costs to make their decisions.

Analysis periods used in LCCA ranged between 20 and 50 years, with an average of 38 years. Approximately half of those using LCCA use analysis periods in the range of 31 to 40 years, and about one third use analysis periods in the range of 21 to 30 years. Traditionally, a 20-year design life has been used for new construction in the United States. Eighty-six percent of those using LCCA use Net Present Worth (NPW) as their cost parameter. Seven percent use Equivalent Uniform Annual Cost (EUAC), and 7 percent use both NPW and EUAC.

The agency costs included in LCCA are not consistent for all agencies in the survey. All agencies included initial construction and rehabilitation costs. On the other hand, 64 percent included routine maintenance, 48 percent included preventative maintenance, and 52 percent included salvage value.

Only 20 percent of the agencies in the survey include user costs in LCCA, with 16 percent considering the cost of time delays caused by construction, and 11 percent considering vehicle operating costs. It is the experience of Caltrans and some other agencies that user costs can be much larger than agency costs, and that they control the strategy selection analysis. Some agencies are uncomfortable with this result, while others consider it an important consideration when selecting projects that are of most benefit to the public. User costs are much more difficult for agencies to accurately estimate than are costs that they directly incur.

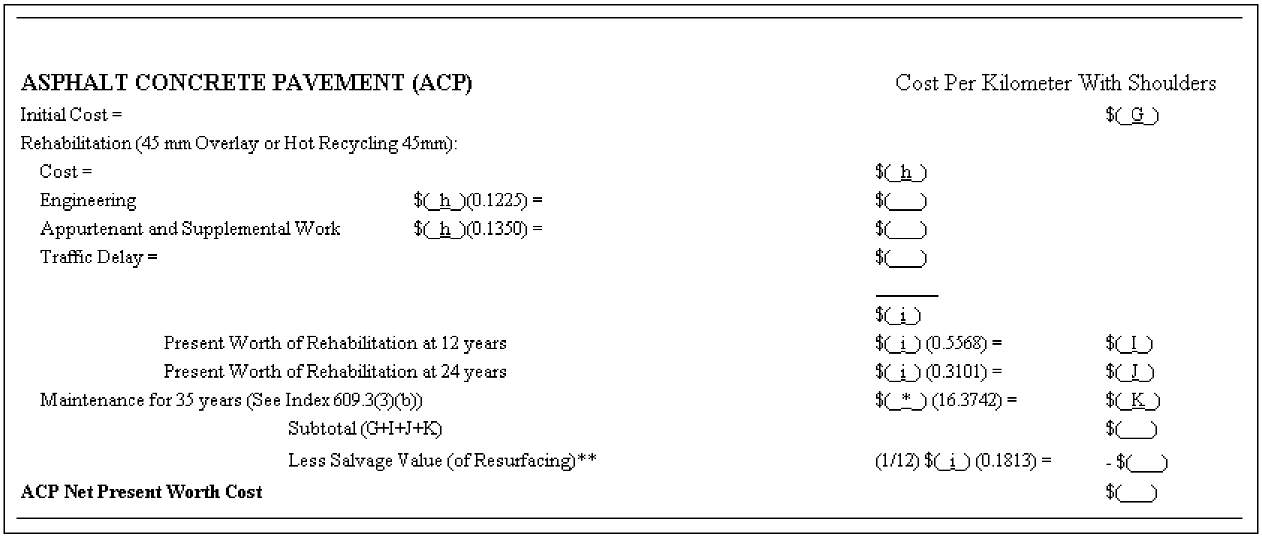
2.3 Caltrans Practice

The Caltrans Highway Design Manual (*11*) requires the use of a life cycle cost analysis for selecting new pavement types for most large projects. The Caltrans Manual also states that economics alone do not always dictate the final choice for structural sections or their alternative elements.

Caltrans uses a Net Present Value analysis, referred to as Present Worth. Caltrans uses a 35-year life cycle period and a five percent discount rate for all life cycle cost analyses. Caltrans includes the following agency and user costs in LCCA:

- Agency costs: initial construction costs, routine maintenance costs, rehabilitation costs, engineering costs, detours, shoulder work, salvage value;
- User costs: traffic delay associated with maintenance and rehabilitation activities.

As can be seen in the Caltrans LCCA analysis spreadsheet for asphalt concrete pavements (Figure 6), Caltrans assumes that a 45-mm overlay, which is considered a maintenance treatment, will be required every 12 years. It is assumed that some routine maintenance will be required throughout the life of the asphalt concrete pavement.



ASPHALT CONCRETE PAVEMENT (ACP)		Cost Per Kilometer With Shoulders	
Initial Cost =			$(G)
Rehabilitation (45 mm Overlay or Hot Recycling 45mm):			
Cost =		$(h)	
Engineering	$(h)(0.1225) =	$(___)	
Appurtenant and Supplemental Work	$(h)(0.1350) =	$(___)	
Traffic Delay =		$(___)	
		$(i)	
Present Worth of Rehabilitation at 12 years		$(i) (0.5568) =	$(I)
Present Worth of Rehabilitation at 24 years		$(i) (0.3101) =	$(J)
Maintenance for 35 years (See Index 609.3(3)(b))		$(*) (16.3742) =	$(K)
Subtotal (G+I+J+K)			$(___)
Less Salvage Value (of Resurfacing)**		(1/12) $(i) (0.1813) =	- $(___)
ACP Net Present Worth Cost			$(___)

Figure 6. Life Cycle Cost Analysis Worksheet, from Reference (*11*).

The structural designs for all new pavements are based on 20 years of traffic; the designs for structural asphalt concrete overlays are based on 10 years of traffic.

3.0 ASSESSMENT OF ADOPTING RECOMMENDED CHANGES TO CALTRANS PAVEMENT TECHNOLOGY

3.1 Summary of Recommended Changes to Caltrans Pavement Technology

Each of the recommended changes to Caltrans pavement technology is briefly summarized in this part of the report. The rationale and data used to develop the recommendations regarding increased asphalt concrete compaction, use of tack coats to improve bonding between asphalt concrete lifts, and use of a fatigue resistant “rich bottom layer” pavement design are presented in detail in (*3, 12-17*). The Appendixes of this report also includes references to the relevant CAL/APT reports.

3.1.1 Increased Asphalt Concrete Compaction

The recommendation regarding asphalt concrete compaction includes the following steps:

1. Change the basis for measurement of compaction from the current Laboratory Test Maximum Density (LTMD) to the theoretical maximum specific gravity (G_{max}) as determined by ASTM D 2041 (Rice Method) or the equivalent Superpave test method.
2. Require 93 percent compaction relative to theoretical maximum specific gravity (G_{max}) for all asphalt concrete work, except the most critical projects. This recommendation applies to both contract work and work performed directly by Caltrans.
3. Require 94 percent compaction relative to theoretical maximum specific gravity (G_{max}) for critical asphalt concrete projects, including new construction, reconstruction, and overlays of important pavements such as interstates and other routes of economic importance, and routes where maintenance is dangerous, difficult, or expensive.

4. Require that compaction not be permitted to exceed 96 percent relative to G_{max}, to minimize the risk of rutting.

A set of asphalt concrete construction pay factors has been submitted to Caltrans by CAL/APT based on expected fatigue cracking performance for projects that will be constructed under the Caltrans QC/QA system.(*12*) The pay factors include the combined effects of compaction, asphalt content and asphalt concrete layer thickness. A set of pay factors that combines fatigue and rutting performance based on CAL/APT and WesTrack results is currently under development, and will be submitted to Caltrans by CAL/APT in the near future.

The recommended changes should result in air-void contents of about six percent for typical asphalt concrete jobs, and five percent for critical projects.

3.1.2 Use of Tack Coat between Asphalt Concrete Lifts

The recommendation regarding the use of tack coats involves requirement of tack coats between lifts of asphalt concrete, unless it can be demonstrated that a strong bond is occurring between lifts within several days after construction without use of the tack coat.

This recommendation should result in improved bonding between asphalt concrete lifts and as a result, improved fatigue resistance of asphalt concrete pavements.

3.1.3 Use of Fatigue Resistant "Rich Bottom Layer" for Thick Asphalt Concrete Structures

The recommendation regarding the inclusion of fatigue resistant "Rich Bottom Layer" structures for thick asphalt concrete structures includes the following steps:

1. For new asphalt concrete layers thicker than 150 mm, require the use of a material with superior fatigue resistance in the bottom 50 mm of the asphalt concrete layer.

2. For new asphalt concrete layers thicker than 200 mm, require the use of a material with superior fatigue resistance in the bottom 75 mm of the asphalt concrete layer.
3. Specify that the asphalt concrete to be used as the bottom lift with superior fatigue resistance use the same mix design as the upper lifts, except that the asphalt content shall be increased by 0.5 percent by mass of aggregate.
4. Require that the bottom fatigue resistant lift be compacted to between 97 and 99 percent of the theoretical maximum density (G_{max}) determined using ASTM D 2041 or the equivalent Superpave test method.

This recommendation should result in greatly improved fatigue life, without significantly increasing the risk of rutting in the asphalt concrete.

3.2 Caltrans Operations Affected by Pavement Technology Changes

Each of the three recommendations evaluated in this report will have an impact on current Caltrans operations. This part of the report presents a summary of the Caltrans operations that will need to be changed if the recommendations are implemented.

3.2.1 Increased Asphalt Concrete Compaction

The recommendation to increase the compaction required for Caltrans asphalt concrete pavements will impact Caltrans operations, including initial construction costs, specifications, laboratory and field equipment requirements, and training for Caltrans and Contractor staff.

It has been estimated by members of the Southern California Asphalt Producers Association (*18*) that implementation of the recommended increase in compaction will increase the cost of asphalt concrete in place by about 10 to 15 percent due to required changes in construction operations. These changes include closer control of temperatures, increased coordination of trucks, paver, and crew, and potential increases in the number of rollers on a project. In the QC/QA system, these increased costs would reflect greater risk to the contractor of incurring a negative pay factor. On the other hand, if positive pay factors for achieving improved compaction reflect the reduced life cycle cost for the pavement, the bid prices may not show much increase.

The standard California Test Method (CTM) for measurement of maximum theoretical specific gravity (G_{max}) will need to be written and included in the California Standard Test Methods. Existing standard test methods that currently refer to Laboratory Test Maximum Density (LTMD) will need to be changed to reflect the use of the G_{max} as the reference for relative compaction. Several current CTMs that will need to be changed include:

- CTM 308, Measurement of Air-Voids on Cores
- CTM 367, Method for Recommending Optimum Bitumen Content (O.B.C.)
- CTM 375, Determining the In-Place Density and Relative Compaction of Asphalt Concrete Pavement

The standard test method and the new compaction requirements will need to be referred to in Section 39 of the Caltrans Standard Specifications in place of the current method specification.

The Caltrans Manual for Quality Control and Quality Assurance for Asphalt Concrete will need to be changed to reflect the use of the revised California Test Methods. The QC/QA manual will also need to include the revised compaction specifications.

Caltrans will need to purchase the equipment needed to perform the test for theoretical maximum specific gravity for the Caltrans laboratories that perform or evaluate mix designs and that perform quality assurance testing. Training for Caltrans and Contractor staff will be needed for the following new operations:

- Theoretical maximum specific gravity measurements in the laboratory and field,
- Calculation of relative compaction relative to theoretical maximum specific gravity, and
- New compaction requirements, including the rationale for the changes.

3.2.2 Use of Tack Coat between Asphalt Concrete Lifts

The recommendation to use tack coats between all asphalt concrete lifts will result in the following increases in construction costs:

- Use of a tack coat truck during paving operations, a cost of about $500 per day including the operator, and
- The potential for slight delays in paving while applying the tack coat, although these delays will likely be minimal.

Section 39 of the Caltrans Standard Specifications will need to be changed to reflect the required use of tack coats between lifts. The new tack coat requirements, including their rationale and implementation, should be included in annual training for Caltrans Resident Engineers, Design Engineers, and Construction Inspectors.

3.2.3 Use of Fatigue Resistant “Rich Bottom Layer” Thick Asphalt Concrete Structures

The increased compaction and slightly greater asphalt content of the fatigue resistant Rich Bottom Layer in thick asphalt concrete structures will result in some increases in construction costs for that layer compared to the current structural design. Compaction to two-percent air-void content in the bottom lift will require greater control of mix temperatures during compaction, and potentially require the use of additional rollers. The additional asphalt in the bottom lift will increase the unit cost of producing the material at the plant. The increase in asphalt content is relatively small and should not result in a large cost increase.

The use of the Rich Bottom design will need to be included in the Caltrans flexible pavement design procedures. Specification language for the compaction and asphalt content requirements of the bottom lift will need to be developed for inclusion in the Special Provisions of Caltrans construction documents projects where the Rich Bottom structure is used.

The new structural design, including its rationale and implementation, should be included in annual training for Caltrans Resident Engineers, Design Engineers, and Construction Inspectors. Contractors should also be made aware of the compaction and asphalt concrete job-mix-formula requirements for the bottom lift.

3.3 Costs of Conventional Highway Building, Rehabilitation and Maintenance Programs

Caltrans uses asphalt concrete in pavements for new construction, rehabilitation, and maintenance strategies. Programs in which Caltrans uses asphalt concrete in its strategies include the following:

- State Highway Operation and Protection Program (SHOPP), the pavement portion of which is also referred to as HA22, which includes Rehabilitation, Resurfacing and Restoration of pavements (RRR) activities, and Capitol Preventative Maintenance (CAPM) activities that add structural capacity to the pavement. Long-Life Pavement Rehabilitation Strategies (LLPRS, or AC Long-Life) are a new program within the

SHOPP intended to provide longer service life than the RRR and CAPM types of strategies;

- Highway Maintenance Program, also known as the major maintenance program (HM-1), includes pavement maintenance activities performed by construction contract and by state forces. These do not provide structural capacity, but are intended to provide additional service life until rehabilitation projects are more appropriately identified and programmed. In addition the maintenance program is aggressively targeting preventive maintenance in the form of surface seals as a “Doing the Right Thing at the Right Time” policy.
- State Transportation Improvement Program (STIP), which includes new construction to provide major improvements or increases in capacity.

Caltrans is currently projected to spend approximately $3,175 million on the SHOPP program from 1999 to 2005 and an additional $1,261 million on bridge rehabilitation. The SHOPP program will be targeting approximately $600 million for long-life pavement as part of the overall program.

3.3.1 Resurfacing, Restoration and Rehabilitation

The primary purpose of the Resurfacing, Restoration, and Rehabilitation (RRR) program is to preserve the investment in the existing pavement structure by returning it to a maintainable state. Strategies included in this program are designed to provide a 10-year extension of pavement life.(*19*) Typical strategies included in this program that require the use of asphalt concrete include the following:

- Milling of the existing asphalt concrete and replacement with new asphalt concrete,

- Thick asphalt concrete overlays, and
- Crack and seat portland cement concrete pavement and overlay with asphalt concrete (CSOL).

The three recommendations for changes to Caltrans pavement technology are applicable to all three of these strategies. Only the mill and replace and thick asphalt concrete overlay strategies were included in this report. Methods for predicting improvements in pavement the life for CSOL are currently under development, but were not available for inclusion in the analyses performed for this report.

3.3.2 Capital Preventative Maintenance

The purpose of Capital Preventative Maintenance (CAPM) pavement projects is the preservation of the roadway structure in the safe and useable condition to which it has been improved or constructed. CAPM does not include reconstruction or other improvement.(*19*) Strategies for CAPM projects are intended to extend pavement life by a maximum of five years. A typical CAPM strategy for existing flexible pavements is a thick asphalt concrete overlay.

Depending upon the thickness of the overlay, all three of the recommended changes to Caltrans pavement technology would be applicable to CAPM projects. Most CAPM projects would probably not require overlays thick enough to warrant the Rich Bottom design recommendation.

3.4 Long-Life Pavement Rehabilitation Strategies

Long-Life Pavement Rehabilitation Strategies (LLPRS) are a new category of strategy that Caltrans is implementing beginning in the 1998/99 fiscal year. Long-life strategies are intended for badly distressed concrete freeways in Southern California, the San Francisco Bay Area, and Sacramento, and may primarily involve replacement of the existing concrete with new concrete. Caltrans may include some strategies that involve replacement of the concrete pavement with a new flexible pavement, which permits application of all three of the recommended changes to Caltrans pavement technology considered in this report. Caltrans is projected to spend $600 million in the six-year period of 1999 to 2005 and $1.051 billion in the ten-year period of 1999 to 2008.(*20*)

The purpose of maintenance activities is to preserve the life of the pavement without adding structural capacity. Asphalt concrete overlays that are 30 mm or less are considered to fall within the scope of maintenance. The recommendation for improved asphalt concrete compaction included in this report is applicable to many thin asphalt concrete overlays.

The Caltrans pavement maintenance budget is currently about $60 million for state forces and $100 million for contract maintenance expected to cover approximately 10,000 lane miles per year. This budget includes approximately $38 million per year specifically dedicated to preventive maintenance surface seals.

The State Transportation Improvement Program fund estimate outlines the total resources available to various programs from the State Highway Account. These programs include state operation, SHOPP, local assistance, and the STIP.

The 1998 State Transportation Improvement Program (STIP) is currently a 6-year document that will transition into a 4-year document in the year 2000. It is currently divided into two basic programs based on who nominates projects for programming: the Regional Improvement Program (RIP) or the Interregional Improvement Program (IIP). STIP deals primarily with new construction projects that add capacity and improve the highway infrastructure.

The current funding levels for the 1998 STIP include \$3.7 billion previously programmed in earlier years and \$6.2 billions recently programmed for a combined STIP funding level of approximately \$10 billion.

3.5 Summary of Programs

For all projects, including new construction, maintenance, and rehabilitation, it is estimated that Caltrans purchased approximately 2,800,000 tons of asphalt concrete in fiscal year 1998-99, worth about \$117 million. The asphalt concrete was used on more than 200 projects, which had a total value of \$577 million.(*22*)

To estimate the total number of projects that would be affected by the recommendations evaluated in this report would require analysis of a database of structural designs included in Caltrans projects awarded over the last several years. Unfortunately, Caltrans does not have an electronic database that includes structural designs, or that describes in a general manner what type of pavement type or rehabilitation strategies were used. Therefore, the costs of the current Caltrans operations that would be impacted by the recommendations cannot be made precisely.

The best estimate of the costs of the current program that would be impacted by the recommendations is on the order of \$577 million because the life of the projects in which asphalt concrete is used is highly dependent on the three areas covered by the recommendations. These are agency costs alone. Costs to users are likely much greater, as are indirect costs to Caltrans, such as the need for a large force of maintenance workers and other technical staff to maintain, rehabilitate, and reconstruct pavements.

4.0 ASSESSING THE BENEFITS AND COSTS OF NEW PAVEMENT TECHNOLOGIES

Cost-Benefit analysis [CBA] is used to assess the relative gains of undertaking one course of action rather than another. This could involve a new set of rules, an investment or a new process. In CBA a baseline or counter-factual must be established as the alternative to which the proposed action is compared—in many cases this is the status quo. The counter-factual defines the alternative in the absence of the change and provides a way of defining the data set required to evaluate each alternative. CBA considers both the benefits and the costs of the proposed course of action.

An alternative evaluation method is Cost Effectiveness analysis (CEA). Cost Effectiveness analysis is commonly used as an alternative to CBA. CEA seeks to maximize the extent of achievement of a given beneficial goal within a predetermined budget or, equivalently, to minimize the expenditure required in attaining a prespecified goal. Often, the goal will have been set under a separate process in which benefits and costs may have not been considered. In marked contrast to CBA, no attempt is made to place a monetary value on the beneficial goal. CEA is potentially useful when analysts seek efficient policies but face constraints in undertaking a CBA. Three common constraints are; (i) the inability or unwillingness to monetize some impacts of the project[4], (ii) the inability of the effectiveness measure to capture all of the social benefits of each alternative, and some of these non-captured social benefits are difficult to monetize, [5](iii) a situation in which the project is linked to intermediate goods where the linkages to preferences are not clear.

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[4] CEA is used quite commonly when values must be placed on life in the evaluation of a project.

[5] When CBA is used all impacts must be monetised. If the CEA measures capture 'most' of the benefits, it may be reasonable for analysts to use CEA to avoid the effort of undertaking a CBA.

In the evaluation of new pavement processes described in Section 3 of this report, the use of CEA is ruled out primarily because there are some benefits arising from the use of these processes that need to be taken into account despite their not being the principal motivation for introducing them. In addition, the monetisation of the benefits (potential cost savings) is central to the analysis.

4.1 CBA—A Brief Overview

The first step in Cost-Benefit analysis is the establishment of the merits of a proposed plan or project on an efficiency basis. This is an important point to recognize in choosing among evaluation methods. CBA evaluates strictly on the basis of economic efficiency. There are three components to the measure of economic efficiency: static allocative efficiency, dynamic [allocative] efficiency, and productive efficiency. Productive efficiency addresses the question of whether an organization produces its output at a given level of quality at the least cost possible. Productive efficiency will be achieved if the best available process technology is utilized and the mix of inputs used is consistent with the set of relative input prices in the market. In other words, the firm or agency that has achieved productive efficiency is operating on the lowest cost function available. This is the measure that most people identify with the meaning of efficiency and this is the best representation of where the new pavement process is aimed.

CBA undertakes to compare, in commensurate terms, the sum total of the benefits and costs resulting from a plan or project. This is normally accomplished by deriving monetary estimates of both benefits and costs at a common point in time. Benefits are estimated as the beneficiary’s willingness to pay for the publicly provided good or service. Costs are valued at the input’s opportunity cost, that is, at values adequate to compensate the suppliers of the resource for foregoing its use in the best alternative allocation. One of the major tasks of CBA is the determination of willingness to pay and opportunity cost, for often no market values exist and even where available, they need not be consistent with social value. If, on this basis, benefits exceed costs, the project is considered socially justified, as the beneficiaries of the project could compensate those who lose as a result of the project.

4.1.1 Benefit Cost Analysis: Selection Criteria

The typical problem to which CBA is applied is to evaluate on a comparable basis the stream of social costs arising from the undertaking of a project or program. An essential and often difficult task is to determine the pattern of benefits and costs over the project's life, but once accomplished, the analyst has a time stream of benefits:

$$B_0, B_1, B_2, \ldots , B_{t-1}, B_t \tag{4}$$

and a time stream of costs:

$$C_0, C_1, C_2, \ldots , C_{t-1}, C_t \tag{5}$$

from the present, 0, to the termination date t or some future point such as the lifetime of the project. B_0 is the benefits in the current year, B_1 the benefits next year and so on until B_t is the benefits in year t. Similarly for costs, C. The monetary value of the respective time stream cannot simply be summed and compared to determine the project's viability since the time patterns of benefits and costs are likely to differ significantly. The bulk of the costs usually occur in the early years when the project is under construction, while benefits are generated in later years once the facility becomes operational. The difference in the timing of benefits and costs would not matter if people valued a dollar today and a dollar in the future equally.[6]

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[6] However, they do not, as evidenced by the fact that borrowers are willing to pay interest, a premium for the use of money today rather than waiting for the future, while lenders require the interest as compensation for foregoing their

Because a dollar is valued differently at different periods of time, it is necessary to relate the value of benefits and costs in different years to a common period. This is done by discounting future benefits and costs to their present value. The present value of one dollar available in period *t* and discounted at the rate *i* is:

$$PV = \frac{\$1_t}{(1+i)^t} \tag{6}$$

Hence the present value of the benefit stream can be established as:

$$PV_B = \frac{B_0}{(1+i)^0} + \frac{B_1}{(1+i)^1} + \frac{B_2}{(1+i)^2} + \ldots + \frac{B_t}{(1+i)^t} = \mathop{}\limits_{t=0}^{t} \frac{B_t}{(1+i)^t} \tag{7}$$

and the present value of the cost stream as:

$$PV_C = \mathop{}\limits_{t=0}^{t} \frac{C_t}{(1+i)^t} \tag{8}$$

Once discounted to the present, benefits and costs can be compared. In CBA this comparison is most commonly expressed either as a benefit-cost ratio:

$$\frac{B}{C} = \frac{\mathop{}\limits_{t=0}^{t} \frac{B_t}{(1+i)^t}}{\mathop{}\limits_{t=0}^{t} \frac{C_t}{(1+i)^t}} \tag{9}$$

or as net present value:

$$Net\,PV = \mathop{}\limits_{t=0}^{t} \frac{B_t}{(1+i)^t} - \mathop{}\limits_{t=0}^{t} \frac{C_t}{(1+i)^t} = \mathop{}\limits_{t=0}^{t} \frac{B_t - C_t}{(1+i)^t} \tag{10}$$

The project is viable on efficiency grounds if the B/C is greater than one or if its net present value is positive. The former value provides a measure of the rate of return; the benefits per dollar of expenditure. The latter gauge gives a measure of the magnitude of the return, i.e., how big it is in dollars.

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use of money today and postponing its use until the future. This is the reason that, for example, a $1,000 bond payable one year hence has a market value of $925.93 when the rate of interest is 8 percent.

The major advantage of the net present value (NPV) criterion is that it shows the absolute magnitude of the returns from a project. This is in contrast to the benefit-cost ratio (B/C) and the internal rate of return (IRR), which only reflect relative returns. Absolute magnitudes, while an essential consideration, are not the whole story for projects with the same dollar benefits, which may have much different relative returns. For example, \$10M net benefits might accrue from projects with benefit-cost ratios of \$20M/\$10M = 2, or \$200M/\$190M = 1.05. As a result, one cannot usually select projects on the basis of a single criterion, as both absolute and relative measures deserve consideration.

4.2 Categories of Costs and Cost savings

The benefits of transportation improvement projects represent the difference between the improved and the existing facilities in terms of road user time costs, vehicle operating costs, accident costs, and environmental costs. Additionally, if the rehabilitated roads can be made to last longer, the future cost of repairs to taxpayers and work zone user costs will be reduced. Hence, any improvement that can reduce one, several, or all of these costs delivers “benefits” from such improvements.

Such benefits are not costless, however. Longer lasting roads may cost more per mile and may take longer to build than today’s roads. The issue to be addressed then is whether the benefits from adopting new processes in pavement technology outweigh any costs. Put simply, “is it worth changing the procedures from what we do now?”

To address this issue, a counter-factual must first be established. What would the costs of the life cycle of a facility or network be in the absence of any change in procedure? Next, what costs and benefits would change if the new process were adopted? The categories of costs that would be affected by a change in the pavement process would be:

1. Construction, maintenance, and rehabilitation costs,
2. Safety and environmental costs, and
3. User time costs.

For all intents, the total benefits of the roadway can be treated as fixed between the two scenarios because there is no reason the number of trips or vehicle-miles of travel (VMT) would change. Thus, the purpose is to measure the net savings in costs of supplying the capacity for this given number of trips.

The total cost of building, repairing, or rehabilitating a facility plus user and other costs can be represented as:

$$TC = C + \frac{R}{(1+r)^{n_0}} + \frac{R}{(1+r)^{n_0+n_1}} + M \times \left[\frac{(1+r)^N - 1}{r(1+r)^N} \right] + UC + OC \tag{11}$$

where:

TC = the total life cycle, user and other costs
C = the construction cost per two-lane kilometer
R = the resurfacing cost per two-lane kilometer
M = the annual maintenance per two-lane kilometer
N = the time horizon
n_0 = the initial pavement life (the period over which the PSI declines from 5 to 1)
n_1 = the overlay #1 life generally assumed to be 12
n_2 = the overlay #2 life generally assumed to be 12
r = the discount rate
UC = the summed user costs per two-lane kilometer
OC = the summed other costs per two-lane kilometer

The process of evaluation needs to calculate the construction, maintenance, and re-building costs under the current paving technologies and under the adoption of the proposed technologies.

4.2.1 Measuring Construction, Maintenance and rehabilitation Costs

The major benefit of the new pavement rehabilitation process is that it extends the life of pavement. With a longer life, the life cycle costs of the facility are reduced. An additional benefit may be that larger (heavier) vehicles are able to use the facility with no acceleration in the rate of deterioration of the pavement relative to the status quo.

Using the model explained by Small and Winston (*22*), it is possible to develop a measure of total pavement costs (TPC) and their variability measures of road wear and quality. N is the number of ESALs and π is a measure of pavement quality under conditions of negligible aging.[7] If the pavement were exposed to N ESALs, it would deteriorate to a level of highway quality π_f. At this point, the facility would require resurfacing—this is simply a technological property of the pavement. The introduction of the new pavement rehabilitation described in Section 2 represents a technological change.

The non-linear relationship between pavement quality and loadings applied to it can be represented as:

$$\pi = \pi_0 - \left(\pi_0 - \pi_f\right)\left(n/N\right)^b \qquad \textbf{(12)}$$

where π_0 is the initial pavement quality and π_f is the terminal pavement quality when pavement is considered worn out. n is the number of applications of an axle weight L_1 (measured in thousands of pounds) and type L_2 (L_2=1 for single axles, L_2=2 for tandem axles). N and b are parametrically related to L_1, L_2 and D (Durability). Setting $n = N$, N becomes the number of axle passages that will wear the road out.

The [net] present value of resurfacing costs as a function of traffic loadings N must be calculated. The key feature is pavement durability for given traffic loadings. Let Q be traffic loadings and *N* a variable describing durability. Let *T* be the time interval between overlays; this should be a function of *Q* and *N*. In the absence of aging effects, the entire road would be resurfaced at T^0:

$$T^0 = \frac{N}{\lambda Q} \tag{13}$$

Where λ is the proportion of *Q* that travels primarily on the right lane where heavier vehicles tend to travel. Equation (13) can be modified using a linear transformation that relates pavement roughness and pavement quality. Pavement quality will obey the following [modified] version of Equation (12):

$$\pi(t) = \pi_0 - (\pi_0 - \pi_f)(\lambda Qt/N)e^{mt} \tag{14}$$

As Small and Winston (*22*) show, *T* can be determined as a function of *N* and *Q* by setting $\pi(T) = \pi_f$ in Equation (14). *T* is therefore the solution to the equation:

$$T = \frac{N}{\lambda Q} e^{-mT} \tag{15}$$

M, the present value of overlay costs depends on *T*. Letting *C*(*W*) represent the cost per overlay, *M* will be the present value of a series of expenditures into the future; *C*(*W*) each *T* years. The effect of the new pavement process is to change *T* to *T'* where *T'* > *T*. Thus,

$$M(Q, W, D) = C(W)/(e^{rT} - 1) \tag{16}$$

From this analysis, if one uses a life cycle costing approach and minimizes the sum of capital and maintenance costs for a facility, one can define the total pavement costs (*TPC*) as the portion of capital and maintenance costs affected by pavement thickness, expressed per lane:

$$TPC = k_2 D + k_m \cdot \frac{1}{\left[e^{rT(D)} - 1\right]} \tag{17}$$

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[7] This assumption can easily be relaxed.

where k_2 is the pavement construction cost per lane-kilometers per unit of road thickness, k_m is the rehabilitation cost per lane-kilometer, r is the interest rate (cost of capital) and T is the time between resurfacing (which is a function of D). Durability can be measured in terms of mm of road thickness for rigid pavements and in an engineering unit called 'structural number' for flexible [asphalt] pavements. An alternative way of representing this idea is shown in Equation 11.

These models provide a way of thinking about how the improvement in asphalt-concrete process can affect maintenance costs by both extending T (the time interval between rehabilitation actions) as well as lowering the marginal maintenance costs. The new processes provide results 'as if it were a thicker pavement' by in effect increasing the structural number (increasing durability). Using data from a subset of the California highway network it is possible to assess the magnitudes of such gains. These gains would represent reductions in the costs to the highway agency to provide a given level of highway capacity over time.

The cost savings from differences in pavement processes applied are based on the following assumptions:

- the life of the roadway is increased by anywhere from 10 to 30 percent,
- the time between resurfacing is increased by the equivalent increase in roadway life, and
- the time to rebuilding is increased by the sum of the increased life over all resurfacing cycles.

The calculations are based on a weighted-average of the types of roadways in the Caltrans system. This is expressed in terms of a 2 lane-km equivalent measure. The calculations can therefore be used to measure the amount of savings for the roadway sections Caltrans resurfaces or rebuilds each year. Therefore, the values calculated are the amount of money (resources) Caltrans could save each year (measured in 1998 dollars) if they adopted the new paving processes.

Table 4 Life Cycle Cost Savings with Adoption of New Pavement Processes Lengthening Overlay Period

Change in Overlay Period	Savings/2 lane-km Equivalent	Statewide Savings	NPV of Savings
1	$3,597	$56,398,639	$37,599,092
2	$6,938	$108,779,341	$72,519,561
3	$10,043	$157,457,302	$104,971,535
4	$12,930	$202,721,190	$135,147,460
5	$15,616	$244,835,482	$163,223,655
6	$18,117	$284,042,588	$189,361,725
7	$20,447	$320,564,780	$213,709,854
8	$22,618	$354,605,954	$236,403,970

Table 4 shows that as the change in overlay period increases, the savings increase dramatically. For example, if the new pavement process increases the period between overlays by 15 percent, the period between overlays increases from 12 years to 14 years. This results in savings of $6,938 per two-lane-km equivalent. Applying this saving to the roadway system for the state of California yields potential statewide savings of over $108 million. If the period between overlays is extended by 5 years, the savings to the state is over $244 million—a net present value of more than $163 million. These findings represent only the direct cost savings; additional cost savings are calculated in Section 4.2.2.

4.2.2 User Costs

In addition to construction and materials resource savings, the users of the facility will also have lower costs over the time they utilize the roadway system. Because the roadway will be resurfaced less often, fewer shutdowns and closures for maintenance and rebuilding will be necessary. Hence, users will be subject to less congestion. Costs associated with accidents and safety as well as emissions associated with congestion will also decrease. The lower costs due to accidents will benefit facility users as well as workers involved in roadway maintenance and rehabilitation. Each of these is considered in turn in Sections 4.3.2.1 and 4.3.2.2.

4.2.2.1 Congestion

When road restoration projects are undertaken in urban and near urban areas, they can generate heavy traffic congestion during the time that construction is taking place as well as capacity reduction during non-working hours. This is a result of the need to close the existing adjacent traffic lanes and shoulders or work in close proximity to traffic. With traffic on most of California's major urban freeways running at or near capacity during daylight and early nighttime hours, most contracts on or adjacent to these highways must be undertaken during late night and early morning hours to avoid lengthy delay.

The reduction in road capacity at work zones has two main components. First, if the number of lanes available to traffic is less than the number of lanes available in normal conditions, the roadway capacity is reduced. The second aspect of road capacity reduction can be easily understood in terms of the effect that work zones and their traffic control devices have on lane width and lateral clearance of the roadway. When lane widths are narrower than the 12 foot standard, drivers are forced to travel closer (laterally) to one another than normal. Drivers tend to compensate for this discomfort by maintaining longer spacing between vehicles in the same lane.(*23*)[8] When, for a given speed, drivers leave longer spaces between cars, the volume

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[8] Similarly, when roadside, median objects, or other traffic control devices are too close to the lane edge, drivers shy away from them, positioning themselves further from the edge than under normal conditions. This produces the

or flow accommodated decreases.(*24*) Interestingly, this effect occurs in a work zone even when no work is being done. There is some evidence that the capacity of such zones is about 90 percent of normal.(*25*)[9]

Highway construction work has a number of different effects on the traffic stream that can affect user costs. These costs can be placed in four general categories: delay or travel costs, vehicle operating expenses, speed change cycling costs, and accident costs.(*25*) An example of how these costs are generated is illustrated in Figure 7. Vehicles travel at approach speed and somewhere in advance of the work zone are forced to decelerate. If there is a queue, the vehicle will be stationary for some intervals and moving up through the queue in others. Once the vehicle reaches the front of the queue, it will accelerate up to the speed at which it will travel through the work zone. Upon reaching the end of the work zone, the vehicle will again accelerate back to its initial speed. The rates at which the queue builds up and dissipates are particularly important to consider.

In order to calculate this component of user cost saving, information would be needed for the following variables:

- Time of day
- Duration of highway works
- Traffic volume

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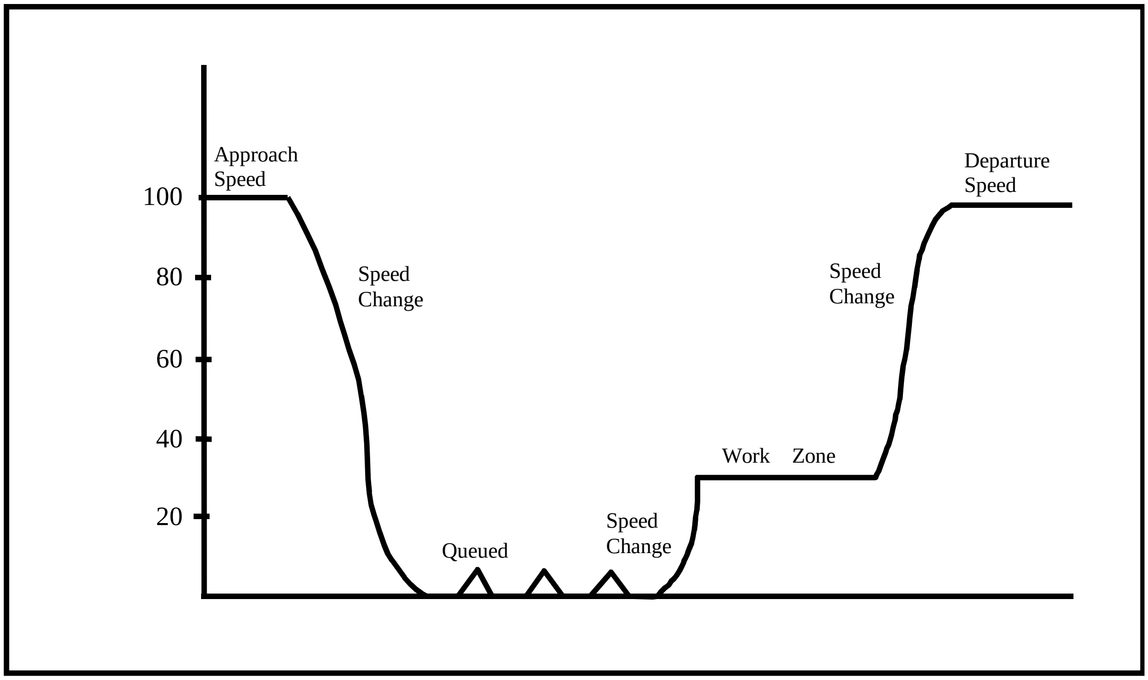
same impact as narrow lanes, and again, drivers usually compensate the lateral closing by leaving more distance between vehicles.

[9] To determine when the contractor should be allowed to work and close existing traffic lanes requires current information on hourly traffic volumes through the proposed construction area as well as estimates of “typical” work zone lane capacities. These capacities depend on motorists reactions to narrower lanes as well as what interesting things there are to look at, which can vary depending on the type of work being done on any given day. In Caltrans District 7 for example, the average capacities used to create lane closure tables are based on 1,500 vehicles per hour per lane for two or more lanes open to traffic and 1,000 to 1,200 vphpl with only a single lane open (Iwamasa, 1995).

- Road capacity
- Lane closure configuration
- Diversion and alternative routes
- Traffic control measures[10]



Source: Greenwood, 1995

Figure 7. Profile of Speed Changes through Work Zone.

In Table 5, the change in traffic flow for different roadway configurations is illustrated. The first row in the lower portion of Table 5 (‘Type of Operation’) shows the traffic flow under non-work and non-congested conditions. The subsequent rows show the decline in traffic flow as different roadway repairs or reconstruction activities take place.

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[10] Ellis, 1997, found that QUEWZ was a suitable piece of software to analyze the additional user costs resulting from work zone lane closures since it was developed specifically for work zone conditions, it is calibrated for rural conditions and does not consider effects on alternative routes when drivers divert due to queues in the work zone in urban areas.

Table 5 Change in Traffic Flow under Alternative Repair/Reconstruction Activities

Number of Lanes in One Direction of Travel (Normal Operations)	2	3 & 4	4
Number of Lanes Open in One Direction	1	2	3
Type of Operation:			
Median barrier	1500 vph	3200 vph	4800 vph
Pavement repair, pavement grooving	1400 vph	3000 vph	4500 vph
Striping, resurfacing, slide removal	1200 vph	2600 vph	4000 vph
Pavement markers installation	1100 vph	2400 vph	3600 vph
Middle lanes--for any reason	------	2200 vph	3400 vph

For striping, resurfacing, and slide removal there is a 20, 18, and 16 percent reduction in traffic flow, respectively, for the different roadway configurations. Another way of viewing this problem is that it now takes 25 percent longer to move the same number of cars through a given roadway section than it did prior to the repair activity.[11] This loss of time is a cost to users that would not occur had the repairs not taken place.

Once the amount of increased travel time caused by a work zone is calculated, it must be converted to an economic value. Numerous studies provide estimates of the value of time. The evidence shows that this value will vary with the amount of time used, when and where it is used, and whether there was any uncertainty as to how much time would be used (or wasted). The value placed on time influences the magnitude of the cost savings realized from reducing traffic disruption. Thus, in an evaluation of any transportation project, it is important to get this value of time correct. The value will differ between trip purposes (work, non-work) and length of trip. Any project to be evaluated should have information concerning the distribution of traffic by trip-purpose and, ideally by length of trip. However, in many cases, practicality dictates the

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[11] For example, prior to repair activity in 4 hours 6000 vehicles would pass a given point but with repairs it takes 5 hours to move the same number of cars past the same point.

selection of just one value of time. Table 6 provides an illustration of the range of time values estimated in the economics and engineering literature.

Table 6 Alternative Estimates of the Value of Time

Author	Country	VTTS as % of Wage Rate	Trip Purpose	Mode
Lave (1968)	USA	42%	commuting	auto
Stopher (1968)	UK	21-32%	commuting	auto
Oort (1969)	USA	33%	commuting	auto
Lee & Dalvi (1969)	UK	30%	commuting	auto
Thomas & Thompson (1970)	USA	40-85%	interurban	auto
Lee & Dalvi (1971)	UK	40%	commuting	auto
Wabe, J. (1971)	UK	43%	commuting	auto
Charles River Associates (1972)	USA	32%	commuting	auto
Kentner (1973)	Germany	91%	commuting	auto
Kenter (1973)	Germany	40%	commuting	auto
Algers et al. (1974)	Sweden	21%	commuting	auto
Hensher & Hotchkiss (1974)	Australia	27%	commuting	auto
Hensher & Delofski (1974)	Australia	39%	interurban	auto
Kraft & Kraft (1974)	USA	38%	interurban	auto
O'Farrell & Markham (1975)	Ireland	86%	commuting	auto
McFadden (1975)	USA	28%	commuting	auto
Ghosh, Lees & Seal (1975)	UK	73-89%	commuting	auto
McDonald (1975)	USA	45-78%	interurban	auto
Ghosh et al. (1975)	UK	73%	interurban	auto
Guttman (1975)	USA	63%	commuting	auto
Hensher (1977)	Australia	145%	commuting	auto
Hensher & McLeod (1977)	Australia	35%	interurban	auto
Nelson (1977)	USA	20%	commuting	auto
Hensher (1982)	Australia	23-45%	commuting	auto
Hauer & Greenough (1982)	Canada	46%	commuting	auto
Algers & Wildert (1985)	Sweden	53%	commuting	auto
Chui & McFarland (1985)	USA	20-30%	commuting	auto
Deacon & Sonsteille (1985)	USA	82%	interurban	auto
Hensher & Troung (1985)	Australia	52-254%	leisure	auto
Fowkes (1986)	UK	59%	commuting	auto
Hau (1986)	USA	27-59%	commuting	auto
Winston et al. (1987)	USA	46%	commuting	auto
Horowitz (1987)	Australia	75%	interurban	auto
Bates et al. (1987)	UK	68%	interurban	auto
Bates et al. (1987b)	UK	62%	commuting	auto
Chui & McFarland (1987)	USA	82%	commuting	auto
Hensher (1989)	Australia	36%	commuting	auto
Hensher (1990)	Australia	34%	commuting	auto
Cole Sherman (1990)	Canada	93%	commuting	auto

In North America, for example, the FHWA is using 60 percent of the per-capita wage rate for the U. S. for the evaluation of highway projects while California uses $7.42/vehicle-hr and Florida uses $13.72 for valuing non-work time. Texas Transportation Institute recommends using a value of $9.92 per person-hr (1985 dollars) or alternatively, 70-80 percent of the wage rate. In the estimates set forth in this study, the figure for California was used.

4.2.2.2 Safety

A number of studies (*26-28*) have found that accident rates are significantly higher in work zones than those under normal operation. Several causes may contribute to the increase in accident rates in work zones. For one, work zones provide a restrictive operating condition affecting the traffic safety. The impact of the restricted operating condition is aggravated by high traffic volume such as that experienced during peak-hour traffic. Failure to slow down at work zones was found to be a major cause of accidents.(*29-32*)

A 1965 California study (*33*) reported that the accident rate during construction was 21.4 percent higher than the accident rate before the construction for 10 long-term construction projects.

In the period 1974 to 1976, Graham et al. (*34*) analyzed 79 projects in 7 states before and during accidents. For all projects as a group, accidents increased 7.5 percent. The change in accident rate was found to vary substantially for individual projects. However; 24 percent of the projects had increases of 50 percent or more, whereas 31 percent of the projects had decreases.

An overall 7 percent accident rate increase was found to have occurred during 21 minor safety upgrading projects on the rural Interstate highways in Ohio between 1975 and 1977.(*35*) A 61 percent increase in total accidents was also observed during 207 two-lane highway resurfacing projects in Georgia.(*36*) In another study, it was found that the accident rate between

1973 and 1975 during the widening of the Virginia's portion of the Capital Beltway (I-495) was approximately 119 percent higher than that before construction (*37*). These studies demonstrate that change in accident rates as a result of construction is highly variable and likely dependent upon specific factors related to traffic conditions, geometry, and environment. Nonetheless, they also indicate that changes in potential accidents need to be taken into account in the assessment of the new pavement technologies. If these new technologies can reduce the amount and length of maintenance work, real resources can be saved.

In order to calculate the expected cost due to increased accidents in the work zone, it was first necessary to calculate the number of accidents that could be expected on that specific section of road under normal (non-construction) conditions. This was done by first multiplying the length of the work zone (not necessarily the entire project length) by the Average Annual Daily Traffic (AADT) to determine the daily vehicle miles of travel through the work zone. This number was then multiplied by the accident rate for that type of road (e.g., 2-lane rural highway) in the county where the project was located to obtain the expected daily accident rate. Finally, this rate was multiplied by the number of days that the work zone was in place:

$$ACC_{EXP} = (L)(AADT)(CAR)(WZD) \tag{18}$$

where:

ACC_{EXP} = the expected number of accidents
L = work zone length
$AADT$ = average annual daily traffic
CAR = county accident rate
WZD = work zone days

This figure counted only days that work was actually going on, or if work was suspended, those days during which the site was intrusive in some other way, e.g., equipment was parked nearby, lanes were narrower than normal, pavement was uneven, or there was an obvious detour.

Once the expected number of accidents is calculated, it must be multiplied by the appropriate work zone accident factor, discussed earlier, to arrive at the expected number of additional accidents caused by the work zone:

$$ADD_{WZ} = ACC_{EXP}\left(F_{WZ}\right) \qquad \textbf{(19)}$$

where:

ADD_{WZ} = additional number of accidents due to the work zone
F_{WZ} = the appropriate work zone multiplier for that type of road

To translate the accident rate into an economic cost information developed in a full cost of transportation study, Gillen et al. (*38*), is utilized. In that study, the accident cost is obtained by determining the value of life, property and injury per accident and multiplying by Equation (19) representing accident rates. The value of life, property and injury has been estimated at $120,000 for rural accidents, which are at higher speeds and thus more likely to be fatal or cause serious injury than urban accidents, which cost $70,000 on average. The costs per crash by location are shown in Table 7.

Table 7 Cost Per Crash by Location

Type of Crash	Cost Per Crash (~1995 Dollars)
Rural	$111,000
Rural interstate	$120,000
Urban	$42,000
Urban interstate	$70,000

For this study, the cost of accidents was estimated to be $0.040/vkt[12] (0.27/pkt)[13] for rural travel or $0.023/vkt (0.15/pkt) for urban travel. These results are similar to values estimated using average accident rates, which were estimated at $0.028/vkt. Marginal accident costs, with

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[12] vkt = vehicle kilometer of travel.
[13] pkt = person kilometer of travel.

the same assumptions, range from \$0.026/vkt to \$0.044/vkt. A composite urban and rural average cost of <u>0.20/pkt</u> was used for this study. These numbers would be multiplied by the probabilities of accidents (in work zones) in the different counties in California. Estimates developed in Section 5 of this report use the average since the calculations are for a ‘generic’ road section in California.

5.0 CALCULATIONS OF BENEFITS AND RETURNS FOR A GENERIC SECTION OF CALIFORNIA HIGHWAY

To illustrate the application of the evaluation framework, a project currently underway in Sacramento County was selected. The following is a portion of a news release made by District 3 of Caltrans.

> *On Interstate 5, work is under way on a nine-mile stretch of I-5 from north of Sacramento between the American River and the Sacramento River Bridges, for freeway and ramp pavement rehabilitation. The $7.6 million project will crack, seat and overlay the I-5 roadway and overlay ramps, primarily in the northbound direction. On- and off-ramps at the Sacramento International Airport will be temporarily widened. The contract also includes bridge work on the American River Bridge and the I-5/I-80 interchange. The contractor for the project is Granite Construction of Watsonville, California. Estimated completion is summer 2000.*
>
> ***Motorists can expect the following lane and ramp closures from 8 p.m. to 6 a.m. the following day (7 a.m. on Saturday) with up to 15-minute delays.***
>
> ***Mon. & Tue., Oct. 18 & 19***
> ***Paving northbound I-5 off-ramp to West El Camino will be closed at 12 midnight to 6 a.m. Paving various southbound lanes from Del Paso to West El Camino. Paving various northbound lanes from West El Camino to I-5/I-80 interchange. Paving the Garden Highway northbound I-5 on-ramp will be closed at 12 midnight to 6 a.m.***
>
> ***Tue., Oct. 19***
> ***Paving northbound I-5 off-ramp to West El Camino will be closed at 12 midnight to 6 a.m. Paving northbound I-5 to eastbound I-80 connector closed. Paving northbound I-5 to westbound I-80 connector closed. Paving various southbound lanes from Del Paso to West El Camino.***
>
> ***Wed., Oct. 20***
> ***Shoulder work closing the I-5 northbound slow lane from Garden Highway to Del Paso. Paving various I-5 southbound lanes from Del Paso to Garden Highway.***
>
> ***Thur., Oct. 21***
> ***Paving various I-5 southbound lanes from one mile south Del Paso Road to West El Camino. Shoulder work closing various I-5 northbound lanes from Del Paso to I-5/Hwy 99. Paving various I-5 northbound lanes from Richards Boulevard to Garden Hwy.***
>
> ***Fri., Oct. 22***
> ***Paving various I-5 southbound lanes from West El Camino to Del Paso. Shoulder work closing various northbound lanes from Del Paso to the I-5/Hwy 99 separation.***

The key features of this project are:

1. It involves rehabilitation,
2. It is a four-lane divided highway,
3. The length is 9 miles (15 km), and
4. The project will last from October through June 21, 2000.14

Given this section of roadway, the question is posed: what would be the economic returns to Caltrans and the economic and social returns to California, generally, if the 'new pavement technology' had been in place (although the increases in pavement life have not yet been calibrated for overlays of cracked over seared PCCP), increases in overlay life would be expected? As discussed in Section 4, benefits will arise from three sources:

1. The savings to Caltrans in maintenance and repair costs to the roadway system over the life of the roadway,
2. The time cost savings to users due to less rehabilitation, and
3. The reduction in accident costs due to less frequent reductions in capacity of the system due to construction.

In Section 4.3.1 the measure of total costs was developed as:

$$TC = C + \frac{R}{(1+r)^{n_0}} + \frac{R}{(1+r)^{n_0+n_1}} + M \times \left[\frac{(1+r)^N - 1}{r(1+r)^N}\right] + UC + OC \qquad \textbf{(11)}$$

where:

TC = the total life cycle, user and other costs
C = the construction cost per two-lane kilometer
R = the resurfacing cost per two-lane kilometer
M = the annual maintenance per two-lane kilometer

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[14] The statement reads completion estimated in summer 2000. The first official day of summer was taken as the completion date.

N = the time horizon
n_0 = the initial pavement life (the period over which the PSI declines from 5 to 1)
n_1 = the overlay #1 life generally assumed to be 12
n_2 = the overlay #2 life generally assumed to be 12
r = the discount rate
UC = the summed user costs per two-lane kilometer
OC = the summed other costs per two-lane kilometer

The new pavement technology would result in a change in the total costs. The measure of benefits is the value of this change. The source of the cost savings is that the pavement lasts longer and does not have to be rehabilitated as frequently.

Using Table 4, and assuming the period between overlay construction has been increased by 5 years, the savings to Caltrans in terms of direct maintenance and rehabilitation costs is \$15,616 per 2-lane-km equivalent. This project is 15 km of 4 lanes, so the total direct savings would be \$468,480 or approximately 6 percent of the total budget.[15]

User time savings would arise from less frequent reductions in roadway capacity due to rehabilitation work. Table 5 shows that with the type of highway, I-5, and assuming one lane open while the other is shut down, in each direction, and assuming normal operations, it takes 20 percent more time to pass the 9-km work zone.

The potential savings in lost time to users if the roadway rehabilitation could be avoided are calculated in the following way: a volume of 1500 vehicles per hour is assumed with each vehicle having 1.2 occupants. This yields 1800 person-trips. Next, each occupant is assumed to have a value of time of \$7.42 per vehicle hour. This value is the one generally used by Caltrans in evaluating projects. Due to the road rehabilitation, the trip time in the work zone is calculated

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[15] The percent savings would be higher because the study counts only the roadway and ignores the ramp work. Calculated as \$15,616 times 15 km times 2 for 2-lane equivalent.

to increase from 6 to 7.5 minutes. Thus, the time lost due to the longer trip time amounts to $1,335,600.[16]

Benefits obtained by safety improvements can be calculated using the formulas in section 4.3.2.2. Using the assumed values of traffic of 1500 vph for 8 months for 30 days per month, travel is calculated to be 129,600,000 vehicle miles. Based on 1998 National Statistics (*38*), the accident rate was 2.419 accidents per million miles of travel.[17] Therefore, it is expected that 313 accidents will occur over the course of the project, ignoring the creation of a construction zone. As discussed in Section 4.2.2.2, the change in accident rate varies significantly. Therefore, a conservative 10 percent increase in the likelihood of an accident due to the construction zone was selected. The cost per crash was assumed to be $42,000—this figure was selected to be conservative, and because with the work zone, the traffic volume and speed will be lower than a normal highway and it is expected that the attributes of a crash occurring in the work zone would therefore closely resemble that of an urban environment.

The total savings are illustrated in Table 8. The increase in pavement life and reduction in frequency of rehabilitation has lead to a benefit of approximately $2.5 million. This benefit is realized at relatively little cost. The use of the new pavement technology is a primarily focused on *method* or *technique* of application rather than new, additional, or more costly materials. New pavement technologies may result in a small initial increase in labor costs while contractors become familiar with the techniques, however, at some point the techniques would be commonplace and have little or no impact on man-hours of labor required on a given contract.

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[16] Assume 25 days per month for 8 months (October through June), for 1500vph for a 1.5-minute time increment.
[17] Total accidents includes fatal, injury, and property damage only.

Table 8 Benefits from Increasing Pavement Life with New Pavement Technologies.[18]

Benefit Measures

			Amount	Proportion
Project Budget		$	7,600,000	
Direct		*$*	*468,480*	0.19
User Savings				
	vph		1500	
	time Change		1.5	
	Project time		8 months	
Total Time Increase			180,000	
Time Cost Savings		*$*	*1,335,600*	0.54
Safety Improvements				
	vph		1500	
	time (months)		8	
	WZD		240	
	Vehicle-miles		129,600,000	
	ACC		314	
	ADD		31	
	Increase in accident costs(forgone)	*$*	*658,627*	0.27
Total Savings (Benefits) from New Pavement Technology		**$**	**2,462,707**	

The direct savings to Caltrans represents almost 20 percent of the total benefits. This is sizable and is for only this project. As suggested in Table 4, applying this process to the entire state would have a NPV of $163.2 million with a 5-year increase in pavement life as demonstrated in the illustrative example.

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[18] The calculations are based on the assumption that the project will last for 8 months and the closures or detours will be in effect for 8 months despite the project involves only 6 nights of paving.

6.0 MEASURING DIFFERENTIAL RETURNS TO NEW PAVEMENT TECHNOLOGY

In Section 5, estimates were provided for a ‘representative’ section of California highway that is currently undergoing repair and rehabilitation. In the calculation, the new pavement technology was treated as if it were homogeneous. In the earlier sections of this report, three different new pavement technologies were described. These technologies could be implemented as California builds and rebuilds its highway system and as conditions apply. The technologies range from:

- Increased compaction—increasing compaction requirements for asphalt concrete to reduce air-voids to 5 percent,
- Use of tack coats—to improve bonding between asphalt concrete lifts, and
- Use of fatigue resistant Rich Bottom Layer—inclusion of a 50- to 75-mm thick asphalt concrete layer with increased fatigue cracking resistance as the first lift in asphalt concrete layers that are 150 mm or thicker.

The measure of total costs used in the calculations in Section 5 can be used to illustrate the different returns applied to a set of sections of the California highway system being rehabilitated, reconstructed, or maintained in the period of 1997 to early 1999. This set is primarily composed of rural highways. The total costs were comprised of savings in maintenance and repair costs, time savings costs, and reduction in accident and environmental costs. For the sake of illustration, the latter two categories can be assumed to be the same for each technology. The formula from Section 4.3.1 would then become:

$$TC = C + \frac{R}{(1+r)^{n_0}} + \frac{R}{(1+r)^{n_0+n_1}} + M \times \left[\frac{(1+r)^N - 1}{r(1+r)^N} \right] \qquad \textbf{(20)}$$

Using the information in Tables 9 through 11, two changes can be evaluated: 1) what is the value of adopting the new pavement technology, and 2) what are the incremental gains from improvements within the technology. For example, using the increased compaction technology, the air-void content can be reduced from 10 percent, to 8 percent to 5 percent. Naturally, the question arises as to what the returns to such a reduction are and whether they vary over the type or age of the facility. Two types of calculations were undertaken to answer this question; the results are reported in Tables 12 and 13.

The expected cost savings from the use of the new pavement technology are listed in detail in Tables 12 and 13. It was not possible to assess the cost savings from adopting the Rich Bottom Layer because there was insufficient data. In Table 12, the technology of increased compaction is considered for a large number of actual projects carried out (or being carried out) by Caltrans. On these projects alone, the total cost savings over the life of the pavement using one typical California asphalt would be $50,611,908; if a different typical California asphalt were used, the savings would amount to $72,515,913. This is clearly a sizable savings from a relatively minor investment in technique. There is a significant amount of variation across sites. There are also differences between the types of asphalt typically used in California. Whether it would be efficient to use one asphalt over another would depend on transportation costs and the expected rise in the price of the chosen asphalt, as demand would increase as a result of its increased use.[19]

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[19] In effect, those who controlled the Coastal asphalt would appropriate some of the rents due to the higher quality and better fatigue resistance of this asphalt.

Table 9 Compaction Levels with Bonded AC Lifts.

Contract Number	County	District	Route	Air Void Content (%)	Design ESALs Asphalt Type A	Design ESALs Asphalt Type B	Actual ESALs per year	Asphalt A Fatigue Life in Years	Asphalt A Percent Change	Asphalt B Fatigue Life in Years	Asphalt B Percent Change	Traffic Growth Rate for Asphalt A 2%	Traffic Growth Rate for Asphalt A 4%	Traffic Growth Rate for Asphalt B 2%	Traffic Growth Rate for Asphalt B 4%	Length of paving (km)	Approxi-mate AC Quantity (tons)
01-224804	Mendocino	1	101	10	3.16E+05	5.16E+07	4.19E+05	0.8	0	> 60	NA	7.41E+05	7.46E+05	NA	NA	3.9	10600
				8	5.00E+05	4.39E+07	4.19E+05	1.2	58	> 60	NA	9.30E+05	9.41E+05	NA	NA		
				5	1.07E+06	5.08E+07	4.19E+05	2.6	239	> 60	NA	1.53E+06	1.57E+06	NA	NA		
01-195624	Mendocino	1	101	10	1.16E+06	5.22E+06	1.41E+06	0.8	0	3.7	0	2.59E+06	2.61E+06	6.89E+06	7.15E+06	2.7	24200
				8	2.34E+06	1.13E+07	1.41E+06	1.7	102	8.0	117	3.81E+06	3.88E+06	1.38E+07	1.50E+07		
				5	7.10E+06	4.26E+07	1.41E+06	5.0	514	30.1	715	8.95E+06	9.42E+06	6.02E+07	8.44E+07		
01-297304	Humboldt	1	101	10	> 100 M	7.52E+07	1.57E+05	> 60	NA	> 60	NA	NA	NA	NA	NA	6.1	17300
				8	> 100 M	8.93E+07	1.57E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	> 100 M	> 100 M	1.57E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
01-297004	Humboldt	1	101	10	3.27E+06	> 100 M	2.76E+05	11.9	0	> 60	NA	4.00E+06	4.52E+06	NA	NA	3.8	24000
				8	5.34E+06	> 100 M	2.76E+05	19.4	63	> 60	NA	6.85E+06	8.43E+06	NA	NA		
				5	1.17E+07	> 100 M	2.76E+05	42.4	258	> 60	NA	1.88E+07	3.09E+07	NA	NA		
01-349704	Lake	1	29	10	6.18E+06	> 100 M	5.50E+04	> 60	NA	> 60	NA	NA	NA	NA	NA	19.2	45400
				8	6.69E+06	> 100 M	5.50E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	8.54E+06	> 100 M	5.50E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
01-350204	Medocino	1	1	10	1.89E+06	> 100 M	5.40E+04	35.0	0	> 60	NA	2.81E+06	4.20E+06	NA	NA	28.8	36000
				8	2.75E+06	> 100 M	5.40E+04	51.0	45	> 60	NA	4.86E+06	9.01E+06	NA	NA		
				5	5.42E+06	> 100 M	5.40E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
01-318404A	Lake	1	175	10	3.42E+05	8.05E+06	6.00E+03	57.0	NA	> 60	NA	6.47E+05	1.31E+06	NA	NA	0.4	1030
				8	6.32E+05	1.11E+07	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	1.70E+06	2.31E+07	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
01-318404B	Lake	1	175	10	1.29E+05	1.72E+05	6.00E+03	21.4	0	28.6	0	1.68E+05	2.12E+05	2.39E+05	3.29E+05		
				8	2.81E+05	4.63E+05	6.00E+03	46.9	119	> 60	NA	4.74E+05	8.30E+05	NA	NA		
				5	8.98E+05	2.29E+06	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
02-259104	Modoc	2	395	10	2.37E+06	> 100 M	5.80E+04	40.9	NA	> 60	NA	3.75E+06	6.06E+06	NA	NA	17.7	33900
				8	3.95E+06	> 100 M	5.80E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	8.85E+06	> 100 M	5.80E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
02-288404A	Modoc	2	299	10	3.04E+06	> 100 M	9.40E+04	32.3	0	> 60	NA	4.39E+06	6.34E+06	NA	NA	7.2	20400
				8	5.21E+06	> 100 M	9.40E+04	55.4	71	> 60	NA	9.66E+06	1.91E+07	NA	NA		
				5	1.23E+07	> 100 M	9.40E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		

Contract Number	County	District	Route	Air Void Content (%)	Design ESALs Asphalt Type		Actual ESALs per year	Asphalt A		Asphalt B		Traffic Growth Rate for Asphalt A		Traffic Growth Rate for Asphalt B		Length of paving (km)	Approxi-mate AC Quantity (tons)
					A	B		Fatigue Life in Years	Percent Change	Fatigue Life in Years	Percent Change	2%	4%	2%	4%		
02-288404B	Modoc	2	299	10	2.27E+06	> 100 M	9.40E+04	24.1	0	> 60	NA	3.03E+06	3.94E+06	NA	NA		
				8	3.86E+06	> 100 M	9.40E+04	41.0	70	> 60	NA	6.10E+06	9.87E+06	NA	NA		
				5	9.23E+06	> 100 M	9.40E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
02-288404C	Modoc	2	299	10	1.52E+06	7.86E+07	9.40E+04	16.2	0	> 60	NA	1.91E+06	2.26E+06	NA	NA		
				8	2.75E+06	9.71E+07	9.40E+04	29.3	81	> 60	NA	3.86E+06	5.35E+06	NA	NA		
				5	6.64E+06	> 100 M	9.40E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
02-288404D	Modoc	2	299	10	7.27E+05	7.12E+05	9.40E+04	7.7	0	7.6	0	8.88E+05	9.61E+05	8.69E+05	9.39E+05		
				8	1.60E+06	2.19E+06	9.40E+04	17.0	119	23.3	207	2.01E+06	2.41E+06	2.90E+06	3.74E+06		
				5	5.56E+06	1.26E+07	9.40E+04	59.2	665	> 60	NA	1.08E+07	2.25E+07	NA	NA		
06-364804A	Kings	6	198	10	1.87E+06	8.11E+07	3.89E+05	4.8	0	> 60	NA	2.37E+06	2.49E+06	NA	NA	6.3	36100
				8	3.27E+06	> 100 M	3.89E+05	8.4	75	> 60	NA	3.98E+06	4.34E+06	NA	NA		
				5	8.16E+06	> 100 M	3.89E+05	21.0	336	> 60	NA	1.06E+07	1.33E+07	NA	NA		
06-364804B	Kings	6	198	10	9.35E+05	> 100 M	3.89E+05	2.4	0	> 60	NA	1.36E+06	1.39E+06	NA	NA		
				8	1.52E+06	> 100 M	3.89E+05	3.9	63	> 60	NA	1.99E+06	2.07E+06	NA	NA		
				5	3.33E+06	> 100 M	3.89E+05	8.6	256	> 60	NA	4.05E+06	4.42E+06	NA	NA		
06-387704	Madera	6	41	10	2.84E+06	> 100 M	1.02E+05	27.8	0	> 60	NA	3.93E+06	5.35E+06	NA	NA	6.3	8140
				8	4.37E+06	> 100 M	1.02E+05	42.9	54	> 60	NA	7.06E+06	1.17E+07	NA	NA		
				5	8.85E+06	> 100 M	1.02E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
06-335904	Kern	6	33	10	> 100 M	> 100 M	1.99E+05	> 60	NA	> 60	NA	NA	NA	NA	NA	2.7	35500
				8	> 100 M	> 100 M	1.99E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	> 100 M	> 100 M	1.99E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
08-420804	San Bernardino	8	95	10	> 100 M	> 100 M	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA	2.0	8760
				8	> 100 M	> 100 M	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	> 100 M	> 100 M	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
08-399204A	Riverside	8	10	10	9.82E+05	> 100 M	4.90E+06	0.2	0	> 60	NA	5.89E+06	5.91E+06	NA	NA	31.2	255000
				8	1.54E+06	> 100 M	4.90E+06	0.3	57	> 60	NA	6.47E+06	6.49E+06	NA	NA		
				5	3.27E+06	> 100 M	4.90E+06	0.7	233	> 60	NA	8.22E+06	8.28E+06	NA	NA		
08-399204B	Riverside	8	10	10	2.10E+06	8.54E+07	4.90E+06	0.4	0	17.4	0	7.03E+06	7.06E+06	1.08E+08	1.30E+08		
				8	3.75E+06	> 100 M	4.90E+06	0.8	78	> 60	NA	8.72E+06	8.78E+06	NA	NA		
				5	9.26E+06	> 100 M	4.90E+06	1.9	341	> 60	NA	1.44E+07	1.47E+07	NA	NA		
09-213004A	Inyo	9	395	10	4.55E+05	4.54E+05	5.10E+05	0.9	0	0.9	0	9.73E+05	9.82E+05	9.72E+05	9.81E+05	4.2	35800

Contract Number	County	District	Route	Air Void Content (%)	Design ESALs Asphalt Type		Actual ESALs per year	Asphalt A		Asphalt B		Traffic Growth Rate for Asphalt A		Traffic Growth Rate for Asphalt B		Length of paving (km)	Approximate AC Quantity (tons)
					A	B		Fatigue Life in Years	Percent Change	Fatigue Life in Years	Percent Change	2%	4%	2%	4%		
				8	1.03E+06	1.37E+06	5.10E+05	2.0	126	2.7	202	1.57E+06	1.60E+06	1.93E+06	1.98E+06		
				5	3.43E+06	7.70E+06	5.10E+05	6.7	654	15.1	1598	4.21E+06	4.51E+06	9.58E+06	1.12E+07		
09-213004B	Inyo	9	395	10	3.81E+05	3.58E+05	5.10E+05	0.7	0	0.7	0	8.98E+05	9.05E+05	8.74E+05	8.80E+05		
				8	8.48E+05	1.07E+06	5.10E+05	1.7	122	2.1	200	1.38E+06	1.40E+06	1.62E+06	1.65E+06		
				5	2.87E+06	6.08E+06	5.10E+05	5.6	654	11.9	1597	3.58E+06	3.79E+06	7.43E+06	8.41E+06		
09-213004C	Inyo	9	395	10	1.09E+04	2.11E+04	5.10E+05	0.0	0	0.0	0	5.21E+05	5.21E+05	5.31E+05	5.31E+05		
				8	2.26E+04	4.83E+04	5.10E+05	0.0	108	0.1	129	5.33E+05	5.33E+05	5.59E+05	5.59E+05		
				5	7.01E+04	1.90E+05	5.10E+05	0.1	545	0.4	801	5.81E+05	5.82E+05	7.02E+05	7.05E+05		
09-251214A	Inyo	9	395	10	1.58E+07	> 100 M	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA	6.9	50700
				8	2.89E+07	> 100 M	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	7.55E+07	> 100 M	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
09-251214B	Inyo	9	395	10	1.23E+05	1.31E+05	1.64E+05	0.8	0	0.8	0	2.89E+05	2.92E+05	2.97E+05	3.00E+05		
				8	1.93E+05	2.54E+05	1.64E+05	1.2	56	1.5	94	3.61E+05	3.65E+05	4.25E+05	4.31E+05		
				5	6.36E+05	1.30E+06	1.64E+05	3.9	416	8.0	896	8.32E+05	8.65E+05	1.59E+06	1.73E+06		
11-201504A	San Diego	11	54	10	2.27E+06	> 100 M	1.17E+05	19.4	0	> 60	NA	2.91E+06	3.58E+06	NA	NA	0.8	1890
				8	3.15E+06	> 100 M	1.17E+05	26.9	39	> 60	NA	4.32E+06	5.83E+06	NA	NA		
				5	5.68E+06	> 100 M	1.17E+05	48.5	150	> 60	NA	9.74E+06	1.75E+07	NA	NA		
11-201504B	San Diego	11	54	10	1.89E+06	> 100 M	1.17E+05	16.2	0	> 60	NA	2.37E+06	2.81E+06	NA	NA		
				8	2.63E+06	> 100 M	1.17E+05	22.5	39	> 60	NA	3.47E+06	4.43E+06	NA	NA		
				5	4.72E+06	> 100 M	1.17E+05	40.4	150	> 60	NA	7.42E+06	1.19E+07	NA	NA		
11-2233U4	San Diego	11	78	10	2.34E+06	> 100 M	5.20E+04	45.0	0	> 60	NA	3.86E+06	6.60E+06	NA	NA	59.9	71200
				8	3.41E+06	> 100 M	5.20E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				5	6.47E+06	> 100 M	5.20E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		

Table 10 Bonding or No Bonding Between Lifts at 8 and 10 Percent Air-Void Content.

Contract Number	County	District	Route	Bonding Condition	Air Void Cont. (%)	Design ESALs Asphalt Type		Actual ESALs per year	Asphalt A		Asphalt B		Traffic Growth Rate for Asphalt A		Traffic Growth Rate for Asphalt B		Length of paving (km)	Approx. AC Quantity (tons)
						A	B		Fatigue Life in Years	Percent Change	Fatigue Life in Years	Percent Change	2%	4%	2%	4%		
01-195624	Mendocino	1	101	No bond	10	1.06E+05	3.38E+04	1.41E+06	0.1	0	0.0	0	1.52E+06	1.52E+06	1.45E+06	1.45E+06	2.7	24200
				No bond	8	2.48E+05	1.35E+05	1.41E+06	0.2	134	0.1	300	1.66E+06	1.67E+06	1.55E+06	1.55E+06		
				Bond	10	1.16E+06	5.22E+06	1.41E+06	0.8	989	3.7	15370	2.59E+06	2.61E+06	6.89E+06	7.15E+06		
				Bond	8	2.34E+06	1.13E+07	1.41E+06	1.7	2105	8.0	33441	3.81E+06	3.88E+06	1.38E+07	1.50E+07		
01-318404A	Lake	1	175	No bond	10	5.85E+04	3.38E+04	6.00E+03	9.8	0	5.6	0	7.12E+04	7.87E+04	4.21E+04	4.45E+04	0.4	1030
				No bond	8	1.26E+05	1.22E+05	6.00E+03	21.1	116	20.3	260	1.64E+05	2.06E+05	1.57E+05	1.96E+05		
				Bond	10	3.42E+05	8.05E+06	6.00E+03	57.0	485	> 60	NA	6.47E+05	1.31E+06	NA	NA		
				Bond	8	6.32E+05	1.11E+07	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
01-318404B	Lake	1	175	No bond	10	3.49E+04	1.20E+04	6.00E+03	5.8	0	2.0	0	4.33E+04	4.60E+04	1.84E+04	1.87E+04		
				No bond	8	7.95E+04	4.48E+04	6.00E+03	13.3	128	7.5	273	9.78E+04	1.12E+05	5.47E+04	5.90E+04		
				Bond	10	1.29E+05	1.72E+05	6.00E+03	21.4	269	28.6	1331	1.68E+05	2.12E+05	2.39E+05	3.29E+05		
				Bond	8	2.81E+05	4.63E+05	6.00E+03	46.9	706	> 60	NA	4.74E+05	8.30E+05	NA	NA		
02-288404A	Modoc	2	299	No bond	10	2.88E+05	2.23E+05	9.40E+04	3.1	0	2.4	0	3.93E+05	4.06E+05	3.25E+05	3.32E+05	7.2	20400
				No bond	8	6.09E+05	8.10E+05	9.40E+04	6.5	112	8.6	263	7.51E+05	8.02E+05	9.86E+05	1.08E+06		
				Bond	10	3.04E+06	> 100 M	9.40E+04	32.3	957	> 60	NA	4.39E+06	6.34E+06	NA	NA		
				Bond	8	5.21E+06	> 100 M	9.40E+04	55.4	1711	> 60	NA	9.66E+06	1.91E+07	NA	NA		
02-288404B	Modoc	2	299	No bond	10	2.25E+05	1.73E+05	9.40E+04	2.4	0	1.8	0	3.27E+05	3.35E+05	2.72E+05	2.77E+05		
				No bond	8	4.69E+05	6.29E+05	9.40E+04	5.0	108	6.7	263	5.91E+05	6.22E+05	7.73E+05	8.27E+05		
				Bond	10	2.27E+06	> 100 M	9.40E+04	24.1	906	> 60	NA	3.03E+06	3.94E+06	NA	NA		
				Bond	8	3.86E+06	> 100 M	9.40E+04	41.0	1612	> 60	NA	6.10E+06	9.87E+06	NA	NA		
02-288404C	Modoc	2	299	No bond	10	1.64E+05	1.29E+05	9.40E+04	1.7	0	1.4	0	2.62E+05	2.67E+05	2.26E+05	2.29E+05		
				No bond	8	3.43E+05	4.58E+05	9.40E+04	3.6	109	4.9	255	4.53E+05	4.70E+05	5.80E+05	6.09E+05		
				Bond	10	1.52E+06	7.86E+07	9.40E+04	16.2	830	> 60	NA	1.91E+06	2.26E+06	NA	NA		
				Bond	8	2.75E+06	9.71E+07	9.40E+04	29.3	1581	> 60	NA	3.86E+06	5.35E+06	NA	NA		
02-288404D	Modoc	2	299	No bond	10	1.15E+05	2.79E+04	9.40E+04	1.2	0	0.3	0	2.11E+05	2.14E+05	1.22E+05	1.23E+05		
				No bond	8	2.78E+05	1.15E+05	9.40E+04	3.0	143	1.2	311	3.84E+05	3.95E+05	2.11E+05	2.14E+05		
				Bond	10	7.27E+05	7.12E+05	9.40E+04	7.7	534	7.6	2449	8.88E+05	9.61E+05	8.69E+05	9.39E+05		
				Bond	8	1.60E+06	2.19E+06	9.40E+04	17.0	1290	23.3	7737	2.01E+06	2.41E+06	2.90E+06	3.74E+06		
06-364804A	Kings	6	198	No bond	10	2.06E+05	1.52E+05	3.89E+05	0.5	0	0.4	0	5.98E+05	6.01E+05	5.43E+05	5.45E+05	6.3	36100
				No bond	8	4.26E+05	5.51E+05	3.89E+05	1.1	107	1.4	263	8.24E+05	8.33E+05	9.53E+05	9.67E+05		

Contract Number	County	District	Route	Bonding Condition	Air Void Cont. (%)	Design ESALs Asphalt Type		Actual ESALs per year	Asphalt A		Asphalt B		Traffic Growth Rate for Asphalt A		Traffic Growth Rate for Asphalt B		Length of paving (km)	Approx. AC Quantity (tons)
						A	B		Fatigue Life in Years	Percent Change	Fatigue Life in Years	Percent Change	2%	4%	2%	4%		
				Bond	10	1.87E+06	8.11E+07	3.89E+05	4.8	807	> 60	NA	2.37E+06	2.49E+06	NA	NA		
				Bond	8	3.27E+06	> 100 M	3.89E+05	8.4	1486	> 60	NA	3.98E+06	4.34E+06	NA	NA		
08-420804	San Berdo.	8	95	No bond	10	2.42E+06	7.44E+05	9.00E+04	26.9	0	8.3	0	3.31E+06	4.46E+06	9.07E+05	9.87E+05	2	8760
				No bond	8	5.31E+06	3.08E+06	9.00E+04	59.0	120	34.2	313	1.03E+07	2.14E+07	4.53E+06	6.69E+06		
				Bond	10	> 100 M	> 100 M	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Bond	8	> 100 M	> 100 M	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
08-399204B	Riverside	8	10	No bond	10	2.46E+05	1.35E+05	4.90E+06	0.1	0	0.0	0	5.15E+06	5.15E+06	5.04E+06	5.04E+06	31.2	255000
				No bond	8	5.41E+05	5.37E+05	4.90E+06	0.1	120	0.1	298	5.45E+06	5.45E+06	5.44E+06	5.45E+06		
				Bond	10	2.10E+06	8.54E+07	4.90E+06	0.4	755	17.4	63174	7.03E+06	7.06E+06	1.08E+08	1.30E+08		
				Bond	8	3.75E+06	> 100 M	4.90E+06	0.8	1425	> 60	NA	8.72E+06	8.78E+06	NA	NA		
09-213004A	Inyo	9	395	No bond	10	2.11E+05	1.01E+05	5.10E+05	0.4	0	0.2	0	7.24E+05	7.27E+05	6.12E+05	6.13E+05	4.2	35800
				No bond	8	3.23E+05	2.75E+05	5.10E+05	0.6	53	0.5	172	8.39E+05	8.44E+05	7.89E+05	7.93E+05		
				Bond	10	4.55E+05	4.54E+05	5.10E+05	0.9	115	0.9	349	9.73E+05	9.82E+05	9.72E+05	9.81E+05		
				Bond	8	1.03E+06	1.37E+06	5.10E+05	2.0	386	2.7	1255	1.57E+06	1.60E+06	1.93E+06	1.98E+06		
09-213004B	Inyo	9	395	No bond	10	1.68E+05	8.07E+04	5.10E+05	0.3	0	0.2	0	6.80E+05	6.83E+05	5.92E+05	5.93E+05		
				No bond	8	2.60E+05	2.20E+05	5.10E+05	0.5	55	0.4	173	7.74E+05	7.78E+05	7.33E+05	7.37E+05		
				Bond	10	3.81E+05	3.58E+05	5.10E+05	0.7	127	0.7	343	8.98E+05	9.05E+05	8.74E+05	8.80E+05		
				Bond	8	8.48E+05	1.07E+06	5.10E+05	1.7	404	2.1	1231	1.38E+06	1.40E+06	1.62E+06	1.65E+06		
09-251214A	Inyo	9	395	No bond	10	7.27E+05	4.11E+05	1.64E+05	4.4	0	2.5	0	9.32E+05	9.74E+05	5.90E+05	6.05E+05	6.9	50700
				No bond	8	1.63E+06	1.65E+06	1.64E+05	9.9	124	10.0	300	1.98E+06	2.19E+06	2.00E+06	2.22E+06		
				Bond	10	1.58E+07	> 100 M	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Bond	8	2.89E+07	> 100 M	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		

Table 11 Effect of Rich Bottom Layer Strategy.

Contract Number	County	District	Route	Strategy	Air Void Content (%)	ESALs Asphalt Type Type A	ESALs Asphalt Type Type B	Actual ESALs per year	Asphalt Type A Fatigue Life in Years	Asphalt Type A Percent Change	Asphalt Type B Fatigue Life in Years	Asphalt Type B Percent Change	Traffic Growth Rate for Asphalt Type A 2%	Traffic Growth Rate for Asphalt Type A 4%	Traffic Growth Rate for Asphalt Type B 2%	Traffic Growth Rate for Asphalt Type B 4%	Length of paving (km)	Approx. AC Quantity (tons)
01-195624	Mendocino	1	101	Normal Comp	10	1.16E+06	5.22E+06	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA	2.7	24200
				Normal Comp	8	2.34E+06	1.13E+07	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Better Comp	5	7.10E+06	4.26E+07	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Rich Bottom	2	2.05E+07	2.09E+08	6.00E+03	> 60	NA	> 60	NA	NA	NA	NA	NA		
08-420804	San Bernardino	8	95	Normal Comp	10	4.45E+08	3.96E+09	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA	2	8760
				Normal Comp	8	6.00E+08	4.50E+09	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Better Comp	5	1.02E+09	7.30E+09	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Rich Bottom	2	2.37E+09	2.29E+10	9.00E+04	> 60	NA	> 60	NA	NA	NA	NA	NA		
09-251214A	Inyo	9	395	Normal Comp	10	1.58E+07	6.81E+08	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA	6.9	50700
				Normal Comp	8	2.89E+07	9.46E+08	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Better Comp	5	7.55E+07	1.98E+09	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		
				Rich Bottom	2	2.02E+08	2.55E+09	1.64E+05	> 60	NA	> 60	NA	NA	NA	NA	NA		

Table 12 Cost Savings from Adopting New Compaction Standards

Contract No.	County	District	Route	Air Void Content (%)	Actual ESALs per year	Asphalt Type A Fatigue Life (Yrs)	Asphalt Type B Fatigue Life (Yrs)	Length - Km	Base Cost	New Cost - Asphalt A	Cost Savings - Asphalt A	New Cost - Asphalt B	Cost Savings - Asphalt B
01-224804	Mendocino	1	101	10	4.19E+05	0.8	> 60	3.9	$2,606,658	$2,592,882	$(13,776)	$2,245,768	$(360,890)
				8	4.19E+05	1.2	> 60	3.9	$2,606,658	$2,585,101	$(21,557)	$2,245,768	$(360,890)
				5	4.19E+05	2.6	> 60	3.9	$2,606,658	$2,561,990	$(44,668)	$2,245,768	$(360,890)
01-195624	Mendocino	1	101	10	1.41E+06	0.8	3.7	2.7	$1,853,875	$1,843,551	$(10,325)	$1,810,301	$(43,574)
				8	1.41E+06	1.7	8.0	2.7	$1,853,875	$1,833,393	$(20,482)	$1,768,422	$(85,454)
				5	1.41E+06	5.0	30.1	2.7	$1,853,875	$1,796,484	$(57,392)	$1,650,615	$(203,261)
01-297304	Humboldt	1	101	10	1.57E+05	> 60	> 60	6.1	$3,987,199	$3,422,730	$(564,469)	$3,422,730	$(564,469)
				8	1.57E+05	> 60	> 60	6.1	$3,987,199	$3,422,730	$(564,469)	$3,422,730	$(564,469)
				5	1.57E+05	> 60	> 60	6.1	$3,987,199	$3,422,730	$(564,469)	$3,422,730	$(564,469)
01-297004	Humboldt	1	101	10	2.76E+05	11.9	> 60	3.8	$2,516,008	$2,352,857	$(163,151)	$2,164,372	$(351,636)
				8	2.76E+05	19.4	> 60	3.8	$2,516,008	$2,288,962	$(227,046)	$2,164,372	$(351,636)
				5	2.76E+05	42.4	> 60	3.8	$2,516,008	$2,191,474	$(324,535)	$2,164,372	$(351,636)
01-349704	Lake	1	29	10	5.50E+04	> 60	> 60	19.2	$12,247,574	$10,470,886	$(1,776,688)	$10,470,886	$(1,776,688)
				8	5.50E+04	> 60	> 60	19.2	$12,247,574	$10,470,886	$(1,776,688)	$10,470,886	$(1,776,688)
				5	5.50E+04	> 60	> 60	19.2	$12,247,574	$10,470,886	$(1,776,688)	$10,470,886	$(1,776,688)
01-350204	Medocino	1	1	10	5.40E+04	35.0	> 60	28.8	$18,363,429	$16,057,127	$(2,306,301)	$15,698,396	$(2,665,032)
				8	5.40E+04	51.0	> 60	28.8	$18,363,429	$15,781,947	$(2,581,482)	$15,698,396	$(2,665,032)
				5	5.40E+04	> 60	> 60	28.8	$18,363,429	$15,698,396	$(2,665,032)	$15,698,396	$(2,665,032)
01-318404A	Lake	1	175	10	6.00E+03	57.0	> 60	0.4	$241,855	$205,166	$(36,689)	$204,841	$(37,014)
				8	6.00E+03	> 60	> 60	0.4	$241,855	$204,841	$(37,014)	$204,841	$(37,014)
				5	6.00E+03	> 60	> 60	0.4	$241,855	$204,841	$(37,014)	$204,841	$(37,014)
01-318404B	Lake	1	175	10	6.00E+03	21.4	28.6	0.4	$241,855	$216,481	$(25,374)	$212,429	$(29,426)
				8	6.00E+03	46.9	> 60	0.4	$241,855	$206,721	$(35,134)	$204,841	$(37,014)
				5	6.00E+03	> 60	> 60	0.4	$241,855	$204,841	$(37,014)	$204,841	$(37,014)
02-259104	Modoc	2	395	10	5.80E+04	40.9	> 60	17.7	$11,304,843	$9,809,221	$(1,495,621)	$9,666,958	$(1,637,884)
				8	5.80E+04	> 60	> 60	17.7	$11,304,843	$9,666,958	$(1,637,884)	$9,666,958	$(1,637,884)
				5	5.80E+04	> 60	> 60	17.7	$11,304,843	$9,666,958	$(1,637,884)	$9,666,958	$(1,637,884)
02-288404A	Modoc	2	299	10	9.40E+04	32.3	> 60	7.2	$4,650,765	$4,092,176	$(558,589)	$3,984,506	$(666,258)
				8	9.40E+04	55.4	> 60	7.2	$4,650,765	$3,993,963	$(656,801)	$3,984,506	$(666,258)
				5	9.40E+04	> 60	> 60	7.2	$4,650,765	$3,984,506	$(666,258)	$3,984,506	$(666,258)

Contract No.	County	District	Route	Air Void Content (%)	Actual ESALs per year	Asphalt Type A Fatigue Life (Yrs)	Asphalt Type B Fatigue Life (Yrs)	Length - Km	Base Cost	New Cost - Asphalt A	Cost Savings - Asphalt A	New Cost - Asphalt B	Cost Savings - Asphalt B
02-288404B	Modoc	2	299	10	9.40E+04	24.1	> 60	7.2	$4,650,765	$4,163,868	$(486,897)	$3,984,506	$(666,258)
				8	9.40E+04	41.0	> 60	7.2	$4,650,765	$4,041,891	$(608,874)	$3,984,506	$(666,258)
				5	9.40E+04	> 60	> 60	7.2	$4,650,765	$3,984,506	$(666,258)	$3,984,506	$(666,258)
02-288404C	Modoc	2	299	10	9.40E+04	16.2	> 60	7.2	$4,650,765	$4,266,204	$(384,560)	$3,984,506	$(666,258)
				8	9.40E+04	29.3	> 60	7.2	$4,650,765	$4,115,556	$(535,208)	$3,984,506	$(666,258)
				5	9.40E+04	> 60	> 60	7.2	$4,650,765	$3,984,506	$(666,258)	$3,984,506	$(666,258)
02-288404D	Modoc	2	299	10	9.40E+04	7.7	7.6	7.2	$4,650,765	$4,429,419	$(221,345)	$4,433,397	$(217,368)
				8	9.40E+04	17.0	23.3	7.2	$4,650,765	$4,254,364	$(396,400)	$4,173,007	$(477,758)
				5	9.40E+04	59.2	> 60	7.2	$4,650,765	$3,986,096	$(664,669)	$3,984,506	$(666,258)
06-364804A	Kings	6	198	10	3.89E+05	4.8	> 60	6.3	$4,203,730	$4,074,976	$(128,754)	$3,620,754	$(582,976)
				8	3.89E+05	8.4	> 60	6.3	$4,203,730	$3,996,530	$(207,199)	$3,620,754	$(582,976)
				5	3.89E+05	21.0	> 60	6.3	$4,203,730	$3,809,192	$(394,538)	$3,620,754	$(582,976)
06-364804B	Kings	6	198	10	3.89E+05	2.4	> 60	6.3	$4,203,730	$4,135,552	$(68,178)	$3,620,754	$(582,976)
				8	3.89E+05	3.9	> 60	6.3	$4,203,730	$4,096,636	$(107,094)	$3,620,754	$(582,976)
				5	3.89E+05	8.6	> 60	6.3	$4,203,730	$3,993,422	$(210,307)	$3,620,754	$(582,976)
06-387704	Madera	6	41	10	1.02E+05	27.8	> 60	6.3	$4,077,143	$3,619,500	$(457,643)	$3,494,167	$(582,976)
				8	1.02E+05	42.9	> 60	6.3	$4,077,143	$3,537,186	$(539,957)	$3,494,167	$(582,976)
				5	1.02E+05	> 60	> 60	6.3	$4,077,143	$3,494,167	$(582,976)	$3,494,167	$(582,976)
06-335904	Kern	6	33	10	1.99E+05	> 60	> 60	2.7	$1,774,433	$1,524,587	$(249,847)	$1,524,587	$(249,847)
				8	1.99E+05	> 60	> 60	2.7	$1,774,433	$1,524,587	$(249,847)	$1,524,587	$(249,847)
				5	1.99E+05	> 60	> 60	2.7	$1,774,433	$1,524,587	$(249,847)	$1,524,587	$(249,847)
08-420804	San Bernardino	8	95	10	9.00E+04	> 60	> 60	2	$1,290,574	$1,105,502	$(185,072)	$1,105,502	$(185,072)
				8	9.00E+04	> 60	> 60	2	$1,290,574	$1,105,502	$(185,072)	$1,105,502	$(185,072)
				5	9.00E+04	> 60	> 60	2	$1,290,574	$1,105,502	$(185,072)	$1,105,502	$(185,072)
08-399204A	Riverside	8	10	10	4.90E+06	0.2	> 60	31.2	$22,005,030	$21,975,361	$(29,669)	$19,117,911	$(2,887,118)
				8	4.90E+06	0.3	> 60	31.2	$22,005,030	$21,958,500	$(46,530)	$19,117,911	$(2,887,118)
				5	4.90E+06	0.7	> 60	31.2	$22,005,030	$21,907,408	$(97,622)	$19,117,911	$(2,887,118)
08-399204B	Riverside	8	10	10	4.90E+06	0.4	17.4	31.2	$22,005,030	$21,941,860	$(63,170)	$20,258,516	$(1,746,514)
				8	4.90E+06	0.8	> 60	31.2	$22,005,030	$21,893,285	$(111,745)	$19,117,911	$(2,887,118)
				5	4.90E+06	1.9	> 60	31.2	$22,005,030	$21,736,375	$(268,655)	$19,117,911	$(2,887,118)
09-213004A	Inyo	9	395	10	5.10E+05	0.9	0.9	4.2	$2,819,561	$2,802,087	$(17,474)	$2,802,123	$(17,438)
				8	5.10E+05	2.0	2.7	4.2	$2,819,561	$2,781,131	$(38,429)	$2,769,140	$(50,421)

Contract No.	County	District	Route	Air Void Content (%)	Actual ESALs per year	Asphalt Type A Fatigue Life (Yrs)	Asphalt Type B Fatigue Life (Yrs)	Length - Km	Base Cost	New Cost - Asphalt A	Cost Savings - Asphalt A	New Cost - Asphalt B	Cost Savings - Asphalt B
				5	5.10E+05	6.7	15.1	4.2	$2,819,561	$2,704,745	$(114,816)	$2,605,464	$(214,097)
09-213004B	Inyo	9	395	10	5.10E+05	0.7	0.7	4.2	$2,819,561	$2,804,849	$(14,712)	$2,805,733	$(13,828)
				8	5.10E+05	1.7	2.1	4.2	$2,819,561	$2,787,571	$(31,989)	$2,779,434	$(40,126)
				5	5.10E+05	5.6	11.9	4.2	$2,819,561	$2,720,826	$(98,734)	$2,638,530	$(181,030)
09-213004C	Inyo	9	395	10	5.10E+05	0.0	0.0	4.2	$2,819,561	$2,819,134	$(427)	$2,818,734	$(826)
				8	5.10E+05	0.0	0.1	4.2	$2,819,561	$2,818,675	$(886)	$2,817,667	$(1,894)
				5	5.10E+05	0.1	0.4	4.2	$2,819,561	$2,816,818	$(2,743)	$2,812,179	$(7,382)
09-251214A	Inyo	9	395	10	1.64E+05	> 60	> 60	6.9	$4,514,628	$3,876,131	$(638,497)	$3,876,131	$(638,497)
				8	1.64E+05	> 60	> 60	6.9	$4,514,628	$3,876,131	$(638,497)	$3,876,131	$(638,497)
				5	1.64E+05	> 60	> 60	6.9	$4,514,628	$3,876,131	$(638,497)	$3,876,131	$(638,497)
09-251214B	Inyo	9	395	10	1.64E+05	0.8	0.8	6.9	$4,514,628	$4,490,339	$(24,289)	$4,488,831	$(25,797)
				8	1.64E+05	1.2	1.5	6.9	$4,514,628	$4,477,028	$(37,601)	$4,465,523	$(49,105)
				5	1.64E+05	3.9	8.0	6.9	$4,514,628	$4,398,327	$(116,301)	$4,297,572	$(217,056)
11-201504A	San Diego	11	54	10	1.17E+05	19.4	> 60	0.8	$519,380	$471,556	$(47,824)	$445,351	$(74,029)
				8	1.17E+05	26.9	> 60	0.8	$519,380	$462,166	$(57,214)	$445,351	$(74,029)
				5	1.17E+05	48.5	> 60	0.8	$519,380	$448,500	$(70,880)	$445,351	$(74,029)
11-201504B	San Diego	11	54	10	1.17E+05	16.2	> 60	0.8	$519,380	$476,696	$(42,684)	$445,351	$(74,029)
				8	1.17E+05	22.5	> 60	0.8	$519,380	$467,264	$(52,116)	$445,351	$(74,029)
				5	1.17E+05	40.4	> 60	0.8	$519,380	$452,081	$(67,299)	$445,351	$(74,029)
11-2233U4	San Diego	11	78	10	5.20E+04	45.0	> 60	59.9	$38,159,448	$32,955,003	$(5,204,446)	$32,616,551	$(5,542,897)
				8	5.20E+04	> 60	> 60	59.9	$38,159,448	$32,616,551	$(5,542,897)	$32,616,551	$(5,542,897)
				5	5.20E+04	> 60	> 60	59.9	$38,159,448	$32,616,551	$(5,542,897)	$32,616,551	$(5,542,897)

Table 13 Cost Savings from Use of Tack Coat

Contract Number	County	District	Route	Air-Void Content (%)	Actual ESALs per year	Valley Fatigue Life (Yrs)	Coastal Fatigue Life (Yrs)	Length - Kms	Base Cost	New Cost - Asphalt Type A	Cost Savings - Asphalt Type A	New Cost - Asphalt Type B	Cost Savings – Asphalt Type B	Bonding Condition
01-195624	Mendocino	1	101	10	1.41E+06	0.1	0.0	2.7	$1,853,875	$1,852,910	$(965)	$1,853,568	$(308)	No bond
				8	1.41E+06	0.2	0.1	2.7	$1,853,875	$1,851,625	$(2,251)	$1,852,647	$(1,228)	No bond
				10	1.41E+06	0.8	3.7	2.7	$1,853,875	$1,843,551	$(10,325)	$1,810,301	$(43,574)	Bond
				8	1.41E+06	1.7	8.0	2.7	$1,853,875	$1,833,393	$(20,482)	$1,768,422	$(85,454)	Bond
01-318404A	Lake	1	175	10	6.00E+03	9.8	5.6	0.4	$241,855	$227,045	$(14,810)	$232,463	$(9,392)	No bond
				8	6.00E+03	21.1	20.3	0.4	$241,855	$216,737	$(25,118)	$217,290	$(24,566)	No bond
				10	6.00E+03	57.0	60.0	0.4	$241,855	$205,166	$(36,689)	$204,841	$(37,014)	Bond
				8	6.00E+03	60.0	60.0	0.4	$241,855	$204,841	$(37,014)	$204,841	$(37,014)	Bond
01-318404B	Lake	1	175	10	6.00E+03	5.8	2.0	0.4	$241,855	$232,196	$(9,659)	$238,219	$(3,636)	No bond
				8	6.00E+03	13.3	7.5	0.4	$241,855	$223,232	$(18,623)	$229,925	$(11,930)	No bond
				10	6.00E+03	21.4	28.6	0.4	$241,855	$216,481	$(25,374)	$212,429	$(29,426)	Bond
				8	6.00E+03	46.9	60.0	0.4	$241,855	$206,721	$(35,134)	$204,841	$(37,014)	Bond
02-288404A	Modoc	2	299	10	9.40E+04	3.1	2.4	7.2	$4,650,765	$4,553,168	$(97,597)	$4,573,813	$(76,951)	No bond
				8	9.40E+04	6.5	8.6	7.2	$4,650,765	$4,459,857	$(190,907)	$4,409,242	$(241,522)	No bond
				10	9.40E+04	32.3	60.0	7.2	$4,650,765	$4,092,176	$(558,589)	$3,984,506	$(666,258)	Bond
				8	9.40E+04	55.4	60.0	7.2	$4,650,765	$3,993,963	$(656,801)	$3,984,506	$(666,258)	Bond
02-288404B	Modoc	2	299	10	9.40E+04	2.4	1.8	7.2	$4,650,765	$4,573,088	$(77,677)	$4,590,290	$(60,474)	No bond
				8	9.40E+04	5.0	6.7	7.2	$4,650,765	$4,498,803	$(151,962)	$4,454,744	$(196,020)	No bond
				10	9.40E+04	24.1	60.0	7.2	$4,650,765	$4,163,868	$(486,897)	$3,984,506	$(666,258)	Bond
				8	9.40E+04	41.0	60.0	7.2	$4,650,765	$4,041,891	$(608,874)	$3,984,506	$(666,258)	Bond
02-288404C	Modoc	2	299	10	9.40E+04	1.7	1.4	7.2	$4,650,765	$4,593,414	$(57,351)	$4,605,091	$(45,673)	No bond
				8	9.40E+04	3.6	4.9	7.2	$4,650,765	$4,535,981	$(114,783)	$4,501,751	$(149,014)	No bond
				10	9.40E+04	16.2	60.0	7.2	$4,650,765	$4,266,204	$(384,560)	$3,984,506	$(666,258)	Bond
				8	9.40E+04	29.3	60.0	7.2	$4,650,765	$4,115,556	$(535,208)	$3,984,506	$(666,258)	Bond
02-288404D	Modoc	2	299	10	9.40E+04	1.2	0.3	7.2	$4,650,765	$4,610,049	$(40,715)	$4,640,640	$(10,125)	No bond
				8	9.40E+04	3.0	1.2	7.2	$4,650,765	$4,556,045	$(94,719)	$4,610,083	$(40,681)	No bond
				10	9.40E+04	7.7	7.6	7.2	$4,650,765	$4,429,419	$(221,345)	$4,433,397	$(217,368)	Bond
				8	9.40E+04	17.0	23.3	7.2	$4,650,765	$4,254,364	$(396,400)	$4,173,007	$(477,758)	Bond
06-364804A	Kings	6	198	10	3.89E+05	0.5	0.4	6.3	$4,203,730	$4,188,010	$(15,719)	$4,192,117	$(11,613)	No bond
				8	3.89E+05	1.1	1.4	6.3	$4,203,730	$4,171,693	$(32,037)	$4,162,603	$(41,127)	No bond
				10	3.89E+05	4.8	60.0	6.3	$4,203,730	$4,074,976	$(128,754)	$3,620,754	$(582,976)	Bond

Contract Number	County	District	Route	Air-Void Content (%)	Actual ESALs per year	Valley Fatigue Life (Yrs)	Coastal Fatigue Life (Yrs)	Length - Kms	Base Cost	New Cost - Asphalt Type A	Cost Savings - Asphalt Type A	New Cost - Asphalt Type B	Cost Savings – Asphalt Type B	Bonding Condition
				8	3.89E+05	8.4	60.0	6.3	$4,203,730	$3,996,530	$(207,199)	$3,620,754	$(582,976)	Bond
08-420804	San Bernardino	8	95	10	9.00E+04	26.9	8.3	2	$1,290,574	$1,147,774	$(142,800)	$1,225,648	$(64,926)	No bond
				8	9.00E+04	59.0	34.2	2	$1,290,574	$1,106,049	$(184,525)	$1,131,931	$(158,642)	No bond
				10	9.00E+04	60.0	60.0	2	$1,290,574	$1,105,502	$(185,072)	$1,105,502	$(185,072)	Bond
				8	9.00E+04	60.0	60.0	2	$1,290,574	$1,105,502	$(185,072)	$1,105,502	$(185,072)	Bond
08-399204B	Riverside	8	10	10	4.90E+06	0.1	0.0	31.2	$22,005,030	$21,997,574	$(7,456)	$22,000,935	$(4,095)	No bond
				8	4.90E+06	0.1	0.1	31.2	$22,005,030	$21,988,659	$(16,371)	$21,988,771	$(16,259)	No bond
				10	4.90E+06	0.4	17.4	31.2	$22,005,030	$21,941,860	$(63,170)	$20,258,516	$(1,746,514)	Bond
				8	4.90E+06	0.8	60.0	31.2	$22,005,030	$21,893,285	$(111,745)	$19,117,911	$(2,887,118)	Bond
09-213004A	Inyo	9	395	10	5.10E+05	0.4	0.2	4.2	$2,819,561	$2,811,339	$(8,222)	$2,815,609	$(3,952)	No bond
				8	5.10E+05	0.6	0.5	4.2	$2,819,561	$2,807,052	$(12,509)	$2,808,907	$(10,653)	No bond
				10	5.10E+05	0.9	0.9	4.2	$2,819,561	$2,802,087	$(17,474)	$2,802,123	$(17,438)	Bond
				8	5.10E+05	2.0	2.7	4.2	$2,819,561	$2,781,131	$(38,429)	$2,769,140	$(50,421)	Bond
09-213004B	Inyo	9	395	10	5.10E+05	0.3	0.2	4.2	$2,819,561	$2,813,008	$(6,552)	$2,816,401	$(3,160)	No bond
				8	5.10E+05	0.5	0.4	4.2	$2,819,561	$2,809,457	$(10,104)	$2,810,996	$(8,564)	No bond
				10	5.10E+05	0.7	0.7	4.2	$2,819,561	$2,804,849	$(14,712)	$2,805,733	$(13,828)	Bond
				8	5.10E+05	1.7	2.1	4.2	$2,819,561	$2,787,571	$(31,989)	$2,779,434	$(40,126)	Bond
09-251214A	Inyo	9	395	10	1.64E+05	4.4	2.5	6.9	$4,514,628	$4,383,396	$(131,232)	$4,436,926	$(77,702)	No bond
				8	1.64E+05	9.9	10.0	6.9	$4,514,628	$4,255,581	$(259,047)	$4,253,483	$(261,145)	No bond
				10	1.64E+05	60.0	60.0	6.9	$4,514,628	$3,876,131	$(638,497)	$3,876,131	$(638,497)	Bond
				8	1.64E+05	60.0	60.0	6.9	$4,514,628	$3,876,131	$(638,497)	$3,876,131	$(638,497)	Bond

This research has clearly established that increased compaction results in significant cost savings. The next issue this study explored was whether there were increasing returns from increasing compaction even further. For example, would a move from 10 percent air-void content to 8 percent air-void content lead to greater than a 20 percent increase in cost savings? When the data was examined, significant variation were found. Increasing compaction always resulted in cost savings, but a move from 10 to 8 to 5 percent air-void content would in some cases lead to even larger cost savings and in other cases the increase in cost savings was linear with the increase in compaction (decrease in air-void content). This is an area requiring more research and, in particular, exploration of the question of the 'optimal' level of air-void content.

In Table 13, similar calculations are shown for the use of a tack coat. The results are similar to those for increased compaction. One asphalt type provides much higher cost savings than the other. In fact, <u>the total cost savings from using tack coats with one asphalt type is approximately $6 million while with the another asphalt type, the cost savings are in excess of $12 million</u>. Again, it is shown that the use of the new pavement technology provides a sizable return and that the differences between the sources of asphalt persist.

It is also possible, using the information in Table 13, to assess the expected return of combining technologies. The projects carried out had differences in their air-void contents as well as whether they included tack coats between asphalt concrete lifts. When one compares the cost savings, regardless of the source of the asphalt, reducing air-void content has a significant cost savings; when coupled with the use of tack coats, the cost savings increases dramatically. For one type of asphalt, the reduction of air-void contents from 10 to 8 percent provides cost savings of approximately $2 million; when coupled with the use of tack coats, this savings increases by $6 million for a total of near $8 million. Comparable figures for the other asphalt considered are $1.5 million for the reduction in air-void contents alone, and an additional $12 million when using tack coats.

It would be useful to explore how the cost savings differed across projects and perhaps by location. As with the case of compaction, when comparisons were made, there did not seem to be a regular pattern or discernable characteristic that led to consistently higher cost savings.

7.0 SUMMARY

This research has shown that new pavement technologies, primarily consisting of the method of application of pavement materials, can deliver significant cost savings for Caltrans in maintenance and rehabilitation efforts on the California roadway system. Under the present system, the agency uses a life cycle costing model to minimize the sum of capital and maintenance costs. In calculating future maintenance costs, the agency considers the direct costs to the agency through contracts. What is not considered is the impact on traffic flow, safety, and the environment. In other words, users are not considered as part of the equation. Yet, the optimization problem should be to minimize *the sum* of infrastructure, maintenance, and user costs. The first two components reflect the conventional life cycle cost model, however, consideration of user costs is new. What has been missing is the recognition that once user costs over the lifetime of the facility are taken into account, the standard to which a facility is built and the frequency of required repair and rehabilitation would change from that which it is currently. The new pavement technologies reviewed and evaluated in this research provide a means of reducing all costs, including those directly incurred by Caltrans and those incurred by users and the general public.

The objective of this study was to evaluate the net economic benefits of three changes in flexible pavement technology recommended by CAL/APT. The recommended changes are:

- Increase compaction requirements for asphalt concrete. As part of this recommendation, this study also recommends that Caltrans change the basis for measurement of compaction from the Laboratory Test Maximum Density (LTMD) to the theoretical maximum specific gravity (G_{max}) as determined by ASTM D 2041 (Rice Method) or the equivalent Superpave test method. Caltrans currently typically requires 95 percent or 96 percent compaction relative to LTMD. It is recommended that Caltrans require 93 percent compaction relative to G_{max} for less critical asphalt concrete projects, and 94 percent compaction relative to G_{max} on more critical projects. The recommended change should result in air-void contents of about five percent.

- Require the use of tack coats to improve bonding between asphalt concrete lifts on all construction projects. Caltrans currently requires placement of a tack coat on overlay projects between the top of the existing pavement and the first lift of the overlay. Caltrans currently does not require tack coats between multiple lifts being constructed as part of the same project, unless directed by the Engineer. It has been found that even under ideal construction conditions, a bond is not always formed between successive lifts of an asphalt pavement without the use of a tack coat.(*3*)
- Include a Rich Bottom Layer in thick asphalt concrete structures. In asphalt concrete structures that are 150 mm or thicker, include an asphalt concrete layer with increased fatigue resistance as the first lift. This layer is known as a "Rich Bottom Layer"; its increased fatigue resistance is achieved through compaction to two percent air voids and increase of the asphalt content by 0.5 percent. The Rich Bottom Layer should be 50 to 75 mm thick.

Applying these recommendations to standard Caltrans practice would result in a roadway that lasts longer and does not require the amount of maintenance and rehabilitation that currently exists, thereby saving Caltrans and the public significant dollar amounts.

The full cost model, developed in Section 4.2.1, was used to calculate the direct cost savings to Caltrans with the use of the new pavement technologies. The new pavement technologies were represented as increasing the life of the roadway and the time between necessary maintenance and rehabilitation actions. This study showed that an increase of the period between overlays by 15 percent results in savings of $6,933 per two-lane-km equivalent. Applying this saving to the roadway system for the state of California yields potential statewide savings of over $56 million. If the period between overlays is extended by 5 years, the statewide savings is more than $244 million, a net present value of more than $163 million.

In addition to these direct savings, user cost savings and safety cost savings will also be realized. Because maintenance and rehabilitation actions will be required less frequently, and therefore, fewer shutdowns, closures, and roadway capacity reductions will be required, user costs and safety costs will be reduced. These savings were calculated for a representative project on I-5 near Sacramento. For this example, this study shows that the time cost savings would be $1,335,600, or 54 percent of the total benefits. Benefits to safety improvements amounted to $658,627, approximately 20 percent of the total benefits. The direct cost savings to Caltrans on this project amounted to $468,480, or 19 percent of the total.

The increase in pavement life and reduction in frequency of required rehabilitation has led to a benefit of approximately $2.5 million for this representative project. This benefit is realized at relatively little cost. The use of the new pavement technology is a primarily focused on *method* or *technique* of application rather than new, additional, or more costly materials. New pavement technologies may result in a small initial increase in labor costs while contractors become familiar with the techniques, however, at some point the techniques would be commonplace and have little or no impact on man-hours of labor required on a given contract.

The potential for cost savings using these new pavement technologies appears to be quite large. In the representative project they were 19 percent of total benefits. If applied statewide, and using the factor of proportionality of 19 percent, the total savings potential may be in the neighborhood of $857 million (1998 dollars). More research is required to explore the additional costs, if any, and how benefits may vary among types of projects, pavement age, and project location.

This study examined the cost savings from introducing different pavement technologies for a set of projects being carried out by Caltrans in the period of 1997 to early 1999, primarily in rural locations. The information is set out in Tables 11 through 13 inclusive. The total life cycle cost savings from the use of increased compaction for this set of actual projects being carried out by Caltrans would be between $50,611,908 and $72,515,913 over the life of the pavement. This is clearly a sizable savings from a relatively minor investment in technique. Note that there is a significant amount of variation across sites, and that asphalt type has a significant effect on cost and benefit.

This study also compared proportionate change in air-void content with the proportionate change in costs for both types of asphalt considered. There did not appear to be any pattern. In some cases, a move from 10 to 8 to 5 percent air-void content led to huge cost savings; in other cases, the cost savings were minor. Further work needs to be conducted to determine the optimal air-void content.

The total savings from using tack coats varied from $6-12 million for a number of projects. These savings, as those discussed elsewhere in this study, only apply to the projects considered and are not reflective of the expected savings if the technologies were adopted statewide—statewide adoption of these technologies would lead to a multifold increase in these cost savings.

This study also found that there are synergies between technologies. Coupling two pavement technologies appeared to lead to a better than linear increase in cost savings. However, this observation needs more investigation to be validated.

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